Graded Microstructure of Additively Manufactured Ti-6Al-4V via Electron Beam Melting

Hansheng Chen[1,2,3], Christopher Cooper[1], Cameron Durrant[1], Yingluo Li[1], Katja Eder[1,3], Sophie Primig[4], Xiaozhou Liao[1], Sudarsanam Suresh Babu[5,6], and Simon P. Ringer[1,3]

[1]*School of Aerospace, Mechanical, and Mechatronic Engineering, The University of Sydney, Sydney, NSW, 2006, Australia*
[2]*The University of Sydney Nano Institute, The University of Sydney, Sydney, NSW, 2006, Australia*
[3]*Australian Centre for Microscopy and Microanalysis, The University of Sydney, NSW, 2006, Australia*
[4]*School of Materials Science and Engineering, UNSW Sydney, NSW, 2052, Australia*
[5]*Department of Mechanical, Aerospace, and Biomedical Engineering, University of Tennessee, Knoxville, Tennessee, TN, 37996, USA*
[6]*Manufacturing Demonstration Facility, Oak Ridge National Laboratory, Knoxville, TN, 37830, USA*
e: hansheng.chen@sydney.edu.au

Ti-6Al-4V alloy is one of the most vital engineering materials and has been applied in aerosapce and biomedical industry due to its high strength-to-weight ratio and ourstanding biocampatility.

This work will report preliminary observations of the electron beam melted Ti-6Al-4V alloys by light optical microscopy (LOM), scanning electron microscopy/electron backscatter diffraction/energy dispersive spectroscopy (SEM/EBSD/EDS), and atom probe tomography (APT). The LOM was utilized to reveal the morphology and microstructural evolution from top to bottom layers. The data collected by SEM/EBSD/EDS can be plotted in the form of maps, showing the grain size distribution, phase distribution, grain boundary information, crystallographic orientation, texture, and corresponding elemental distribution of top, middle and bottom layers. APT was used to detect individual atoms in three dimensions to visualize the phase interfacial elemental variation at the nanoscale.

This is part of the broader AUSMURI project concerning additively manufactured Ti- and Ni-based alloys.

The authors acknowledge the facilities, scientific and technical assistance of the Microscopy Australia node at the University of Sydney (Sydney Microscopy & Microanalysis). The research was sponsored by the Department of Industry, Innovation and Science under the auspices of the AUSMURI program. The authors also gratefully acknowledge financial support from the Department of the Navy, Office of Naval Research under ONR award number N00014-18-1-2794. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Office of Naval Research. The research was also sponsored by the US Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office under contract DE-AC05-00OR22725 with UT-Battelle, LLC. Access to the Oak Ridge National Laboratory's (ORNL) additive manufacturing equipment at ORNL's Manufacturing Demonstration Facility (MDF) was facilitated by US Department of Energy's Strategic Partnership Projects (SPP) mechanism. More information can be found at https://science.energy.gov/lp/strategic-partnership-projects. Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

New applications of hybrid multi-materials and smart design

Maxence Bourjol[1]
[1] *3DCERAM Sinto, Limoges, 87280, France*
e: maxence.bourjol@3dceram.com

Technical ceramics is no stranger to the fourth industrial revolution. There is a clear demand for production of complex parts, new designs or new applications, that involve short lead times and limited investment. Many users of technical ceramics are counting of 3D printing to make ceramics more accessible by cutting development times and simplifying the production process. Yet, aside from 3D printing technology itself, the complexity involved in working with ceramics puts off 3DCERAM Sinto compelled to design their own tool to meet their needs. Among other initiatives, 3DCERAM developed its 3D printer (CERAMAKER) based on stereolithography (SLA) to satisfy demands.

3DCERAM Sinto lets users push back production limits. To open up this technology to a wider spread of professionals, 3DCERAM is sharing its maker experience to propose smart design (multi-function parts) and multi-material solutions. Thus, the new Ceramaker Hybrid is able to print several materials at the same time. Our hybrid solutions are based on SLA process for the subtract, and another deposit technology for the track of the other material(s). In all cases the objective is to have a compatible system between all materials deposited to have cofired system at the end (compatible ceramic material and solid loading)

Implementing metal Additive Manufacturing - A practical guide

Matthias Bringezu
CONSULT3D Pty Ltd, Melbourne, 3000, Australia
mbringezu@consult3D.com

Implementing metal Additive Manufacturing (AM) such as Laser Powder Bed Fusion (LPBF) always represents a multi-faceted challenge. In a systematic approach, the tasks can be categorised into three work packages:
First, machine selection through a structured evaluation and benchmarking process; Second, determination of the optimal machine layout under consideration of infrastructure and OHS requirements; Third, process design from material handling to post-processing and measures for quality assurance and certification. Usually, these steps must be taken under the pressure of heavy capital investment and the objective of a quick ROI. This session will shed light on risks and opportunities and provide practical guidance for implementing metal AM.

Laval Nozzle Optimisation for Titomic Kinetic Fusion® Systems

Mr Jayesh Modi
Titomic Limited, Melbourne, 3168, Australia;
e: info@titomic.com

Application of Kinetic deposition is rapidly expanding, and varied applications are being developed. A vast body of research has been carried out in field of coatings using Kinetic deposition technology, however, in order to progress from coatings to additive manufacturing we need specific improvements in deposition rates, porosity, and residual stress to create ductile materials directly from the nozzle.

A key component of a cold spray system is a Convergent-Divergent / Laval Nozzle, wherein the energy of high-temperature, high-pressure gas is converted into kinetic energy accelerating it to supersonic speed, typically 3 to 4 times speed of sound. Metal particles introduced in this gas stream pickup speed and upon impinging the substrate fuse together making a strong interparticle metallurgical bond.

New metal powders, combined with a high-efficiency nozzle, would lead to improved build quality at increased build rates, improving commercial attractiveness of Titomic Kinetic Fusion® technology. We will present through numerical study interplay of various design parameters and propose a method to optimise nozzle design by expanding on the application of knowledge from the aerospace industry.

Selective Laser Melting of Ti6Al4V: Effect of Remelting

J. Karimi[1], Prashanth Konda Gokuldoss[1, 2]
[1]*Department of Mechanical and Industrial Engineering, Tallinn University of Technology, Tallinn, 19086, Estonia;*
[2]*Erich Schmid Institute of Materials Science, Austrian Academy of Sciences, Leoben, 8700, Austria;*
e: jkarim@ttu.ee

Selective Laser Melting (SLM) is an additive manufacturing technique, which produces complex metallic components from alloy powder by selectively melting micron-sized powder in successive layers. This process is characterized by highly localized heat inputs with rapid solidification. The typical Ti-6Al-4V microstructure consists of transformed β containing acicular α as well as α at prior-β grain boundaries. In this paper, the remelting and hatch style effects on Ti6Al4V parts fabricated by SLM on microstructure, microhardness and tensile properties are studied. Microstructural characterization was carried out using both optical and scanning electron microscopy. The microstructure consists of a fine acicular martensite (α′ phase). Results of double and triple melted samples suggest that both microstructure and mechanical properties were altered significantly and this interesting aspect will be discussed in detail.

Stereolithographic Additive Manufacturing of Fine Ceramic Components

Soshu Kirihara, Osaka University

Artificial dendrite structures with spatially ordered micro-cavities were successfully fabricated using three-dimensional stereolithographic printing. Micrometer-scale metals or ceramic lattices with various coordination numbers were propagated spatially in a computer graphic space. The model data were converted into a stereolithographic format using polyhedral approximations. The ceramic nanoparticles were dispersed in photosensitive liquid resins to obtain thixotropic slurries. The highly viscous resin paste was fed using controlled air pressure, and uniformly spread using a mechanical knife edge. Cross-sectional patterns were formed using laser drawing and micro-patterning. A high-resolution image could be achieved by using a finely focused laser beam and digital micro-mirror device. Solid microstructures were built by stacking these patterns layer by layer. In order to avoid deformation and cracking during dewaxing and sintering, careful investigation of the heat treatment process was required. The formed precursors with dendrite structures were heated in an air atmosphere. Ceramic micro-components with geometrically designed patterns composed of functional ceramics were fabricated successfully. The components showed dendrite structures with periodic arrangements of micro-lattices to effectively control and modulate electromagnetic wave propagations and liquid material fluid flows. The technological details of the ceramic free forming and applications of the functional dendrite structures will be discussed herein.

Fabrication of Microstructures by Electric Discharge Deposition Technique

J. Shimizu[1], M. Ishii[2], Y. Koinuma[2], T. Yamamoto[1], H. Ojima[1], T. Onuki[1], L. Zhou[1]
[1]*College of Engineering, Ibaraki University, Hitachi, 316-8511, Japan;*
[2]*Graduate School, Ibaraki University, Hitachi, 316-8511, Japan*
e: jun.shimizu.nlab@vc.ibaraki.ac.jp

In this research, to realize the fabrication of 3-D microstructures using the electric discharge deposition technique, two different types of scanning methods such as traversable and layer stacking ones were examined using needle-like micro Cu-W electrodes in the atmospheric environment. As a result, a few different types of 3-D microstructures including straight and spring-like inclined micro needles were fabricated using the traversable scanning method, although there were still some issues in both the repeatability and accuracies. Fabrication of a simple 3-D microstructure was also examined by using the layer stacking method, and it was achieved almost successfully.

The effect of addition of trace boron on the microstructure and mechanical properties of Ti6Al4V produced by laser directed energy deposition

Aitang Xue[1,2], Lilin Wang[1,2], Xin Lin[1,2]*, Jian Wang[1,2], Weidong Huang[1,2]
[1]*State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an, Shaanxi, 710072, PR China*
[2]*Key Laboratory of Metal High Performance Additive Manufacturing and Innovative Design, MIIT China, Northwestern Polytechnical University, Xi'an, Shaanxi, 710072, P R China*
* Corresponding author.
E-mail address: xlin@nwpu.edu.cn (X. Lin).

Abstract
The characteristics of rapid cooling and repeat heating of laser directed energy deposition (L-DED) titanium alloy using laser solid forming (LSF) lead to the coarse β columnar grains and fine intragranular α phases, resulting in high-strength, low-elongation and significant anisotropy. This paper studies the effect of the addition of boron on the morphology of β grains and α phases, and the tensile properties of Ti6Al4V deposits. With the addition of boron, the prior β columnar grains are significantly refined owing to the growth restricting effect induced by boron and the continuous coarse grain boundary α laths are eliminated due to the discontinuous distribution of TiB between the dendrites, the length and aspect ratio of intragranular α phases are gradually reduced due to the growing space limit induced by the refined prior β grains and the heterogeneous nucleation of α phases on the TiB phases. With the increase of boron content, the ultimate tensile strength and yield strength of the Ti6Al4V deposits in longitudinal direction (parallel to the building direction) increase due to the fine-grain strengthening and the load-bearing of TiB phases, but the elongation decreases due to the poor compatible deformation capability between the TiB phase and β matrix.

Microstructure and mechanical properties of wire and arc additive manufacturing Zr-alloying low alloy high strength steel

Dai Yili[1], *Yu Shengfu*[1], *Shi Yusheng*[1]

[1]Huazhong University of Science and Technology, Hubei Wuhan, 430074, China

E-mail: daiyili1208@hust.edu.cn;

yushengfu@hust.edu.cn .

In the paper, zirconium is alloyed with low alloy high strength steel and its effect on the microstructure and mechanical properties during wire and arc additive manufacturing is investigated. This study demonstrates that in the depositing metal, zirconium exists in the form of zirconium containing composited inclusions which is $ZrO_2 \cdot Al_2O_3 \cdot MnO \cdot SiO_2 \cdot MnS$. The average size of composited inclusions is around 0.7~0.8μm and the areal density is 6411mm^{-2}.

The composited inclusions inside austenite grains effectively induce the intragranular nucleation of ferrite. Zirconium addition to the depositing metal reduce the content of pro-eutectoid ferrite (PF), ferrite side plate (FSP) and acicular ferrite (AF), and instead produce a homogeneous fine grain ferrite. Under the several thermal cycles during wire and arc additive manufacturing, the inclusions induce intragranular ferrite nucleation several times during multiple austenitization, which promotes the columnar crystals to the equiaxed grains in formed metal. At the same time, the inclusions located at austenite grain boundaries pin the austenite grains and limit the excessive growth of austenite grains. The microstructure of forming part with the addition of zirconium is consisted of fine grain ferrite and pearlite, and the average size is under 20μm. Compared to the forming part without zirconium, the forming part

with zirconium shows up to 20% improvement in strength and 35% in impact toughness.

Multifunctional cellulose fabric by sol-gel coating with silica and titania nano-composite material

Awais Khatri*, Abdul Khaliq and Shamshad Ali
Department of Textile Engineering, Mehran University of Engineering and Technology, Jamshoro – 76060 Sindh Pakistan
e: awais.khatri@faculty.muet.edu.pk

This research work reports on the preparation of a hydrophobic bamboo cellulose knitted fabric with multifunctional properties using composite of silica and titania nanoparticles (Aerosil® 200 and Aeroxide TiO2® P 25) by sol-gel coating. The citric acid was used as a cross-linking precursor. The fabric was functionalized by the dip-pad-dry-pad-cure method. Different ratios of silica (SNPs) and titania (TNPs) composite sols were made. The process parameters were optimized to achieve functional properties such as water repellency, soil release and UV resistance. ATR-FTIR spectroscopy and SEM analysis were carried out to characterize the untreated and treated fabrics. The whiteness index, air permeability, fabric handle, tensile breaking force and wash-durability of the fabrics functionalized with SNPs and TNPs composite were also measured. The results revealed that coating with silica and titania composite improves the said functional properties and is durable up to 5 industrial washes. Moreover, extent of air permeability and fabric soft handle did not change after sol gel treatment, indicating that fabric inherent comfort is unaffected.The abstract should be in English. Please follow the format and style described in this template. Please use A4 (210 mm x 297 mm) paper size.

The effect of process parameters on density, hardness and surface quality of selective laser melted 18Ni300 Steel

Gan Li[1], Cheng Guo[1], Hongxing Lu[1], Xinwei Li[2,3], Qiang Zhu[1,2,3*]
[1]*Innovation Center for Intelligent Manufacturing, Southern University of Science and Technology, Shenzhen, 518055, China*
[2]*Department of Mechanical and Energy Engineering, Southern University of Science and Technology, Shenzhen, 518055, China*
[3]*Shenzhen Key Laboratory for Additive Manufacturing of High-performance Materials, Shenzhen, 518055, China*
e: 11749173@mail.sustech.edu.cn

Selective laser melting (SLM) is an advanced manufacturing process which offers flexibility in geometric design and rapid production of complex components. Owing to the high strength and excellent ductility, maraging steels have been extensively used in aerospace and tooling sectors for many years. This work aims to study the effect of process parameters comprising laser power, scan speed, hatch space in relation to density, hardness and surface quality of SLM 18Ni300. The results reveal that higher laser power led to increasing density and reduction of surface roughness. Higher scan speed produced lower density and hardness due to the worse melting pool quality. In the case of sufficient energy density, lower hatch space value had no obvious impact on the density while reducing the surface roughness.

Laser additive manufacturing of Ni-based nanocomposites with enhanced mechanical and anti-corrosion performances

Hongmei Zhang[1,2], Dongdong Gu[1,2*]
[1]*College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing 210016, Jiangsu Province, PR China;*
[2]*Jiangsu Provincial Engineering Laboratory for Laser Additive Manufacturing of High-Performance Metallic Components, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing 210016, Jiangsu Province, PR China*
E-mail: dongdonggu@nuaa.edu.cn
hongmeizhang@nuaa.edu.cn

Laser additive manufacturing has demonstrated a promising capability in the simultaneous formation of high-performance nanocomposites with unique microstructures. The present work studied the microstructure, mechanical and corrosion properties of TiC/Inconel 718 nanocomposites by selective laser melting (SLM) with variation of laser scan speed (*v*). The results showed that the surface morphology transformed from relatively smooth to hierarchical rough structures, and the nano-TiC experienced severe agglomeration to uniform distribution with the increase of *v*. The columnar dendrites spacing of *γ* matrix refined with the addition of TiC reinforcements. Especially, at an optimal *v* of 800 mm/s, a microhardness of 369.5 $HV_{0.2}$, ultimate strength (σ_s) of 1030.5 MPa and elongation (δ) of 26.92% were obtained. Moreover, the electrochemical measurements indicated that the nanocomposites showed excellent corrosion resistance with higher corrosion potential and lower corrosion current density. The excellent performances were benefited from the high densification, uniform microstructures and nano reinforcements.

Long-period stacking ordered phase in Ti-47Al-2Cr-2Nb alloy produced by direct laser deposition

Jianfeng GU, Xingyu ZHANG, Chuanwei LI
Shanghai Jiao Tong University, Shanghai, 200240, P.R.China;
e: gujf@sjtu.edu.cn

Intermetallic γ-TiAl alloys are promising candidates of light-weight materials with high specific strength, good oxidation resistance and creep properties up to high temperatures. However, the lack of sufficient ductility at ambient temperature is a critical defect for TiAl alloys, which severely restricts their fabrication and raises the costs by traditional manufacturing technologies. Additive manufacturing (AM) is competent to fabricate near-fully dense and complex metal parts directly from computer-aided design models, offering a novel way for fabricating TiAl alloys with acceptable quality, costs and complex geometries. To date, most attempts focus on the processing parameter optimization and crack controlling instead of the relationship between process and microstructure. Long-period stacking ordered (LPSO) phase has been widely introduced in magnesium alloys to promote a high yield strength, good ductility, high elevated-temperature strength and high thermal stability through suppressing the basal plane slip and activating non-basal plane slip. Very few reports can be found on LPSO phase in TiAl alloy with the only exceptional cases of its presence under large deformation.

In present work, Ti-47Al-2Cr-2Nb (at. %) single-track wall with the size of 50 mm × 40 mm × 2 mm, was fabricated using a self-developed direct laser deposition (DLD) system. Microstructure characterization, such as X-ray Diffraction and HRTEM, were conducted to confirm the existence of LPSO phases with structures of 6H and 18R in the as deposited TiAl alloys, whose microstructure consists of alternating dendritic band and equiaxed colony band. Low ordering 6H with stacking sequence of ABCBACA is found to form in dendrite that are rich in Al element and massive 18R with stacking sequence of ABCABCBCAB-CACABCABA only turns up in interdendrite. High ordering 6H with the same stacking sequence of ABCBACA is also observed in equiaxed colonies. The formation of LPSO is supposed to owe to inhomogeneous chemical distribution of Al and Cr, which lowers the fault stacking energy both in α2 and γ.

The present work demonstrates that DLD process can provide a novel pathway to introduce LPSO, thus may potentially effectively enhance mechanical property of TiAl alloy.

Keywords: TiAl alloy; Direct laser deposition; Long-period stacking phase

Laser 3D printed mantis shrimp bio-inspired impact resistant structure: Structure optimization and failure mechanism

Jiankai Yang[1,2], Dongdong Gu[1,2*]

[1]*College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing 210016, Jiangsu Province, PR China;*

[2]*Jiangsu Provincial Engineering Laboratory for Laser Additive Manufacturing of High-Performance Metallic Components, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing 210016, Jiangsu Province, PR China*

E-mail: dongdonggu@nuaa.edu.cn

yangjiankai@nuaa.edu.cn

The telson (tail plate) of Stomatopoda (mantis shrimp) shows excellent impact resistance properties, and its special structure is an ideal prototype to mimic. In this work, a series of bi-directionally corrugated panel (DCP) structures inspired by the telson of mantis shrimp was designed. The crush simulation of DCP structures with different structural parameters was carried out using ANSYS LS-DYNA. In order to verify the simulation results, DCP components were fabricated by selective laser melting and the out-of-plane compression tests were conducted to investigate the compression performance. The SLM-processed components with DCP structures showed high surface quality and good forming accuracy. The numerical simulation results indicated that the influence of wavelength of DCP structure on the energy absorption (EA) and specific energy absorption (SEA) capability was greater than that of the amplitude. This work also presented a comprehensive failure mechanism study of the bi-directionally corrugated panel (DCP) structures.

Evaluation of the PLGA/TCP/Mg Porous Scaffold Fabricated by 3D printing for Bone Regeneration

Yuxiao Lai[a,b,*,1], Jing Long[a], Long Li[a], Cairong Li[a], Yingqi Chen[a], Ling Qin[a,c,***]
[a]*Centre for Translational Medicine Research & Development, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen, 518055, China;*
[b]*Key Laboratory of Health Informatics, Chinese Academy of Sciences, Shenzhen, 518055,China;*
[c]*Musculoskeletal Research Laboratory, Department of Orthopaedics & Traumatology, The Chinese University of Hong Kong, Hong Kong SAR, 999077, China;*
*E-mail addresses: yx.lai@siat.ac.cn

Abstract
Bone regeneration is a significant event in bone tissue engineering. The beta-tricalcium phosphate (TCP) and poly(L-lactide-co-glycolide) (PLGA) are well known for their exllent biodegradability, bioabsorbability and osteogenic properties. They can be combined to fabricate a porous scaffold, and used as a bone substitute for bone defect repair. In order to promote bone regeneration, we designed and fabricated an innovative bioactive porous scaffold composed of PLGA, TCP and magnesium (Mg) with well-defined biomimic microstructure through the low-temperature 3D printing technology. The effect of Mg in angiogensis and osteogenesis was observed in this study. Firstly, Porous scaffolds were fabricated at -30℃ using an advanced low-temperature rapid-prototyping machine. Then, a steroid－associated osteonecrosis rabbit model with 3 mm bone defect tunnel in both distal femora was developed. The samples were randomly divided into three groups: control group without any implantation, PLGA/TCP group and PLGA/TCP/Mg group implanted into the bone tunnel. Finally, DCE-MRI was used to observe the blood perfusion function at the defect sites at 0,2,4,8 weeks post surgery. X-ray were used to analysis the in vivo osteogenetic effect of the PLGA/TCP/Mg. Micro-CT based angiography was used to evaluate the vascular architecture by injecting Microfil into the abdominal aorta. Bone tissue volume density (BV/TV, %), connectivity density (Conn.D, 1/mm3), trabecular number (Tb.N, 1/mm), in bone tunnel were measured by Micro-CT. Acording to the DCE-MRI results, we found that at week 2 and 4, PLGA/TCP/Mg group performed good blood perfusion and showed significantly higher “maximum enhancement” than the PLGA/TCP group and control group($p<0.05$, n=3). Micro-CT data showed that at week 12, the BV/TV, Conn.D and Tb.N of PLGA/TCP/Mg group increased significantly than those in control group ($p<0.05$, n=8). The in vivo study shows that the PLGA/TCP/Mg scaffolds have good osteogenetic and angiogenic effect and the scaffold is a promising biomaterial for bone regeneration.

3D printing metals via plastics:
Fused filament fabrication of 316L stainless steel

Z. Y. Liu[1], Y. Ge[1], P. Yu[2], C. Y. Yu[3]
[1]*College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen, 518060, China;*
[2]*Department of Materials Science and Engineering, S*outhern *University of Science and Technology, Shenzhen, 518060, China;*
[3]*College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen, 518060, China;*
e: zyliu@szu.edu.cn

Metals exhibit good combination of strength and ductility over plastics due to strong nonlocalized metallic bonds, which also endowing them with high additive manufacturing temperature, therefore 3D printing of metals is high-energy consuming and challenging. Here, using composite filament composed of metal powder blended with plastic carrier, metal plastic co-printing (MPCP) method is developed to take full advantage of metals and plastics. At relative low temperature, the composite filament is fused and deposited layer by layer, afterwards, plastic binder is removed and remaining metallic powder is sintered. 316L stainless steel with relative density of 98.4% can be fabricated. The printed 316L has excellent comprehensive mechanical properties, with ultimate strength of 500 MPa and plasticity of 87%. Owning to the similarity between MPCP and FFF of plastics, this method may be readily employed to print various metals for practical application.

Effect of ceramic particle size on microstructure formation and performance of TiB_2 reinforced Al-based composites prepared by selective laser melting

Lixia Xi[1,2], Dongdong Gu[1,2], Xuan Zhao[1,2], Yang Liu[1,2], Yuxin Li[1,2], Meng Guo[1,2], Kaijie Lin[1,2]

[1]*College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, 210016 Nanjing, China*

[2]*Jiangsu Provincial Engineering Laboratory for Laser Additive Manufacturing of High-Performance Metallic Components, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, 210016 Nanjing, China*

e: xilixia880@nuaa.edu.cn

Al-based composites with micrometer and submicron TiB_2 reinforcements have been produced by selective laser melting from mixed powder under different processing conditions. The densification behaviour, microstructure formation and performance of both bulk-form composites were investigated. The densification level of SLM-processed composite with submicron TiB_2 particles (>99.0%) was 0.3-2.4% larger than that of composite with micrometer TiB_2 particles under the same processing conditions. The microstructural analysis exhibits that Si distribution in the matrix experienced a transform from continuous cellular to directional line-like morphology with TiB_2 particle size decreasing from micron to submicron size. The particle size of TiB_2 reinforcements added in the matrix also exhibited a critical influence on the preferred orientation and grain size of matrix. The results of microstructure analysis reveal that a unique microstructure of composite parts can be produced by appropriately compositing the feedstock powder by altering reinforcement size. With addition of TiB2 ceramic particles, the SLM-processed composites exhibited improved ultimate tensile strength and ductility, particularly with addition of submicron TiB2 particles. High ultimate tensile strength of ~436 MPa and elongation of ~4.6 % was obtained for fine TiB_2 reinforced composites, increasing by 16% and 45% compared to that of micro-TiB2 added composites, respectively.

Effects of processing parameters on properties of selective laser melting Mg–Al-Zn alloy

Shuai Liu[1, 2] ,Xiangmin Qi[3] ,Hanjie Guo[1, 2,*]

[1] *School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, Beijing, 100083, China;*

[2] *Beijing Key Laboratory of Special Melting and Preparation of High-End Metal Materials, Beijing, 100083, China;*

[3] *Shanxi United Magnesium Co., Ltd., Taiyuan City, Shanxi Province, 030006, China.*

*e: guohanjie@ustb.edu.cn

Selective laser melting (SLM) technology was used to fabricate the dense AZ61 magnesium alloy and the effect of process parameters of selective laser melting (SLM) on macro-morphology, molding characteristics and compactness of AZ61 magnesium alloy were investigated. The experiment clarifies that the process parameters have a strong influence on the top surface morphology, surface roughness and relative density of the sample. The top surface was divided into four stages: strong surface balling—pores region, weak surface balling—pores region, rough scan track region, flat—smooth region. The results indicated that the reduction in hatch spacing was beneficial to enhance the compactness of the sample, and the shape of the pore changed as the scanning speed decreased. It can be found that a maximum relative density was 99.4% with preferable process parameters of v = 400 mm/s, H = 0.06mm. The optimal energy density range for dense samples is 125-250 J/mm^3.

Microstructure formation of Ti-6Al-4V in synchronous induction assisted laser forming

Wei Fan[#], Hua Tan[#,*], Xin Lin, Weidong Huang
State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an, 710072, PR China
Key Laboratory of Metal High Performance Additive Manufacturing and Innovative Design, MIIT China, Northwestern Polytechnical University, Xi'an, 710072, PR China
** corresponding author: E-mail: tanhua@nwpu.edu.cn (Hua Tan); Tel: +86-29-8849-4001; Fax: +86-29-8849-4001*
 # these authors contributed equally to this work

In traditional laser additive manufacturing, the thermal behaviors during solidification and phase transformation are closely related due to the single heat source working and the microstructure control ability is inevitably limited. Introducing a synchronous induction heat source into laser solid forming process have the potential to weaken this thermal connection. In this research, the synchronous induction assisted laser forming of Ti-6Al-4V alloy were conducted and the influence of laser and induction energy on the β grains, α phase and martensite were investigated with the thermal analysis. Results showed that the increasing induction current and decreasing scanning velocity promotes the epitaxial growth of the β grains owing to the more flat solidification interface. The fraction of α phase increases and the fraction of martensite decreases with increasing laser and induction energy due to the longer holding time above martensite decomposition temperature. Meanwhile, the slower cooling rate in phase transformation period lead to the morphology of α phase transformed from basket-weave to Widmanstatten.

CoAlW ternary alloy high-throughput laser additive manufacturing

Yang Haiou[1], Ma Fuhuan[1], Lin Xin[1]
[1]*State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an, 710072, P.R.China*

According to phase diagram and different process parameters, the Co-Al-W ternary alloys with different compositions were prepared by multi-channel laser additive manufacturing (LAM), the effects of Al and W contents on the microstructure of Co-Al-W ternary alloys were studied. The results show that the increase of Al content promotes the formation of B2 phase CoAl, and the increase of W content promotes the formation of μ phase Co_7W_6. In the case of low laser power, a part of the smaller size W particles can be completely melted and enter the solution, while another part of the larger size W particles reacts with Co and Al in the molten by dissolution and diffusion. A reaction layer is formed on the surface thereof. When the laser power is increased to 1500W, the reaction layer formed on the surface of some W particles begins to break into small squares and leaves, while the W particles themselves are subjected to large thermal damage due to thermal stress. It breaks into small fragments under action and accelerates its reaction with the molten metal. The experimental results show that LAM is a promising method for discovery and screening of new materials.

Here we present evolution of the beta phase in laser deposited Ti-6Al-4V via track of the cyclic phase transformation processes by dilatation experiments and characterization of the laser deposited microstructures by transmission electron microscopy (TEM) and an energy dispersive X-ray spectrometer (EDS). The formation temperature of the b phase in as-received mill-annealed Ti-6Al-4V decreased with increasing number of thermal cycles at the heating and cooling rates of 50℃/s, while the vanadium (V) content in the bet phase increased with decreasing b phase formation temperature. The distribution of the V content in the b phase in the laser deposited Ti-6Al-4V showed an increasing gradient from the top

layer (i.e., the last deposited) to the fourth layer from the top, which is related to the thermal cycles and the formation temperature of the beta phase. Also, the enrichment of beta-stabilizers promotes the formation of omega phase. The formation mechanism of the beta phase was discussed based on the experimental observations.

Mechanical properties of martensitic Ti6Al4V alloy

Shoujin Sun[1,2,6]*, Duyao Zhang[3,6], Maksym Rybachuk[2], Suresh Palanisamy[4,6], Qian Ma[3], Matthew S. Dargusch[5,6]

1. Advanced Design and Prototyping Technologies Institute, Griffith University, Southport, Gold Coast, Queensland 4215, Australia
2. School of Engineering and Built Environment, Griffith University, Southport, Gold Coast, Queensland 4215, Australia
3. School of Engineering, RMIT University, Melbourne, Victoria 3001, Australia

4. Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia

5. Queensland Centre for Advanced Materials Processing and Manufacturing (AMPAM), School of Mining and Mechanical Engineering, the University of Queensland, St Lucia, Brisbane, Queensland 4072, Australia

6. Defence Materials Technology Centre, Australia

*Tel: +61-7-56780640

Email: shoujin.sun@griffith.edu.au

The microstructure, mechanical properties and failure mechanisms of martensitic Ti6Al4V alloy processed by selective laser melting (SLM) and water-quenching (WQ) have been investigated. The microstructure is characterized as equiaxed β grains with randomly distributed α' lath in water-quenched wrought samples, columnar β grains with α' lath orientated in $\pm 45^o$ and 90^o with loading axis in as-fabricated SLM built samples.

The difference in tensile strengths including 0.2% yield strength and ultimate tensile strength (UTS) is marginal in the as-fabricated SLM built samples, water quenched wrought samples. The total strain at fracture in the water quenched wrought samples is lower than that in SLM built samples. The better ductility of the SLM built Ti6Al4V samples is attributed to the morphological orientation of α' laths.

A Review on Additively Manufactured Immobilizers in Radiation Therapy

A. Asfia[1], M. I. Mohammed[2], B. Rolfe[1], W. Xu[1] T. Kron[3]
[1]*School of Engineering, Faculty of Science, Engineering and Built Environment, Deakin University, Geelong, 3216, Australia;*
[2]*School of Medicine, Faculty of Health, Deakin University, Geelong, 3216, Australia;*
[3]*Peter MacCallum Cancer Centre, Melbourne, 3000, Australia;*
e: aasfia@deakin.edu.au

Radiotherapy is one of the most effective cancer treatment techniques which also has toxic side effects for the healthy tissues. To reduce these toxicities, patients need to be immobilized during the treatment through different immobilizers.

This paper mainly aimed at evaluating the feasibility of the additively manufactured fixation devices in radiation therapy. Traditionally made immobilizers have also been investigated.

37 data bases have been searched in the time period between 2000 till 2019. 4015 papers were identified. After excluding duplicate and irrelevant papers, 19 papers left. About 66% of publications investigated the technique on human objects while the rest of articles discussed the technique on the animal objects (22%) and phantom models (11%). Approximately 77% of the articles investigated immobilization of head and neck and just about 11% included the breast holders and 11% comprised the whole body immobilization of small animals.

The broad range of advantages of the 3D printed immobilizers over conventional devices have been confirmed by the investigated articles comprising more accurate patient positioning and reproducibility between treatment fractions, discarding the moulding procedure, reducing the patient visits to the clinic, reducing the patient discomfort and distress during the immobilizer manufacturing procedure, to name a few.

Selective laser melted 316L stainless steel: the effect of annealing on mechanical properties and corrosion behaviour

Daniel Fabijanic and Qi Chao

Deakin University, Institute for Frontier Materials, Geelong, Vic 3216

Selective laser melted (SLM) 316L austenitic stainless steel produces an interesting microstructure in the as-printed condition. Often termed hierarchical, the microstructure consists of large elongated grains directionally grown along the highest thermal gradient (build direction), and within the grains is a sub-structure of dislocation tangles forming a cellular network. Associated with the cellular walls are segregated solutes elements (Cr, Mo). Finally there is a large fraction of spherical oxynitride dispersoids rich in Si, Mn and Al which form during solidification. Here the oxygen source is contamination in the process atmosphere and the native oxide layer on the input powders. This microstructure has been shown to have tensile strength exceeding wrought, while maintaining equivalent ductility. Additionally, the formation of oxynitride inclusions in preference to MnS inclusions result in excellent pitting corrosion resistance. Due to rapid solidification and complicated thermal cycling additive manufactured materials possess considerable residual stress and are routinely thermally stress relieved. Despite the attractive as-printed properties there is a lack of understanding on the effect of post-processing heat treatment on the microstructure and properties of SLM 316L. In this present study SLM 316L columns were subjected to annealing/stress relieving heat treatments over a wide range of temperature from 450 °C to 1400 °C and holding times (5 – 3600 min) and the tensile behaviour and corrosion (3.5% NaCl solution, RT) properties assessed. At low post-processing temperatures (400 and 650 °C, all isothermal times), the SLM 316L build reveals only moderate stress-relief (~10-20%), without any major alteration of the microstructure or tensile properties. Increasing the annealing temperature to 800 °C and at longer hold times resulted in the precipitation of a chromium-rich sigma phase at grain boundaries. Although ~50% of the residual stress was relieved, the sigma phase resulted in a significant reduction in ductility (~25%). Solution annealing at 1100 °C resulted in full stress relief in 5 min and a complete annihilation of the dislocation cellular sub-structure. At longer hold times recrystallization and grain growth occurred, producing an equi-axed structure with low yield strength. Simultaneous coarsening of the nano-oxide inclusions occurred at annealing temperatures at and above 1100 °C and contributed to the slight reduction in tensile elongation. These microstructural changes with annealing also resulted in a general decrease in corrosion resistance.

Additive Manufacturing of Tungsten Alloys: Manufacturing and Performance

K. Li[1], J. Chen[1], J. Ma[1], W. Liu[1,*], Z. Shen[1,2]
[1] *School of Materials Science and Engineering, Tsinghua University, Beijing, 100084, China;*
[2] *Department of Materials and Environmental Chemistry, Arrhenius Laboratory, Stockholm University, SE-106 91 Stockholm, Sweden*
Email: likl16@mails.tsinghua.edu.cn

The intrinsic hardness and brittleness of W at room temperature limits the applications of W. As an additive manufacturing method, selective laser melting (SLM) enables the production of metal components with complex geometry, which brings the new solution to tungsten fabrication. However, the high melting point, high thermal conductivity, high viscosity, and susceptible to oxidation makes the W SLM a challenge task, resulting parts with cracked and porous microstructure. In this study Pure W, W-6wt%Ta, and W-0.5wt%ZrC bulks were additively manufactured via the SLM technique, and their cracking behaviour was compared. It was observed that the crack density of W-Ta and W-ZrC was largely reduced compared with that of pure W. The grains in W-Ta and W-ZrC were obviously refined compared with the grains in pure W, which significantly increased the cracking resistance. In addition, Ta and ZrC may scavenge the oxygen impurities and furtherly increase the cracking resistance. In W-ZrC, the ZrC nanoparticles were all changed into ZrO_2, while in W-Ta large amount of dislocations was found tangled with in-situ oxidized TaO_2. This study provides a promising strategy for the additive manufacturing of high-quality W by alloying.

*Corresponding author

Email address: liuw@tsinghua.edu.cn (Wei Liu)

Influences of energy density on porosity and microstructure of selective laser melted Al-Cu-Mg-Ag alloy

Joe Elambasseril, Suming Zhu, Edward Lui, Mark Easton, Ma Qian and Milan Brandt

Centre for Additive Manufacturing, School of Engineering, RMIT University, Melbourne, Australia

Abstract

Additive manufacturing of high strength wrought aluminium alloys by selective laser melting (SLM) is challenging due to their high susceptibility to hot cracking. A systematic study was conducted to reduce hot cracking in SLM of Al-Mg-Cu-Ag alloy Al2139 by optimising processing parameters and by adding TiB2 grain refiner. Volumetric energy density was the key factor considered when optimising the process parameters. Porosity, microstructure and mechanical properties of SLM fabricated parts were studied using a SLM125HL machine. Particle size distribution and particle morphology of the pre-alloyed powders were analysed to establish the powder rheology and SLM processing parameters. Chemical composition of the powders and the as-built samples were analysed to identify the loss of any elements during SLM process. Cubic samples were fabricated at different SLM parameters and were used for microstructural examination by X-ray computed tomography (CT), scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) and electron backscatter diffraction (EBSD). The optimised SLM parameters were used to fabricate tensile specimens. This work provides new implications for additive manufacturing high strength wrought aluminium alloys by SLM.

How the Interdependence Model reveals the mechanisms of nucleation and grain formation during additive manufacturing

D.H. StJohn

Centre for Advanced Materials and Manufacturing (AMPAM), School of Mechanical and Mining Engineering, The University of Queensland; St Lucia, 4072, Australia

e: d.stjohn@uq.edu.au

The Interdependence model is now widely used to analyse the results of grain refinement studies. Although the model was developed to predict the grain size of an alloy cast under the assumptions of near equilibrium solidification and the presence of potent nucleant particles, the model is applicable to a wide variety of alloys, casting methods and cooling conditions. However, the strength of the Interdependence model is when it is used as a diagnostic tool that can reveal the mechanisms influencing the refinement of alloys under particular casting conditions. This presentation covers an introduction to the Interdependence model, its recent validation by experiment and simulation, and examples of how it can be applied to the solidification of alloys during additive manufacturing. For example, the model explains the difficulties in promoting a transition from columnar to equiaxed grains during additive manufacturing while also providing insights into how a fully equiaxed grain structure can be achieved.

An effective discrete element modeling of heat transfer in selective laser sintering

Yuanqiang Tan*[1] Ruohan Gao[1] Jiangtao Zhang[1]
Institute of Manufacturing Engineering, Huaqiao University, Xiamen 361021, China

Heat-transfer between powders, which greatly influence the quality of the final molded part include residual thermal stresses and thermal deformation, plays an important role in the selective laser sintering. We developed an effective and comprehensive selective laser sintering simulation framework based on discrete element method, which includes (a)simulation of laser beam and powder interaction by Monte Carlo ray tracing algorithm; (b) a viscoelastic discrete element model of high temperature particles; and (3) a thermal radiation model which is suitable for the large scale and non-uniform high temperature particles. This model reproduces the whole process of thermal diffusion, softening, inter-particles sintering and final molding of particles heated by laser. On the one hand, the heat transfer characteristics between mesoscopic particles can be detected; on the other hand, the numerical simulation of multi-track and multi-layer scanning on the powder layer at the macro scale can be realized, which facilitates the investigation of the influence of various powders and process window on the forming quality of workpiece from the perspective of heat transfer between particles.

* Corresponding authors.
E-mail addresses: tanyq@hqu.edu.cn

Effects of nano-SiC content on microstructure, phase and mechanical properties of AlSi7Mg alloys fabricated by selective laser melting

Min Wang, Bo Song，Qingsong Wei, Yusheng Shi
State Key Laboratory of Materials Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan 430074, China
e: Contact's e-mail address: 1114537764@qq.com

In this study, the effect of nano-SiC_p addition on the microstructural characteristics, phase transformation and tensile properties of AlSi7Mg alloy is investigated. The results showed that with the increase of the nano-SiC_p content, in situ phase Al_4C_3 formed, and the average grain size gradually decreased. When the content of nano-SiC is proper, both the tensile strength and elongation increased. The reason is that fine-grain strengthening and precipitation strengthening as well as the dislocations formed during the rapid solidification adjusted the tensile behavior. However, when too many nano-SiC_p added, the tensile strength decreased and the elongation decreased rapidly.

Mechanical Properties of Additively Manufactured Auxetic Structures

Amer Alomarah[1], Dong Ruan[1]*, Syed Masood[1] and Zhanyuan Gao[2]

[1]Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC3122

[2]Tianjin Key Laboratory of Civil Structure Protection and Reinforcement, Tianjin Chengjian University, China

*Corresponding author. Tel: +61 3 9214 8258; email: druan@swin.edu.au

Abstract

Auxetic materials/structures expand laterally when stretched and contract laterally when compressed, exhibiting negative Poisson's ratio (NPR). In this study, a recently developed 2D auxetic structure with a combination of the topological features of re-entrant honeycomb and chiral honeycomb has been fabricated from Nylon-12 using Multi Jet Fusion (MJF) 3D Printing process. The external surfaces and dimensions have been examined using an optical stereomicroscope. The microscopic measurements show that MJF 3D printing process is able to produce robust parts with precise dimensions. The mechanical properties of the proposed structure under both quasi-static and dynamic loads have been investigated experimentally and numerically. A number of experimental tests have been conducted to study the load carrying capacity and Poisson's ratio of this structure under various loading velocities using different test machines such as Zwick Roell and high-speed Instron testing machine. Finite element (FE) models have been established using ABAQUS/Explicit and validated by the experimental results. Numerical simulations have been conducted in order to examine the effects of velocity and geometrical parameters of the proposed structure. The stress-strain curves, Poisson's ratio and energy absorption of this structure have been presented and compared with those of the two popular auxetic structures, re-entrant honeycomb and chiral honeycomb.

Microstructural evolution in SLM and PM fabricated parts: Nano-mechanical and microstructural characterization of Ti6Al4V

Alireza Dareh Baghi [1*], Reza Ghomashchi [1], Reza H. Oskouei [2], Heike Ebendorff-Heidepriem [3]

[1] *School of Mechanical Engineering, University of Adelaide, Australia*

[2] *College of Science and Engineering, Flinders University, Adelaide, Australia*

[3] *Institute for Photonics and Advanced Sensing and School of Physical Sciences, University of Adelaide, Adelaide, Australia*

e: alireza.darehbaghi@adelaide.edu.au (Alireza Darehbaghi)

Abstract

This study compares the microstructural characteristics and nano-mechanical characterization of Ti6Al4V samples fabricated by two methods of PM and SLM. The optical microscopy, SEM and XRD analysis confirmed that the microstructure of PM samples were mainly composed of coarse hcp (α) grains with a small amount of bcc (β) while the SLM fabricated parts were fully composed of single phase martensitic, α', with a unique architecture. The α' phase appeared in randomly oriented acicular (laths) morphology enclosed within the high angle boundaries of their elongated parent grains.

The microhardness and nanohardness results for the parts fabricated by PM and SLM were in the converse of each other. The nanohardness results revealed that the martensitic laths (α') in Ti64 is 36% softer than α while its microhardness showed approximately 27% higher hardness.

This higher microhardness of SLM parts may be due to laths morphology with large concentration of low angle boundaries while nanohardness only measures the hardness of a couple of laths at the most, i.e. no contribution from the low angle boundaries.

This needs more investigation to explore if the size of α' parent grains play any major role on the mechanical properties of SLM fabricated titanium alloys.

Anisotropic tensile behavior and microstructure of a near-α titanium alloy fabricated by electron beam selective melting

J.X. Yang[1,2], Y.J. Huang[1,2*], B.K. Liu[1,2], C. Guo[3], J.F. Sun[1,2*]
[1]*School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China;*
[2]*National Key laboratory for Precision Hot Processing of Metals, Harbin Institute of Technology, Harbin 150001, China;*
[3]*Tianjin Qingyanzhisu Technology Co., Ltd, Tianjin 300300, China;*
yjhuang@hit.edu.cn; jfsun_hit@263.net

A near-α titanium alloy (Ti6.5Al2Zr1Mo1V) was fabricated by electron beam selective melting (EBSM) in this work. The mechanical properties of the EBSM built component in different directions were tested under uniaxial tension at room temperature. Results showed that the average ultimate tensile strength in transverse directions was higher than longitudinal direction. This significant anisotropy in the mechanical performance was caused by the formation of columnar β grains of preferred orientation along building direction. The existence of grain boundary α provides a path for damage accumulate preferentially, lacking of which make horizontal samples exhibit better ductility. Due to different cooling rate at different building heights, the vertical samples exhibit similar columnar β grains, but different morphologies of α phase. Globular and platelet α were obtained in the top region, whereas platelet α with a low aspect ratio existed in other regions, leading to the enhanced ultimate tensile strength without the sacrifice of ductility in the top region. The present findings provide guidance for fabricating EBSM built titanium alloy with excellent mechanical properties.

ADDITIVE MANUFACTURING OF METASTABLE BETA TITANIUM ALLOYS

E. Ivanov[1], Srinivas Aditya Mantri[2], Rajarshi Banerjee[2,] . James Williams[2].
[1]*Tosoh SMD Inc., Grove City, 43123 OH, USA;*
[2]*Materials Science and Engineering, University of North Texas, Denton, 76209, USA,*
eugene.ivanov@tosoh.com

The directed energy deposition based additive manufacturing (AM) process, laser engineered net shaping (LENS™), has been used for the processing of various beta-rich titanium alloys. With regard to titanium alloys, the use of AM technology has been well established; but the evolution of microstructure and texture, and their consequent influence on properties has yet to be fully understood. Furthermore, the principal worldwide focus has been on the AM of Ti-6Al-4V, with very limited investigations on AM of metastable beta titanium alloys. Pre-alloyed powder was used for the deposition of Ti-35Nb-7Zr-5Ta (TNZT), a low modulus biomedical alloy, as well as Beta-21S, and Ti-185. Site-specific microstructure and texture analysis, and mechanical properties along and across the build direction will be presented in this paper. The effect of Fe (eutectoid forming element in Ti-alloys) on the presence of β-flaking will also be discussed. Additionally, Ti-Cu and Ti-Cu-Al alloys have also been deposited using the LENS™ process and their microstructure and mechanical properties have been characterized. The results from these various LENS processed metastable beta Ti alloys will be summarized in this presentation.

The characterization of the residual stresses in laser melting deposited CrMnFeCoNi high entropy alloys using neutron diffraction

H.G. Li[1], Y.Z. Lu[2]*, H.B.C Yin[1], T.L. Lee[3], X.Y. Gao[2],
Y.J. Huang[1]*, J.F. Sun[1]

[1]*School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China;*

[2]*School of Materials Science and Engineering, Dalian Jiaotong University, Dalian 116028, China;*

[3]*ISIS Neutron Source, Science and Technology Facilities Council, Rutherford Appleton Laboratory, Didcot OX11 0QX, UK;*

e: yjhuang@hit.edu.cn, luyz@djtu.edu.cn

Laser melting deposition (LMD) has been considered as an increasing attractive technique for the fabrication of metal components with complex geometries. However, the inevitable residual stresses generated during LMD can cause part distortion or cracks, dramatically deteriorating the functionality of metal components. Here, CrMnFeCoNi high entropy alloys (HEAs) were manufactured by laser melting deposition. Neutron diffraction was employed to characterize in situ the residual stresses within the as-printed CrMnFeCoNi HEAs. The thermal history and residual stress fields of the as-printed CrMnFeCoNi HEAs were elucidated. The relationship between residual stress, microstructure and mechanical properties was also established. Together, these findings may be beneficial for better understanding the evolution of residual stress during additive manufacturing of HEAs, and thus favoring the near-net-shaping of high-performance HEA parts.

Effect of Build Inclination Angle on Additively Manufactured Titanium Implants and their Implications on Mammalian Cell Attachment and Staphylococcus Aureus Biofilm Formation

Avik Sarker[1,2], Milan Brandt[1,2], Richard Williams[3,4], Martin Leary[1,2], Kate Fox[1,2]
[1]*School of Engineering, RMIT University, Melbourne, Victoria 3001, Australia*
[2]*Centre for Additive Manufacturing, RMIT University, Melbourne, Victoria 3001, Australia*
[3]*BioFab3D, St Vincent's Hospital, 29 Regent Street, Fitzroy, Victoria 3065, Australia*
[4]*School of medicine, Deakin University, Geelong, VIC 3216, Australia*

e: avik.sarker@rmit.edu.au

The design of tissue engineering materials for both orthopaedic and dental implants is a great challenge in terms of desirable mechanical properties, biocompatibility, and improved osseointegration. Titanium has been an effective implant material due to its excellent strength to weight ratio, corrosion resistance, toughness, and bio-inert oxide surface. Selective laser melting (SLM) is an additive manufacturing process that fabricates constructs based on CAD Files by scanning powdered materials using the thermal energy supplied by a focused and computer-controlled laser beam. This work reports the fabrication of SLM part with different inclinations and their relationship with the cellular attachment and bacterial adhesion. The SLM printed samples were characterized first by the electron microscopy, Profilometer, X-ray photoelectron spectroscopy. During the SLM process, we show that as the inclination angles increase, there is a corresponding increase in the number of partially melted particles adhering to the surface, greatly affecting the surface topography, morphology, roughness which greatly influence the attachment and morphology of mammalian cells confirmed by seeding Chinese Hamster Ovarian (CHO) cells. It has also been confirmed that printing a low build angle is a facile yet effective mechanism to minimize the colonization of *S. aureus*, one of the most common pathogens associated with the majority of implant related infections.

Keywords: Additive manufacturing, SLM, inclination angle, cell attachment, *S. aureus*.

Metal Additive Manufacturing Standardization Issues

M. Seifi[1]
[1]*ASTM International, Washington, DC, 20036, USA*
[2] *Case Western Reserve University, Cleveland, OH, 44106, USA*
e: mseifi@astm.org , mseifi@case.edu

As the Additive Manufacturing (AM) industry moves towards series industrial production, the need for standards covering all aspects of the technology value chain becomes ever more prevalent. While standards and specifications for the various aspects of the AM materials and process chain continue to evolve, many such standards still need to be matured or are under consideration/development within standards development organizations (SDOs). In particular, materials feedstock, process qualification, testing, evaluation and structural integrity issues continue to be the main focus of ongoing efforts in the standardization community. This presentation will discuss the state of the metal AM standardization including gaps, challenges, opportunities, and insight based on a recent initiative to establish a global center of excellence to support standard related research and development to be able to close the standardization gaps.

Development of additive manufacturing for cutting tools

Ahmad Zadi-Maad[1], Muhammad Fakhry Hatta[2]
[1]*Sumbawa University of Technology, Sumbawa, Indonesia;*
[2]*TU Delft master graduate, Bandung , Indonesia;*
e: ahmad2014@postech.ac.kr ; fakhryhatta15@gmail.com

Cutting tool materials have excellent properties due to extreme environment and work load. The features include high hardness and abrasion resistance, increased thermal conductivity, high strength at elevated temperatures, as well as resistance to oxidation and corrosion. However, manufacturing cutting tools have a fundamental problems such as high levels of vibrations in machining systems, the high values of cutting forces, the growth of cutting temperature, the concentration of heat, the risk of catastrophic tool failure and rapid tool wear, as well as significant deterioration of surface finish and frequent stability loss.

In recent years, additive manufacturing (AM) technology has been applied to made cutting tools due to its potentially lower cost and flexibility on the production process. AM can circumvent the limitation of traditional cutting tools by adding special features inherently such as functionally graded design, dual material, non-traditional shape, special internal cooling system, and repairment of damage cutting tools This paper provide a comprehensive review of the previous work related to the AM while highlighting current challenges and methods to solved.

A novel framework for identifying nucleant particles and its application to titanium alloys produced by additive manufacturing

S.N Tedman-Jones[1]
[1] *The University of Queensland, Brisbane, 4067, Australia;*
e: samuel.tedmanjones@uqconnect.edu.au

It is currently difficult to reliably promote equiaxed primary β-grain morphologies during additive manufacturing (AM) of titanium alloys. In contrast, columnar β-grain morphologies are often reported, which may span multiple deposition layers and can affect the components mechanical properties. The thermal conditions present in AM melt pools and the low density of potent nucleant particles are believed to be key factors in the formation of these columnar grain morphologies. In this work, a novel framework for promoting equiaxed crystal formation in titanium is discussed, which may help resolve desirable grain morphologies during AM.

Grain Growth during Keyhole Mode SLM of IN738LC

Z.W. Chen[1], T. Guraya [2], S. Singamneni[1].
[1]*Department of Mechanical Engineering, Auckland University of Technology, Auckland, NZ;*
[2]*Second Department of Mining & Metallurgical Engineering & Materials Science. University of the Basque Country UPV/EHU, Bilbao, Spain*
e: zhan.chen@aut.ac.nz

Cracking readily occurs along grain boundaries over many layers and in close to build direction (BD) during metal additive manufacturing (MAM) of difficult-to-weld alloys. Thus, understanding how grains grow and how growth direction can deviate considerably from BD is necessary. In this work, solidification during keyhole mode selective laser melting (SLM) of IN738LC is studied. We will present and discuss SLM conditions suitable for keyhole mode. In keyhole mode, heat is conducted away more horizontally and thus grains have been found to grow in directions considerably different from BD, minimising the formation of vertically orientated and long columnar grains. Increasing laser power with other parameters kept unchanged increases the keyhole depth and thus growth is more horizontal but keyhole instability increases. λ_1 as small as 0.14 μm has been identified at track bottom, corresponding to G and dT/dt being in the order of 10^8 K/m and 10^8 K/s, respectively, as a result of unstable flow. Under the stable condition, dT/dt is in the other of 10^7 K/s. As solidification proceeds from the track bottom to the top surface over 200-300 μm, λ_1 increases from 0.2-0.3 μm to over 1 μm because of the rapid decrease in dT/dt to ~10^5 K/s.

Wire Arc Additively Manufactured materials: relationships between process and material property

Bintao Wu, Zengxi Pan, Huijun Li
[1]*School of Mechanical, Materials, Mechatronic and Biomedical Engineering, University of Wollongong, Wollongong NSW 2522, Australia;*
e: bw677@uowmail.edu.au

Wire arc additive manufacturing (WAAM) has attracted significant attention in industrial sectors due to its ability to economically produce large-scale metal components with relatively high buy-to-fly ratio. As electric arc and additive deposition have involved, the complex heat transfer and thermal cycles cause a serious of material processing challenges in WAAM. This subject provides a comprehensive overview of the thermal characteristics during WAAM process and fully identified the effects of thermal behaviors on the process stability, dimensional geometry and material properties of the deposited part. An innovative method for controlling thermal profiles during the build process is proposed and discussed, taking account the requirement of the various alloys. This paper concludes that the wide application of WAAM still presents many challenges, and these may need to be addressed in specific ways for different materials in order to achieve an operational system in an acceptable time frame. Highly accurate control of thermal profiles in deposition to produce defect-free and structurally-sound produced parts still remains a crucial effort into the future.

Wire Arc Additive Manufacturing Process Assisted by Magnetic Arc Oscillation

D.R. Corradi[1,2,3], B. Wu[3], Z. Pan[3]
[1]*Federal University of São João del-Rei, Ouro Branco, 36420-000, Brazil;*
[2]*Federal University of Minas Gerais, Belo Horizonte, 31270-901, Brazil;*
[3]*University of Wollongong, Wollongong, 2522, Australia;*
e: diego.corradi@ufsj.edu.br

Wire Arc Additive Manufacturing process is a metal additive manufacturing process based on arc welding processes. The heat source and the feedstock are welding arc and wire, respectively. This innovative process presents some advantages such as lower cost of equipment and raw material, more efficient use of materials and high deposition rates. It also presents several disadvantages including high degree of anisotropy, unsatisfactory surface finish and high heat input that results in residual stresses and distortions in the components produced. This study will focus on the anisotropy problem. As consequence, mechanical properties vary with orientation and position. It occurs due to the layer structure and the heterogeneous microstructure composed by elongated and vertically oriented grains intercepting the deposited layers, caused by epitaxial growth. Previous studies show that Magnetic Arc Oscillation is efficient to produce fine and equiaxed grains in the weld bead (Fusion Zone) microstructure. Based on that information, Magnetic Arc Oscillation has been applied during the construction of titanium alloy thin walls by Wire Arc Additive Manufacturing process based on Gas Tungsten Arc Welding process. Then, the influence of Magnetic Arc Oscillation on microstructure, mechanical properties and layer solidification has been investigated.

In vitro Characterizations of PCL/Magnesium Hydroxide Nanocomposites 3D Printed Scaffold

Abdalla Abdal-hay[1*], Karan Gulati[1], .Saso Ivanovsoki[1]..
The University of Queensland, School of Dentistry, Herston, Queensland, Australia,
*E_mail: abdalla.ali@uq.edu.au

In the present study, polycaprolactone (PCL)-based composite scaffolds containing 5 and 20 wt% of magnesium hydroxide (MH) fine nanoparticles (< 50 nm) were fabricated into 3D interconnected prorous scaffolds using an additive manufacturing technique for bone tissue engineering purposes. The degrdation was studied in two different media, simulated body fluid (SBF) and phosphate-buffered saline (PBS) at 37 ° C upto 150 days. Immersion of the PCL/MH nanocomposite scaffolds reacted diffrently in both SBF and PBS solution. All scaffolds showed a weight gain after immerssed in SBF due to the CaP formation on scaffold surface, while in PBS showed a weight loss.Thus, addition of MH into PCL scaffold, moderately increase the degrdation rate of PCL polymer after incubation in PBS as the PCL well know with its low degrdation rate (3 - 4 years) in physiological environment. In terms of cell viability, the scaffold modified with MH significantly convinced the attachment and growth of osteoblasts as compared with the PCL-only scaffold. In conclusion, these promising results suggested that the incorporation of MH nanoparticles into PCL 3D porous scaffold could enhance its mechanical and biological properties. This modified porous bio-scaffold may potentially apply in the surgical management of large bone defect fixation.

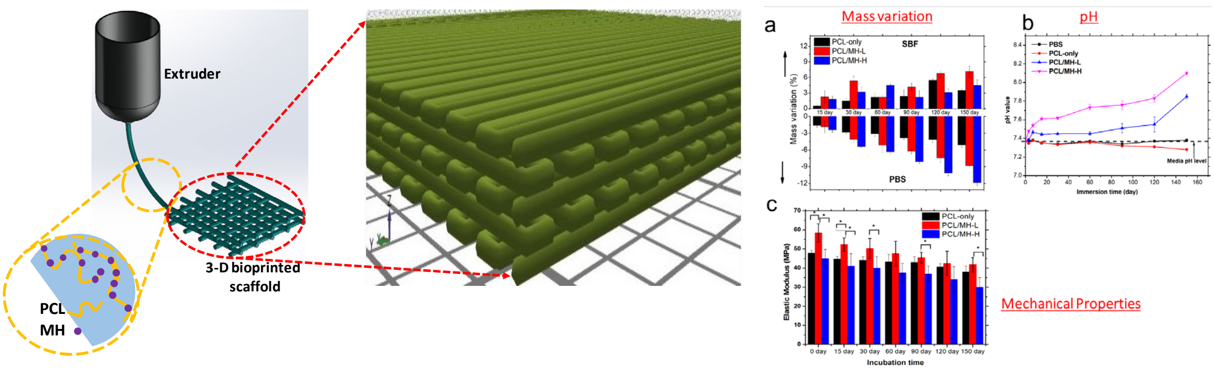


Fig. 1 Shows the scaffold fabrication process and their behaviour after immersion in PBS and SBF on mass variation, pH and mechanical properties.

Mechanical compatibility of 3D-printed metallic lattices for hard tissue engineering

Nicolas Soro [1]
[1]*Centre for Advanced Materials Processing and Manufacturing (AMPAM), School of Mechanical and Mining Engineering, The University of Queensland, QLD 4072, Australia;*
e: n.soro@uq.edu.au

While stochastic porous metals are still widely used in the biomedical industry, new generations of 3D-printed regular lattices have the potential to offer superior overall performances and durability. Triply periodic minimal surfaces (TPMS) can provide a better strength-to-weight ratio and better osseointegration compared to conventional designs.
In this work, we investigated the mechanical properties of lattice structures produced with selective laser melting using the well-known Ti-6Al-4V biomedical alloy as well as a novel Ti-Ta alloy. The geometry consisted of a Schwartz primitive unit-cell, repeated periodically in 3 dimensions. Three levels of porosity were studied, ranging from 24% to 64%. The main focus of this study was to evaluate the mechanical compatibility of the produced samples with cortical bones via experimental and numerical tools. The reported mechanical properties from the compression testing revealed a good match for the Young's moduli and yield strengths. Not only did our numerical simulations support these results, but they also gave further insight into the deformation mechanisms and the effect of manufacturing irregularities.
The positive outcomes reported in this work will contribute toward the development of new generations of metallic biomaterials.

Characterization of topology optimized Ti6Al4V-ELI and Ti6Al4V-ELI +3%Cu lattice structures by laser powder bed fusion for biomedical applications

A.M. Vilardell[1]*, A. Takezawa[2], A. du Plessis[3], N.Takata[4], M.Kobashi[4], P.Krakhmalev[1] I.Yadroitsava[5], I.Yadroitsev[5]

[1] *Karlstad University, Department of Engineering and Physics, Karlstad SE-651 88, Sweden.*

[2]*Department of Transportation and Environmental Systems, Graduate School of Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan*

[3]*CT Scanner Facility and Physics Department, Stellenbosch University, Stellenbosch, South Africa 7602*

[4]*Department of Materials Process Engineering, Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan*

[5]*Department of Mechanical and Mechatronics Engineering, Central University of Technology, Bloemfontein, South Africa 9301*

e: anna.martin@kau.se

ABSTRACT

Ti6Al4V-ELI lattice structures were produced by laser powder bed fusion (LPBF) for biomedical applications. The approach of the design was to produce light-weight lattice structures with high porosity and elastic modulus close to the human bone (E~20GPa). A total of three designs were obtained through topological optimization with predicted porosity percentages of: 55, 60 and 65%, and expected elastic modulus of 27.4GPa, 23.1GPa and 18.6GPa, respectively.

Strut thickness, as well as porosity percentage of LPBF Ti6Al4V ELI lattice structures was analyzed and compared with CAD models. Microstructural characterizations were carried out by means of optical microscopy, scanning electron microscopy and electron backscatter diffraction. Mechanical characterization was performed by compression test. MicroCT studies were performed for defect analysis and accuracy. MicroCT-based load simulation allowed the calculation of the effective elastic modulus of the structure compared to its design. The differences between the predicted and experimental values may be attributed to the effect of different strut thickness values and LPBF imperfections. Fracture mechanisms of the samples were studied by SEM and MicroCT. Additionally, same lattice structure design was used to in-situ alloyed Ti6Al4V-ELI+3%Cu by LPBF for antibacterial purposes. Microstructural and mechanical characterization were carried out and compared with Ti6Al4V-ELI lattice structures.

A modified line heat input model for the thermal-mechanical modelling of selective laser melting

Ming LIU[1], Louis N. S. CHIU[2,3], Chris Davies[1], Xinhua WU[2,3], Wenyi YAN[1]
[1]*Department of Mechanical and Aerospace Engineering, Monash University, Melbourne, VIC3800, Australia;*
[2]*Department of Material Engineering, Monash University, Melbourne, VIC3800, Australia;*
[3]*Monash Centre for Additive Manufacturing, Monash University, Melbourne, VIC3800, Australia;*
e: wenyi.yan@monash.edu

Due to the large difference in the time- and length-scales involved in the selective laser melting (SLM) process, most of simulation strategies have significant computational demands which limits its application in component scale modelling. In an attempt to reduce this demand, Irwin's line heat input model [1] was developed, which averaged total energy input over a linear segment. However, this approach severely underestimates the peak temperature in the process, which is detrimental in the prediction of subsequent quantities such as strain and stress. A modified line heat input model was proposed based on Goldak's welding heat source [2] to address this issue. In this model, the laser traveling time in a single track is divided into heating period and cooling period. After that, the total energy is input on the single track during the heating period to capture the maximum temperature change during printing processing. Our trial tests demonstrated that the modified line heat input model can significantly improve the accuracy of the predicted peak temperature during an SLM process.

1. Irwin, J., et al., *Predicting Microstructure From Thermal History During Additive Manufacturing for Ti-6Al-4V.* Journal of Manufacturing Science and Engineering, 2016. **138**(11).
2. Goldak, J., A. Chakravarti, and M. Bibby, *A new finite element model for welding heat sources.* Metallurgical Transactions B, 1984. **15**(2): p. 299-305.

Grain boundary α formation and thickening in additive manufactured Ti-6Al-4V

Kai Zhang [a,b], Mu Gao [c], Huizhi Peng [c], Jeremy Rao [b,c], Aijun Huang [b,c], Xinhua Wu [b,c]

[a] Department of Mechanical and Aerospace Engineering, Monash University, Clayton, VIC 3800, Australia
[b] Monash Centre for Additive Manufacturing, 15-17 Normanby Road, Notting Hill, VIC 3168, Australia
[c] Department of Materials Science and Engineering, Monash University, Clayton, VIC 3800, Australia

Grain boundary α, which is the α layer decorating the prior β grain boundary, is formed during the slow cooling process from β regime in conventionally manufactured titanium alloys and could be detrimental to the fatigue resistance. In additive manufactured titanium alloys, the rapid cooling from the β regime during the process could mostly suppress the grain boundary α formation. However, the presence of grain boundary α is still identified in the additive manufactured titanium alloy products and little research has been done about this. In this study, the formation and thickening of grain boundary α in direct laser deposited (DLDed) Ti-6Al-4V is investigated. The presence of grain boundary α is difficult to be identified in as-deposited Ti-6Al-4V due to the rapid cooling, while thick grain boundary α could be easily identified in heat treated DLDed Ti-6Al-4V. A series of heat treatments on direct laser deposited Ti-6Al-4V is carried out and is correlated with the grain boundary α growth.

Numerical simulation of direct laser metal deposition for restoration and prediction of optimal process parameters

Chaitanya Vundru[1,2], Ramesh Singh[1], Wenyi Yan[2], Shyamprasad Karagadde[1]
[1]*Department of Mechanical Engineering, Indian Institute of Technology Bombay, Mumbai 400076, INDIA*
[2] *Department of Mechanical and Aerospace Engineering, Monash University, Clayton, Melbourne VIC 3800, AUSTRALIA*
Email: wenyi.yan@monash.edu

Abstract

Direct laser metal deposition (DLMD)-based restoration is an effective technique to repair cracks and holes on the surfaces of metal components. This technique can be employed even to enhance the service life of repaired components by depositing superior materials. However, the service life of a restored component may also be compromised if tensile residual stresses present in the deposited layer. Consequently, predicting the residual stress developed in the material deposited via DLMD is important to improve the integrity of the restored components. Residual stress is induced due to the temperature gradient, the dissimilarity of the coefficients of thermal expansion and the elastoplastic behaviour of the deposit/substrate materials. Furthermore, rapid cooling in a DLMD process results in martensitic transformation, which induces additional transformation strains due to transformation induced plasticity and volumetric dilation. A 3-D fully coupled metallo-thermomechanical finite element model of the laser DLMD process has been developed to capture the individual and coupled effects of strains due to volume dilation and transformation induced plasticity on residual stress evolution. The prediction errors decreased from ~48% to ~15.6% with the inclusion of the strains due to martensitic transformation. Furthermore, the metallo-thermomechanical model is employed to estimate the optimal deposition parameters to ensure that the longitudinal residual stress is compressive in the entire cladding (CPM9V) deposited on substrate (H13) during a single layer deposition.

Keywords: Direct laser metal depositions, repair, residual stress, martensitic transformation, metallo- thermomechanical finite element model.

ICME-based alloy development for additive manufacturing applications

Christian Haase[1], Patrick Köhnen[1], Seyedamirhossein Motaman[1], Mingxuan Lin[1], Andrey Molotnikov[2], Johannes H. Schleifenbaum[3]
[1]*Steel Institute, RWTH Aachen University, Aachen, 52072, Germany;*
[2]*Department of Materials Science and Engineering, Monash University, Clayton VIC 3800, Australia;*
[3]*Chair of Digital Additive Production, RWTH Aachen University, Aachen, 52074, Germany*
e: christian.haase@iehk.rwth-aachen.de

Additive manufacturing (AM) techniques have gained industrial importance during the last years. In contrast to the AM machines with high technology readiness levels, specific alloys that have been adapted to the AM processing conditions do hardly exist. However, precise adjustment of process and material is necessary to uncover the full potential of AM. It requires the establishment of a methodology to describe and predict the complex process-microstructure-property relationships.
In this presentation, an ICME (Integrative Computational Materials Engineering)-based methodology will be introduced that allows for AM-specific material development using a combination of multi-scale alloy and process simulation. Thermodynamic calculations for alloy selection are coupled with FEM simulation of the melt pool while a phase-field approach is used to predict a microstructure development. . The plastic deformation behavior on the micro-scale is described using crystal plasticity-FEM, which serves as a basis for simulation of the macroscopic deformation behavior using FEM calculations. The ICME approach is demonstrated for fabrication of highly alloyed steels using laser powder bed fusion process. The simulation results are validated by microstructural and mechanical characterization on the respective length scale. Potential applications of the presented example are relevant for light-weight structures with energy-absorption functionality, whereas the ICME-based methodology can be transferred to various alloy systems and metallic components.

Laser metal powder directed energy deposition of Alloy 718 - Modelling microstructure evolution during the process and subsequent heat treatments

Chamara Kumara[1], AndreasSegerstark[2], Fabian Hanning[3], NikhilDixit[1], ShrikantJoshi[1], Johan Moverarea[4], Per Nylén[1]
[1]*Department of Engineering Science, University West, 461 86 Trollhättan, Sweden.*
[2]*GKN Aerospace Engine Systems AB, Trollhättan, SE-461 81, Sweden.*
[3]*Department of Industrial and Materials Science, Chalmers University of Technology, 412 96 Gothenburg, Sweden.*
[4]*Division of Engineering Materials, Department of Management and Engineering, Linköping University, SE-58183 Linköping, Sweden.*

email: chamara.kumara@hv.se

Among the repair methods for worn and corroded gas turbine components, laser metal powder directed energy deposition (LMPDED) has become a popular method due to the fact that the parts can be repaired with minimal dilution and distortion. However, the inherent nature of the layer-by-layer material deposition involves in the process create complex thermal conditions that caused the material to experience solid to liquid as well as solid-state phase transformations. In addition, subsequent heat treatment causes microstructural changes. Therefore, understanding how microstructure is evolving during the process and subsequent heat treatment will be important in order to control the microstructure to get the desired performance out of the parts. In this work, we show how this can be achieved using a computational modelling approach. A multi-component and multi-phase-field modelling approach, combined with transformation kinetics modelling were used for this purpose. Experimental temperature measurements were utilized to predict microstructural evolution during successive addition of layers. Thereafter, heat treatment simulations were performed on the solidified microstructure. Segregation of alloying elements, as well as formation of Laves and δ phase, was specifically modelled. Modelling results showed good agreement with experimentally observed phase evolution within the microstructure.

Mechanistic Models of Powder Bed Fusion and directed Energy Deposition Processes

T. DebRoy
The Pennsylvania State University, University Park, PA 16802, USA
debroy@psu.edu

There are three compelling reasons why the optimization of part quality in additive manufacturing (AM) cannot follow the usual trial and error testing adapted in welding: (a) building parts is much slower, (b) equipment and feedstock are orders of magnitude more expensive and (c) cooling rates and solidification parameters are strikingly sensitive to the selection of AM variants and process variables. Building and validating mechanistic models based on the numerical solution of the equations of conservation of mass, momentum and energy can provide a viable path to optimize microstructure and properties. This approach can reduce the number of expensive and time-consuming part testing and qualification, and compute the causative variables that affect microstructure, properties and defects. This presentation will discuss how heat transfer and fluid flow calculations for powder bed fusion and directed energy deposition processes, when adequately validated, can provide insight about the evolution of solidification structure, microstructure and common defects. In particular, the ability of mechanistic models in evaluating features of solidification structure, microstructure, lack of fusion defects and residual stresses and distortion will be examined. The application of these models to understand printability of different alloys will also be discussed.

A Semi-Empirical Microstructure Evolution Model for Titanium Alloys in Additive Manufacturing Processes

S.J. Cummins[1], A. Phua[2], V. Nguyen[2], P.W. Cleary[1], M. D. Sinnott[1]
[1]*CSIRO Data61, Clayton South VIC 3169, Australia;*
[2]*CSIRO Manufacturing, Clayton South VIC 3169, Australia.*

e: sharen.cummins@csiro.au

The mechanical properties of titanium and its alloys are sensitive to its microstructure so the ability to predict and control the microstructure evolution during a titanium fabrication process is vital in order to obtain a high quality final product. We will present a semi-empirical microstructure model designed to predict the evolving phase fractions of Ti-6Al-4V in multi-pass additive manufacturing processes. The model is based on the Johnson-Mehl-Avrami (JMA) theory and simulates transformations between phases as a function of temperature and time only. This means the model is simple and robust and able to be coupled easily to other numerical models to simulate metal additive processes. We present results of the model linked to a Smoothed Particle Hydrodynamics (SPH) solver and linked to the MSC MARC Finite Element Method (FEM) solver to simulate microstructure evolution in powder bed fusion and Electron Beam Direct Manufacturing (EBDM) processes. We will also discuss some of the limitations of the semi-empirical microstructure model compared to more detailed models such as Phase Field and Cellular Automata.

Strength and strain hardening of additively manufactured AlSi10Mg alloys

B. Chen[1], K. Kondoh[2], J. Li[1]
[1]*State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an, 710072, China*
[2]*Joining & Welding Research Institute, Osaka University, 11-1 Mihogaoka, Ibaraki, Osaka, 567-0047, Japan*
Email: chen@nwpu.edu.cn

In this study, the microstructure and mechanical behaviors of additively manufactured (AM) AlSi10Mg alloys processes by selective laser melting were investigated, in comparison to conventional powder metallurgy (PM) AlSi10Mg alloys. We find that AM alloys have unique hierarchical microstructures. There are micro-sized Al grains and transgranular ultrafine cellular structures around primary Al, and the cell boundary is made up of interval eutectic Si and eutectic Al phases. AM alloy had coarser Al grains but much finer Si precipitates compared with the PM alloy. Consequently, the AM alloy show more than 100% increment in strength and hardness compared with the PM alloy. AM alloys have both high tensile strength and high strain-hardening capability, which are superior to those fabricated by PM and cast methods. After heat-treated above 350℃for 5 min, there are dramatic decreases of strength and strain hardening rates for AM AlSi10Mg alloys, which is mainly attributed to the increased size of Si precipitates.

Effect of energy input during Arcam EBM

D. Fraser[1], Johnson Jacob[2], Stefan Gulizia[1], Kenong Xia[2]
[1]*CSIRO Manufacturing, Metal Industries, Normanby Road, Clayton, Victoria 3169, Australia*

[2]*Department of Mechanical Engineering, University of Melbourne, Victoria 3010, Australia*
e: Darren.Fraser@csiro.au

Processing of TiAl and superalloy additive manufacturing using Electron Beam Melting is increasingly of interest as the process can modify the microstructure and resultant mechanical properties. In particular the microstructural uniformity along the build direction has been carried out under different energy input process conditions for TiAl. We also studied the effect of the in-situ heat treatment and associated discontinuous coarsening of the primary lamellar microstructure in the final layers of the build. It was found that the energy density and layer thickness created different microstructures in the build direction and better uniformity was found at certain parameters. With in-situ heat treatment in the machine discontinuous coarsening of the primary lamellar structure was completely surpassed by a structure of small colonies and wide lamellae.

Effect of copper on microstructure and mechanical properties in additive manufactured Ti alloys

Duyao Zhang[1], Dong Qiu[1], Mark Easton[1]
[1] *RMIT University, Melbourne, 3000, Australia*
e: duyao.zhang@rmit.edu.au

Additively manufactured titanium alloys with increased complexity have a wide applications in biomedical, aerospace and other industries. However, additively manufactured titanium alloys usually contain unendurable big columnar grains, which leads to property anisotropy. Though grain refiner can be used to suppress columnar grains, potent grain refiner is limited especially in titanium-based system because it cannot survive in liquid titanium. Here, we demonstrate that copper addition to titanium alloy produced by direct laser deposition is an effective way to eliminate columnar grains. The effect of copper on the prior-β grains size is investigated in this study. The results also present associated high tensile properties with refined eutectoid structure. It opens up the metal additive manufacturing of ultrafine equiaxed-grain component without additional inoculants.

A time-saving and cost-effective method to process new alloys by Laser Powder Bed Fusion

Federico Bosio[1], Alberta Aversa[1], Massimo Lorusso[2], Silvia Marola[3], Dario Gianoglio[3], Livio Battezzati[3], Paolo Fino[1], Diego Manfredi[2], Mariangela Lombardi[1]
[1]*Department of Applied Science and Technology, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy;*
[2]*Center for Sustainable Future Technologies CSFT@Polito, Istituto Italiano di Tecnologia, Via Livorno 60, 10144, Torino, Italy;*
[3]*Dipartimento di Chimica, Università di Torino, Torino, Italy;*
e: federico.bosio@polito.it

Additive manufacturing (AM), and in particular Laser Powder Bed Fusion (LPBF), opens completely new possibilities to produce novel alloy compositions.

Optimization of the main process parameters is a core procedure while developing novel alloy compositions for LPBF. To that aim, traditional Design Of Experiment (DOE) approaches have been widely used to determine the operating process windows through the manufacturing of several matrices of massive samples. However, considering the high cost of spherical gas-atomized powders, this represents a time consuming and expensive route.

In this work, a novel method to quickly manufacture dense samples of new alloys through LPBF is proposed. This method was applied on an aluminum alloy system obtained mixing AlSi10Mg and Cu powders. At first, a power (*P*)- speed (*v*) operating window is easily defined by means of Single Scan Tracks (SSTs). Then, the proper hatching distance (h_d) is designed considering to have an optimum overlap among adjacent scan tracks. In this way, massive samples can be directly produced by using the best *P*-*v*-h_d combinations, avoiding many experiments. Finally, a scenario of hardness and productivity vs. energy density is given for the investigated AlSi10Mg+4Cu alloy, in order to find the optimum compromise between mechanical properties and industrial needs.

Cracking Behaviour in Direct Laser Metal Deposition (LMD) of Inconel 738 alloy

X.Q. Zhang[1], X.Q. Chen[1,2]
[1]*Shanghai Key Laboratory of Materials Laser Processing and Modification,*
School of Materials Science and Engineering,
Shanghai Jiao Tong University, Shanghai 200240, P.R. China
[2]*Manufacturing Futures Research Institute,*
Swinburne University of Technology
24 Wakefield Street, H68, Hawthorn, VIC, 3122, Australia
email: xiaoqichen@swin.edu.au

Direct Laser Metal Deposition (LMD) of Inconel 738 alloy (IN738) is a promising process for the remanufacturing of gas turbines and aerospace engines, but the cracking has not been thoroughly understood and controlled. This talk discusses applications of superalloys additive manufacturing using robotic systems, and explores the cracking behavior of additive manufacturing of superalloys. The experimental study was conducted with a range of instruments including optical microscope (OM), scanning electron microscopy (SEM), energy dispersion spectrum (EDS), electron backscatter diffraction (EBSD), X-ray diffraction (XRD) and differential scanning calorimetry (DSC). The study reveals the mechanism of liquation cracking and ductility-dip cracking (DDC). It is also proved that the cracks are very sensitive to Grain Boundary (GB) morphology. The long-straight GBs which result from higher heat input or unidirectional scanning strategy are very vulnerable to cracking. Moreover, GB oxidation always plays an important role in accelerating crack propagation, the local protection from the cladding head is not enough for the LMD of IN738. Bidirectional LMD in an Argon (Ar) chamber with lower heat input achieves better tensile strengthen reaching 1100.2 MPa.

Powder to Product: Tools for Quantitative Characterisations of Starting Materials and Finished Products in 3D Printing

David Myint[1], Antonis Nanakoudis[2], Anne Virden[3], Cathryn Langley[3]
[1]*ATA Scientific, Sydney, 2229, Australia;*
[2]*PhenomWorld, Eindhoven, 5652, The Netherlands;*
[3]*Malvern Panalytical, Malvern,* WR14 1XZ*, The United Kingdom*
e: dmyint@atascientific.com.au

Optimisation of additive manufacturing has benefited from the use of analytical tools for characterising the physical and morphological properties of the constituents. A cradle-to-grave story, the presentation discusses the application of laser diffraction, automated optical image analysis and desktop scanning electron microscopy for rapid visualisation and quantitative analysis of the components at each stage of the building process.

Joining between Additive-Manufactured Porous TC4 and UHMWPE via Friction Spot Welding for Biomedical Application

Ke CHEN[1,2*], Muyang JIANG[1,2],Binxi CHEN[1,2], Shanyong ZHANG[3,4], Min WANG[1,2], Lanting ZHANG[1], Aidang SHAN[1]

[1] *School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*
[2] *Shanghai Key Laboratory of Material Laser Processing and Modification, Shanghai Jiao Tong University, Shanghai 200240, China*
[c] *Department of Oral Surgery, Ninth People's Hospital, College of Stomatology, Shanghai Jiao Tong University School of Medicine, Shanghai 200011, China*
[d] *Shanghai Key Laboratory of Stomatology & Shanghai Research Institute of Stomatology; National Clinical Research Center of Stomatology, Zhi-Zao-Ju Rd., No. 639 Shanghai 200011, China*
**Email: chenke83@sjtu.edu.cn*

Joining between polymer and metal has attracted significant attention recently due to its advantage of great weight reduction and excellent integrated physical/chemical properties. There is an increasing demand of high quality metal-polymer hybrid structures in automotive, aerospace and biomedical industries. In this study, based on previous results, specially designed biomedical additive manufactured porous TC4 titanium alloy plate was successfully joined with ultra-high molecular weight polyethylene (UHMWPE) plate by friction spot welding (FSpW). The z-axial load (F_z) and welding temperature near TC4/UHMWPE interface (T_w) during welding has been properly measured. A strong coupling effect between F_z and dT_w/dt at both low and high temperature has been found. By controlling F_z and T_w through adjusting welding parameters (e.g. welding time and plunge speed), not only can we achieve a good macro filling (up to 80% filling rate) of UHMWPE into TC4 porous structure, sound micro-interlocking between metal and polymer is also obtained. High shear tensile strength (~3000N, 20MPa) has been realized with proper T_w-F_z control during welding. So far, the technique developed in present study has been successfully applied into clinical implantation of temporomandibular joint prosthesis.

High Resolution Custom 3D Printed Medical Grade Scaffolds for Alveolar Bone Regeneration

M. Bartnikowski[1], S. Ivanovski[2]
[1, 2]*The University of Queensland, School of Dentistry, Herston, 4006, QLD, Australia;*
e: michal.bartnikowski@uq.edu.au

Large volume alveolar bone defects are challenging to treat in dental implantology. This is particularly the case when extensive vertical alveolar resorption is present, with highly mixed results and a high prevalence of complications reported in the literature. The additive manufacturing technology of three dimensional (3D) printing offers a solution to this clinical issue, as it may be used to produce highly porous, degradable, medical grade, custom implants. These constructs can be used in a scaffold guided bone regeneration (S-GBR) approach to help regenerate bony defects, where structurally stable porous constructs can maintain volumetric space in a defect and guide the growth of bone tissue. We have developed a complete workflow process for the generation of such high resolution, custom implants from clinical computed tomography (CT) scan data, with the aim of reaching clinical treatments in the next 12 months. To comply with regulatory requirements, we have developed and instituted a complete Quality Management System (QMS) compliant to international standards. We are currently undertaking design and process verification and validation testing prior to transitioning into the clinic. This work is transformative for the industry, and will imminently lead to the clinical treatment of patients with additively manufactured scaffold implants.

Grain refinement in an additively manufactured aluminum alloy

Qiyang Tan, Jingqi Zhang, Mingxing Zhang
School of Mechaanical and Mining Engineering, The University of Queensland, St Lucia, Brisbane, QLD, 4072, Australia;

A new grain refiner has been successfully identified for additively manufactured (AMed) aluminum alloys through crystallographic calculation based on the edge-to-edge matching model. Small addition of the grain refiner can not only completely eliminated the columnar structure resulted from epitaxial growth, but also significantly refined the grains in the melt pools. As a result, the isotropic mechanical properties were obtained in the AMed aluminum alloy. The grain refinement mechanism was also discussed.

Additive manufacturing of biodegradable porous polymer scaffolds for bone tissue engineering

M. Lu[1], S. Diermann[1], R. Patel[1], D. Monticone[1], H. Huang[1]
[1] *School of Mechanical and Mining Engineering, The University of Queensland, Brisbane, QLD 4072, Australia*
e: mingyuan.lu@uqconnect.edu.au

Traumatic fractures are predominately managed by bone grafts in critical sized defects. Bone graft techniques have inherent limitations, prompting research into viable alternatives. Scaffold assisted bone tissue engineering (TE) is an attractive approach due to the feasibility of fabricating materials with optimal structure to allow load bearing combined with biocompatibility to facilitate bone repair and reduce fracture morbidity. Successful TE approaches will be best achieved when the scaffold has mechanical properties, structural mechanics and surface chemistries that are compatible with that of bones. In this work, biodegradable polymer was used for making scaffolds using selective laser sintering (SLS) processes. SLS was carried out to investigate the effects of processing parameters on the microstructure and mechanical properties of the scaffolds. The mechanical properties of the scaffold are closely related to its microstructure, which in turn dictate how the scaffold deforms when subjected to external loading. Thus, the micro-mechanical behavior of the scaffold under compression was investigated using a numerical method. At last, the surface chemistry of the SLSed scaffold was investigated. The hydrophilicity of the scaffolds surface was found associated with the increment in carboxylic acid end groups and was deemed desirable for TE application.

Development of a Photo-Crosslinkable Gelatin Based Bioink for 3D Bioprinting of Bone Cell

Nimal Thattaruparambil Raveendran [1], Cédryck Vaquette [1], Michal Bartnikowski[1]
Saso Ivanovski[1]

[1]*School of Dentistry, The University of Queensland, Brisbane, QLD 4006, Australia*
e: n.thattaruparambilraveendran@uq.edu.au

Three-dimensional (3D) bio printing is an emerging area of research in regenerative medicine. We have investigated a modified gelatine based biopolymer called gelatine methacryloyl (GelMA) for its potential to use as a bioink for osteoblasts (bone cells). We systematically investigated the printability of various concentrations of GelMA solutions and demonstrated that a 12.5 % (w/v) GelMA solution with 0.15% (w/v) photoinitiator was the optimal composition for achieving high printing resolution, reproducibility and an appropriate printing time window. The optimised printing conditions also demonstrated high cell viability and enabled cell proliferation over 14 days. The mineralisation of the 3D bioprinted bone cells were confirmed using Alizarin red O staining. Further the expression of osteoblast specific mRNAs and proteins in the bioprinted cells were evaluated by real-time polymerase chain reaction and immunostaining respectively. Therefore, the developed bioink system and printing conditions can be used to print bone cells efficently and be utilised as a tool for bone tissue engineering.

Optimizing Design for Additive Manufacturing: From Part to Print with solutions from Dassault Systemes

Alex Kok
Dassault Systemes Australia, Melbourne, VIC 3000 Australia
e-mail: alex.kok@3ds.com

Recent advancements in the world of additive manufacturing has transformed the engineering lifecycle of products, from the way components are conceptualized and designed through to how they are manufactured and delivered to the end user.

The cutting-edge solutions on the Dassault Systemes 3DEXPERIENCE platform provides users a seamless solution to conceptualize designs prior to manufacturing. From class-leading topology optimization to ensure optimal part geometry and generative design capabilities to minimize part count and maximize design efficiency, users are no longer limited to traditional engineering design constraints. Beyond the design to manufacture, the platform provides users ability to seamlessly interact with appropriate additive manufacturing suppliers globally.

This session will illustrate how all these technologies come together on a common platform to provide the design answer for an additive manufacturing solution.

In situ synchrotron x-ray study of additive manufacturing processes and materials

Tao Sun[1]

[1] *X-ray Science Division, Argonne National Laboratory, Lemont, IL, 60439, USA*

Metal additive manufacturing (AM) refers to a suite of disruptive technologies that build metallic three-dimensional objects by adding materials layer by layer based on digital designs. AM holds the promise for completely revolutionizing the way we make things. However, fabrication of defect-free products with precisely controlled microstructures remains challenging. Indeed, many fundamental issues in AM need to be addressed, and many new directions need to explored. Synchrotron x-ray techniques are among the most versatile and effective techniques for characterizing materials microstructures and their evolution in various conditions. At the Advanced Photon Source, we recently applied high-speed x-ray imaging and diffraction techniques for *in situ/operando* characterization of various metal AM processes. The high penetration power of hard x-rays makes it possible to look through dense metallic materials and watch their dynamic structural evolution during AM processes in real time. Many highly transient processes involved in metal AM were quantitatively measured with unprecedented spatial and temporal resolutions, and the mechanisms responsible for different types of defects in AM materials were identified. Here, I will introduce the new understanding gained from our synchrotron x-ray experiments, as well as their broad impact on the development of AM materials, processes, and numerical models.

In situ synchrotron x-ray study of additive manufacturing processes and materials

Tao Sun[1]

[1] *X-ray Science Division, Argonne National Laboratory, Lemont, IL, 60439, USA*

Metal additive manufacturing (AM) refers to a suite of disruptive technologies that build metallic three-dimensional objects by adding materials layer by layer based on digital designs. AM holds the promise for completely revolutionizing the way we make things. However, fabrication of defect-free products with precisely controlled microstructures remains challenging. Indeed, many fundamental issues in AM need to be addressed, and many new directions need to explored. Synchrotron x-ray techniques are among the most versatile and effective techniques for characterizing materials microstructures and their evolution in various conditions. At the Advanced Photon Source, we recently applied high-speed x-ray imaging and diffraction techniques for *in situ/operando* characterization of various metal AM processes. The high penetration power of hard x-rays makes it possible to look through dense metallic materials and watch their dynamic structural evolution during AM processes in real time. Many highly transient processes involved in metal AM were quantitatively measured with unprecedented spatial and temporal resolutions, and the mechanisms responsible for different types of defects in AM materials were identified. Here, I will introduce the new understanding gained from our synchrotron x-ray experiments, as well as their broad impact on the development of AM materials, processes, and numerical models.

Influence of Magnetic Arc Oscillation on Wire Arc Additive Manufacturing Deposition Efficiency

D.R. Corradi[1,2,3], A.Q. Bracarense[2]
[1]*Federal University of São João del-Rei, Ouro Branco, 36420-000, Brazil;*
[2]*Federal University of Minas Gerais, Belo Horizonte, 31270-901, Brazil;*
[3]*University of Wollongong, Wollongong, 2522, Australia;*
e: diego.corradi@ufsj.edu.br

Additive manufacturing processes have attracted interest of many industry segments due to benefits they present in comparison to traditional methods. Among advantages, low cost and short production lead time, material efficient use and freedom of design and customization can be mentioned. In production of metallic parts, Wire Arc Additive Manufacturing processes have been subject of study of several researchers. Compared to other additive manufacturing processes applied in production of metallic components, these present lower cost of equipment and raw material, more efficient use of material and high deposition rates. It also presents some disadvantages such as high degree of anisotropy, unsatisfactory surface finish and high heat input that results in residual stresses and distortions in components produced. This work focused on overflow problem that occurs during thin wall fabrication, which increases amount of material to be removed by machining in surface finishing phase. The aim is to increase deposition efficiency making walls thinner. Longitudinal magnetic arc oscillation was used during additive manufacturing processes based on Gas Tungsten Arc Welding process. It was effective to minimize overflow problem, since total and effective wall width decreased and deposition efficiency increased when it was applied, although total wall height did not change.

The liquation cracking mechanism of laser additive repaired K465 nickel-based superalloy

Qiuge Li, Xin Lin, Weidong Huang
Key Laboratory of Metal High Performance Additive Manufacturing and Innovative Design, MIIT China, Northwestern Polytechnical University, Xi'an,710072,China
E-mail: lqg@nwpu.edu.cn

K465 alloy is considered as key structure materials to manufacture turbine blades of aero-engine for its superior corrosion resistance and excellent high temperature strength. In this work, the characterization of microstructure and liquation cracking mechanism of laser additive repaired (LARed) specimens were investigated. The γ′ particles in cast K465 substrate of LARed samples presented large and "cropland" type cubic morphology with the size of 1.88 μm at the garin boundaries and 0.73 μm inside of the grains.The liquid cracks originated from the heat-affected zone and extended to the repaired zone. The larger γ′ particles at grain boundaries partly dissolved in the γ phase, which made the solutes' concentration at the γ′/γ interface meet the eutectic-type liquation reaction condition of γ+γ′→L. Then, grain boundaries liquation occurred and liquid films appeared with the temperature increasing in a rapid heating process. The simulation study also found that there was large thermal stress near the molten pool interface, when the thermal stress caused by laser remelting was larger than the surface tension of the liquid film, the liquid film was torn apart and then the cracking occurred.

Additive Manufacturing of Type 316L Stainless Steel: Towards Corrosion Performance

Majid Laleh[a,b], Anthony E. Hughes[b,c], Wei Xu[a], Mike Y. Tan[a,b]
[a]Deakin University, School of Engineering, Faculty of Science and Technology, Geelong Waurn Ponds Campus, Waurn Ponds, Victoria 3216, Australia.
[b]Deakin University, Institute for Frontier Materials, Geelong Waurn Ponds Campus, Waurn Ponds, Victoria 3216, Australia.
[c]Commonwealth Scientific and Industrial Research Organisation (CSIRO), Mineral Resources, Private Bag 10, Clayton South, Victoria 3169, Australia.
Email address of presenter: mlaleh@deakin.edu.au

ABSTRACT

Although additive manufacturing of stainless steels has been the focus of lots of research, limited data is available about its corrosion performance. In this study, selective laser melting, as a premier powder-bed additive manufacturing process, was used to produce type 316L stainless steel, and then its corrosion performance was investigated. It was found that the SLM-produced 316L stainless steel behaved quite differently when different types of corrosion were considered. It showed higher resistance to pitting and intergranular corrosion, while lower resistance against erosion-corrosion. The reasons for this behaviour were discussed.

Keywords: Additive manufacturing; Stainless steel; Corrosion

On Process Development of High Strength Al-Mn-Sc alloy using Selective Laser Melting

Mrs. Dina Bayoumy[1], Dr. Aijun Huang[1], Dr. Daniel Schliephake[1], Prof. Xinhua Wu[1]

[1]*Monash Centre for Additive Manufacturing (MCAM), Monash University, Melbourne, VIC 3168, Australia*

e: dina.bayoumy@monash.edu

A Scandium reinforced Aluminium alloy, processed by Selective Laser Melting (SLM), has been designed for high Strength and high temperature aerospace application with an operation capability up to 5000 hours at 250 °C. Prior to introducing the alloy for load bearing applications, it is essential to understand the effect of processing and post-processing parameters on the microstructure and mechanical properties. The process has been developed through systematic optimization of the SLM parameters in order to achieve near-fully dense samples at a faster building rate. A design of experiment approach was employed to reveal the processing window of the alloy and also to study the effect of power and scan speed on the process-induced defects within the manufactured samples. The microhardness and tensile properties were investigated for different processing parameters. The preliminary results show a robust processing window with less dependence on the energy density. The Microstructure in as-fabricated condition revealed the existence of alternating layers of superfine and columnar grain regions. A highly effective precipitation hardening was revealed in a superior tensile strength reaching 600 MPa along with ductility around 14%.

3D Printed Tissue for Surgical Simulation Training

Tosin Famakinwa[1], Scott MacKenzie[2], Michele Smigie[3]

[1]Western Sydney University, Academic Division, Sydney Australia
[2]Western Sydney University, School of Medicine, Sydney Australia
t.famakinwa@westernsydney.edu.au

3D printing technology is gaining increasing interest in the medical field, and it's use in medical and surgical education has been proposed. While several authors have pointed to surgical education as an important future industry for the use of 3D printing, there has been relatively sparse information about the processes by which surgical educators have and could employ 3D printers to create useful adjuncts to surgical skills training.

While we are currently able to print impressively realistic looking 3D models even modelling these on patient's own CT and MRI scans, the challenge is to produce a model which physically behaves like its biological counterpart which is essential for surgical simulation.

In this paper, we present mechanical stress test results of composite multi-material 3D printed coupons in other find optimal materials that will simulate tissue. The tensile stress was conducted according to ASTM D638. The tensile stress results are compared with published tissue data.

We also develop assessment method of 3D printed parts for surgical simulation.

Controlling microstructure *in situ* in additively manufactured Ti-6Al-4V by selective laser melting

Wei Xu[1,2,*], Qi Chao[1], Ma Qian[2], Milan Brandt[2*]

[1] School of Engineering, Deakin University, Victoria 3216, Australia

[2] Centre for Additive Manufacturing, School of Engineering, RMIT University, Victoria 3083, Australia

Achieving consistent mechanical performance is essential for the wider implementation of metal additive manufacturing (AM) but this remains far beyond the reach of current practice of selective laser melting (SLM). As the premier titanium alloy, Ti-6Al-4V made by SLM is strong but suffers from inconsistent anisotropic mechanical behavior as well as inferior ductility and fracture toughness. For instance, SLM Ti-6Al-4V can achieve yield strength over 1200 MPa in the as-built state but has noticeably lower tensile ductility (< 10%), inferior fracture toughness and poor fatigue performance. More critically, mechanical properties attained in SLM Ti-6Al-4V are highly scattered, leading to greater uncertainty about the reliability of SLM parts. This lack of consistency is the most significant barrier to the adoption of SLM Ti-6Al-4V for fracture-critical structures. This study has addressed this intractable challenge by developing a holistic thermal and microstructural control approach that allows the direct SLM manufacture of isotropic stress-relieved Ti-6Al-4V literally with minimal necessary post heat treatment. This newly developed approach leads to three *in-situ* transitions: transformation from columnar prior-β grain structure to equiaxed, conversion of α' martensite into lamellar α+β and simultaneous relief of residual stress.

*Corresponding author: Email: wei.xu@deakin.edu.au

Development of β Ti35Zr28Nb alloy scaffolds by selective laser melting for biomedical applications

Yuncang Li, Khurram Munir, Milan Brandt, Cuie Wen
School of Engineering, RMIT University, Melbourne, Victoria 3001, Australia

Abstract

Selective laser melting (SLM) was used for the fabrication of a new β Ti35Zr28Nb alloy and its scaffolds for biomedical applications. The SLM-manufactured porous scaffolds included an FCCZ structure (face centered cubic unit cell with longitudinal struts) and an FBCCZ structure (face and body centered cubic unit cell with longitudinal struts), exhibiting porosity values of 83.2% and 49.9%, respectively. The SLM-manufactured bulk samples showed a very similar elastic modulus in the longitudinal and transverse directions, but significantly higher yield strength in the transverse direction than in the longitudinal direction. However, both porous FCCZ and FBCCZ structures exhibited significantly higher elastic modulus and plateau strength in the longitudinal direction than in the transverse direction. The FCCZ scaffolds showed a longitudinal elastic modulus of 1.1 GPa and plateau strength of 27 MPa, and a transverse elastic modulus of 0.7 GPa and plateau strength of 8 MPa; while the FBCCZ scaffolds showed a longitudinal elastic modulus of 1.3 GPa and plateau strength of 58 MPa, and a transverse elastic modulus of 1.0 GPa and plateau strength of 45 MPa. These mechanical properties of the SLM-manufactured porous structures fall within the ranges of the mechanical properties of trabecular bone. The SLM-manufactured β-Ti35Zr28Nb alloy showed good corrosion properties. The MTS assay revealed that both the FCCZ and FBCCZ scaffolds displayed cell viability at the same level as that of the control. SEM observation indicated that osteoblast-like cells attached, grew, and spread in a healthy way on the surfaces of both the FCCZ and FBCCZ scaffolds, demonstrating the excellent biocompatibility of these materials. Overall, the SLM-manufactured Ti35Zr28Nb scaffolds possess promising potential for use as hard-tissue implant materials due to their appropriate mechanical properties, good corrosion resistance, and biocompatibility.

Keywords: β phase titanium alloy, biocompatibility, corrosion, mechanical property, selective laser melting.

Detection of defects related to the melt pool stability using high-speed infrared camera system for Laser Beam Melting technology

Bastien FOSSE[1], Christophe COLIN[1], Jean-Dominique BARTOUT[1]
[1]*Mines ParisTech - Centre des Matériaux , Corbeil-Essonne, 91100, France;*
e: bastien.fosse@mines-paristech.fr, christophe.colin@mines-paristech.fr, jean-dominique.bartout@mines-paristech.fr

Laser Beam Melting (LBM) is currently a fast-growing technology, leading machine manufacturers to develop new devices that aim to improve process reliability. Among these developments, *in-situ* monitoring systems are increasingly adopted and marketed by a number of manufacturers. Most of them use systems equipped with photodiodes and high speed cameras working in the visible spectrum. These devices are needed to observe rapid phenomena involving acquisition rates in the range of ten kilohertz. However, they do not provide any quantitative information. For example, the thermal field within the melt pool and its surrounding area is not quantitatively estimated. To understand the process stability and especially, phenomena occuring during both material melting and cooling phases, it is essential to measure thermal information such as local thermal fields. Therefore, as part of the "PALOMA" project, a coaxial high speed infrared camera and a temperature calibration system were developed and installed on a LBM machine at the Centre des Matériaux of Mines-ParisTech. The main purpose is to observe and detect with relevancy, the melt pool stability and its associated defects (balling, keyhole pores...) in order to reduce their occurence by a real-time control.

Uniform margins of 2.54 cm or 1″. **Title: Arial, 14 pt font bold.** Text: Arial, 12 pt font, 250 words maximum

Solidification Behavior and Interfacial Bonding Mechanism of Grapheme-reinforced Ni-based Composites Prepared by Selective Laser Melting

Denghao Yi, Yinghao Feng, XiaofengLi,Bin Liu* and Peikang Bai
School of Materials Science and Engineering
North University of China
E-mail: liubin3y @nuc.edu.cn

This paper focus on the scientific issues in the preparation of nickel-plated graphene and grapheme-reinforced Ni-based compositesfabricated by selective laser melting (SLM) technology. Graphene (GNP) being evenly dispersed in nickel-based powder to form good interfacial bonding is a key concern of this study.Thesolidification behavior of the NiGNP/Ni composite powder by SLM, and the presence of the graphene are expected toaffect the graphene/nickel interface and interface bonding strength, which in turn directly affect the mechanical properties of the SLM-fabricated materials.This paper will use theheat transfer theories, finite-elementanalysis and heat treatment to address these scientific problems. On this basis,it is expected that reasonableSLM parameters and the precise control of microstructure and properties can be realized.

Microstructures and mechanical properties of additively manufactured Inconel 718 superalloy and their evolution during post heat treatment

Chao Chen[1], Kechao Zhou[1]
[1] *State Key Laboratory of Powder Metallurgy, Central South University, Changsha 410083, China*
E-mail: pkhqchenchao@126.com

This work investigated the microstructural evolution and mechanical properties of the as-fabricated and heat-treated Inconel 718 (IN718) component by selective laser melting (SLM). Solidification cellular structures with high density dislocations were observed in the SLM-processed IN718. The as-fabricated longitudinal samples showed lower ultimate tensile strength (UTS) of 1100 MPa but higher elongation of 24.5% compared to the transverse samples, which can be attributed to the {100} fiber texture and columnar grain morphology. After heat treatment, it was demonstrated that the fraction of low angle grain boundaries (LAGBs) and the aspect ratio of the grains decreased with the increase of the solution temperature, while the average grain size increased after solution treatment. The fraction of the γ' and γ'' phases exceeded 45.5% compared to 24% of the as-fabricated alloy while the columnar grains transformed to equiaxed grains with the increase of the solution temperature. Consequently, the static tensile properties showed a combination of high strengths ($\sigma_{0.2}$=1276 MPa and UTS=1505 MPa) and excellent ductility (elongation exceeded 13%) of the SLM-processed IN718 after aging with low temperature solution treatments. The superior mechanical properties were attributed to the combination of hierarchically heterogeneous microstructures (solidification enabled sub-micron cellular structure and large fraction of LAGBs) formed in the SLM process and the full precipitation of the γ' and γ'' phases in the aging treatment.

Forming, Microstructure Evolution and Mechanical Properties of Wire Arc Additively Manufactured AZ80M Magnesium Alloy Using Gas Tungsten Arc Welding

Yangyang Guo, Gaofeng Quan, Houhong Pan

School of Materials Science & Engineering, Southwest Jiaotong University, Chengdu, 610031, China;

15108226903@163.com

Abstract

Magnesium alloys have attracted great attention recently due to the low density, high specific strength and other superior performance. However, it is difficult to fabricate magnesium components with large scale and complex shape by conventional forging and casting methods. Wire arc additive manufacturing (WAAM) offers a potential approach to fabricate them with low cost and high efficiency. In this study, WAAM is applied to fabricate AZ80M magnesium alloy. Single-pass multilayer walls are successfully obtained. The results indicate that microstructural evolution occurred during the deposition process, and microstructure along deposition direction exhibits obvious inhomogeneity. Meanwhile, the heat accumulation has significant effect on the forming, microstructural evolution and mechanical properties. The tensile properties in the horizontal and vertical direction show an asymmetric characteristics, which is caused by the inhomogeneity of grain structure and the aggregation of micro-cracks at interlayer transition zone.

Multi-functional Bio-inspired Integrated Thermal Protection Structures: Design, Numerical Simulation and Selective Laser Melting Fabrication

K. J. LIN[1,2], D. D. GU[1, 2]
[1]*College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing, 210016, Jiangsu Province, PR China*
[2] *Jiangsu Provincial Engineering Laboratory for Laser Additive Manufacturing of High-Performance Metallic Components, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing, 210016, Jiangsu Province, PR China*
e:kaijie_lin@nuaa.edu.cn

With the development of high-speed vehicles, more complex geometries, such as lattice structures and bio-inspired structures, have been introduced into the design of integrated thermal protection (ITP) structures, aiming to enhance the thermal protection and load bearing performances. Additive manufacturing holds high flexibility in processing and enables more complex designs, which is suitable for the fabrication of complex ITP structures. In this work, inspired by the structures of plant stems, a series of ITP structures with different gradient hollow designs was proposed and manufactured by selective laser melting (SLM). The thermal and mechanical behavior of those bio-inspired ITP structures were investigated by numerical simulation. To verify the accuracy of the numerical simulation results, Ti6Al4V components with different structures were fabricated by SLM. Thermal conductivities and compression properties of those SLM-processed components were experimentally measured. Results revealed that the gradient designs greatly influenced the thermal and mechanical performance. The gradient structure with larger hollow tubes near the top and bottom plates and smaller hollow tubes in the center possessed the best thermal insulation and load-bearing capacities. The underlying mechanism was analyzed through the combination of numerical simulation and experimental observation.

Effect of process parameters on sliding wear properties of selective laser melted 316L stainless steel

Hua Li and Maziar Ramezani
Department of Mechanical Engineering, Auckland University of Technology, Auckland, 1010, New Zealand

This study investigates the effect of different process parameters and test conditions on tribological behaviour of 316L stainless steel samples made by selective laser melting (SLM). Samples were printed at different laser powder and along different build-up directions. Sliding wear tests were conducted under different normal loads, temperatures and frequencies. The results showed that the effects of laser power and build-up direction on coefficient of friction (COF) and wear rate are not significant; however, lower laser powers resulted in samples with lower hardness and densities and lack of fusion could be observed at melt pools boundaries. Temperature was found to have a significant influence on tribological performance of the samples. At higher temperatures, COF decreased significantly, while wear rate was maximum at 200 °C and then slightly decreased at higher temperatures due to oxide layers working as lubricants and protecting the samples from further loss of material. At higher contact pressures, wear rate was higher, but COF was not affected remarkably. Higher sliding speeds also produced more wear rates due to the higher kinetic energy introduced into the sliding interfaces that could turn into thermal energy and soften the base material.

Metallurgical defect control of laser 3D printing and new alloys development: case of Al, SMA, HEA

Ruidi Li*, Minbo Wang, Pengda Niu, Tiechui Yuan, Chao Chen, Yong Liu

State Key Laboratory of Powder Metallurgy, Central South University, Changsha 410083，PR China

*Email: liruidi@csu.edu.cn

Laser 3D printing usually accompany metallurgical defects, such as pores and hot-crack. We proposed several methods to solve the crack problem. These methods contain surface plastic deformation, adding alloying element to adjust solidification path, stress inducing phase transformation, etc. On above basis, a high strength Al-Mg-Sc alloys for 3D printing was developed without crack, because the interest of additive manufacturing (AM) Al and Ti-base alloys for lightweight applications is growing. The microstructure exhibits alternately coarse and fine grain. The fine grained band is beneath the weld pool while the coarse epitaxial columnar grains locate at the central zone of weld pool above the fine grain band, which is caused by the segregation of $Al_3(Sc,Zr)$ particles in weld pool boundary. The tensile strength of the optimized alloy system surpasses 460MPa. After heat treatment, the tensile strength is close to 530MPa. The crack inhibiting mechanisms and strengthening mechanisms were discussed. We also developed 3D printing shape memory alloy and high entropy alloy. The microstructure, property and metallic parts were also introduced.

Carbon-Fiber Reinforced Inconel 625 by Additive Manufacturing

B.C. Zhang[1], Guijun Bi[2], Chew Youxiang[2], Pei Wang[3]
[1] *Institute for Advanced Materials and Technologies, University of Science and Technology Beijing, Beijing 100083, China;*
[2] *Joining Technology Group, Singapore Institute of Manufacturing Technology, 73 Nanyang Drive, 637662, Singapore;*
[3]*Institute of Materials Research and Engineering, 2 Fusionopolis Way. Innovis, #08-03, 138634 Singapore.*
e-mail: zhangbc@ustb.edu.cn

Carbon-fiber reinforced composites by additive manufacturing (AM) have exhibited unique superiority, which enabled producing highly customized parts with significantly improved mechanical properties. Almost all commercially available AM methods could benefit from various fiber reinforcement techniques. In our research, the microstructure and tensile properties evolution of laser deposition CNT reinforced Inconel 625 composite was studied. The research results clearly prove that the CNT structure can be completely preserved after high power effect. The SEM and EDS results showed that the CNT was distributed at columnar dendrite boundaries accompanied with precipitated of Laves and γ' phase. The addition CNT structure plays a key role of both strength and ductility improved because of microstructure refinement and fiber strengthening. The UTS and elongation of the laser deposition CNT- Inconel 625 composite can reach 1015 MPa and 22%, respectively. In comparison, the UTS and elongation of the graphite reinforced Inconel 625 are 950 MPa and 13%, respectively..

Uniform margins of 2.54 cm or 1″. **Title: Arial, 14 pt font bold.** Text: Arial, 12 pt font, 250 words maximum

Microstructural Evolution and Mechanical Properties of NbC-containingAlCoCrFeNi High-entropy Alloy Prepared by Laser Cladding

Yinghao Feng, Denghao Yi, Xiaofeng Li*,Bin Liu and Peikang Bai
School of Materials Science and Engineering
North University of China
E-mail: lxf@nuc.edu.cn

High-entropy alloys (HEAs) have attracted increasing attention because of their oxidation and corrosion resistance, fatigue and wear resistance, high hardness and strength with reasonably good ductility. In this study, the effects of NbC content on the microstructural and mechanical behavior of theAlCoCrFeNiHEAsfabricated by selective laser melting (SLM) were investigated. The addition of NbCparticles inhibits the formation of the FCC phase in HEAs composites. NbC particles were found in the matrix, because of their higher melting temperature than other elements. No significantchanges were observed in the lattice parameters of the HEAs. For example, the two-theta values corresponding to the diffraction peaks did not showclear shifts.TheunmeltedNbCparticles in the melt pool during solidificationservedas nucleation sites for heterogeneous nucleation.In addition, some NbC particles offered a strong pinning effect to restrict further grain growth during solidification, resulting in significant grain refinement. The hardness and wearresistance of theNbC-containingHEAs were improved.

Study on 3D printing biodegradable photocurable PGSA/PEG-DA/PCL-DA copolymers

Yih-Lin Cheng[1] and Ruei-Ting Hong[1]
[1]*National Taiwan University of Science and Technology, Taipei, 106, Taiwan; R.O.C.*
e: ylcheng@mail.ntust.edut.w

Biodegradable polycaprolactone (PCL) has been used in many biomedical and tissue engineering applications. To 3D print PCL parts, melt-and-dispense-type or sintering-type approaches were usually adopted. In our previous works, a DLP-type 3D printing system was utilized to cure photocurable PCL, PCL-diacrylate (PCL-DA), mixed with poly(ethylene glycol)-diacrylate (PEG-DA) or poly(glycerol sebacate)-diacrylate (PGSA) to form copolymers. With various mixing ratios, the resultant copolymers can be designed to provide a variety of properties for diverse tissue engineering applications. In this research, copolymers blending of three prepolymers, PGSA, PEG-DA, and PCL-DA, were further studied. Three mixing ratios of the prepolymers were evaluated first, and the one with the best mechanical properties was chosen. To improve the printing quality, vitamin E , as an inhibitor, was added into the material system. Tensile test, contact angle, FTIR, TGA, and DSC were conducted to understand the properties of photocured copolymers. Moreover, single-layer scaffolds were 3D printed to evaluate the accuracy with and without vitamin E. The results showed that adding vitamin E not only improved the printing quality, but also affected the degree of polymerization. In the future, copolymers with various ratios are applicable to different tissue applications.

Keywords: Photocurable, Copolymer, PGSA, PEG, PCL, Tissue Engineering

Micro/Nano- Approaches for Chemical Sensors for 3D Printing

Zhigang Zhu

School of Environmental and Materials Engineering, Shanghai Polytechnic University, Shanghai, 201209, China

zgzhu@sspu.edu.cn

Metal oxide semiconductor (MOS) based gas sensors have been widely used in monitoring air quality, food processing, and detecting of toxic, flammable and explosive gases. These sensors are attractive due to their high sensitivity, low cost, simplicity and compatibility with modern electronic devices. They can have good potential applications for 3D printing, for example, monitoring and detecting gas compositions in 3D printing chambers and gas emissions from various types of binders or polymeric materials during 3D printing or post-processing steps. In general, these oxide semiconductors are broadly classified into two types based on their majority charge carrier: n-type and p-type.

A facile method was used to prepare Pd-doped CuO nanoflowers with various doping concentrations. The samples were characterized through XRD, SEM, TEM, EDX, ICP-AES and BET. The responses (R_g/R_a or R_a/R_g, where R_g is the resistance in gas, and R_a is the resistance in air) of such sensors exposed to 50 ppm CH4, NO_2, C_2H_5OH, H_2S, NH_3, and H_2 were measured for comparison. For 1.25 wt% Pd-doped CuO nanoflowers, the response (R_g/R_a) to 50 ppm H_2S was 123.4 at 80 ^oC, which was significantly higher than that of pure CuO (R_g/R_a=15.7). Furthermore, excellent stability and repeatability of the gas sensor were also demonstrated. The observed results clearly revealed that it is an important and facile approach to detect the H2S at low operating temperature for practical applications.

H_2S sensors based on CuO microspheres modified by $CuFe_2O_4$ nanoparticles were developed. The $CuFe_2O_4$-modified CuO sensor exhibited a significant improvement in its H2S sensing performance compared with sensors based on pristine CuO and pure $CuFe_2O_4$. The enhanced sensing performances would be ascribed to several factors. First, the quantity of the reaction sites and absorbed oxygen species on the surface were increased owing to the hierarchical structural. Second, the gas diffusion rate was enhanced considerably due to the porous $CuFe_2O_4$ layer. Finally, the initial resistance (R_a) of CuO/$CuFe_2O_4$ was increased significantly because of the formation of p-CuO/n-$CuFe_2O_4$ junctions. The optimized composites yielded a sensitivity of 22.3 (R_a/R_g) upon exposure to H_2S gas of 10 ppm at an operating temperature of 240 ^oC.

Microstructures and Fracture Behaviour of Diamond/Ti-6Al-4V joints Brazed using Eutectic Ag-Cu Filler alloy

Ruixiang Liu[1], Dekui Mu[1]
Institute of Manufacturing Engineering, Huaqiao University, Xiamen 361021, China

Synthetic diamond is a super-hard material that has been widely used as grinding abrasives, and active brazing is a new and promising means for the fabrication of diamond grinding tools, which is of essential importance for the manufacturing of brittle and/or hard materials. Moreover, Ti-6Al-4V is one of the most commonly implied alloys for additive manufacturing. The capability of AM technology to effectively build complex geometry is desired for the fabrication of machining tools, for which the molding is often challenging. However, the knowledge of the microstructure, bonding strength and fracture characteristics of diamond/Ti-6Al-4V joints is limited. In this work, the synthetic diamond was brazed to Ti-6Al-4V alloy using an eutectic Ag-Cu alloy at 800, 840, and 880 ^{o}C. It has be found that, the microstructures of diamond joints consisted of multiple Cu-Ti intermetallics and Ti diffusion from Ti-6Al-4V alloy induced well wetting and reliable bonding of synthetic diamond. The microstructure evolution of Ti-6Al-4V alloy during brazing process was also discussed, in order to facilitate the fabrication of diamond grinding tools with substrates prepared with selective laser melting technique.

Additive Manufacturing of Duplex Stainless Steels using Selective Laser Melting

Derui Jiang[1,2], Sebastian Thomas[1,2], Michael Brameld[2,3], Nick Birbilis[1,4], Christopher Hutchinson[1,2]

[1] Department of Materials Science and Engineering, Monash University, Clayton, 3800, VIC, Australia
[2] Woodside Innovation Centre, Monash University, Clayton, 3800, VIC, Australia
[3] Woodside Energy, Perth, 6000, WA, Australia
[4] College of Engineering and Computer Science, The Australian National University, Acton, 2601, ACT, Australia

e: derui.jiang@monash.edu

Stainless steels are used extensively in many industries including food, chemical and oil & gas. Stainless steels are available in a range of grades, with the selection of which depends on the mechanical, chemical or environmental exposure. Grades include single phase ferritic, or austenitic, however duplex (ferrite + austenite), martensitic and precipitation hardened grades are used in specific applications.

Recently stainless steels have also become popular in additive manufacturing. To date, the austenitic 316 grade has been the most widely studied, and can be additively manufactured to create components of sound mechanical integrity, minimal porosity and acceptable corrosion resistance. However, austenitic stainless steels are limited in their achievable strength and are susceptible to stress corrosion cracking (SCC) in particular environments (that may include chemical or thermal regimes). In more demanding applications, where SCC is possible and/or higher strengths are required, duplex stainless steels (such as 22Cr duplex or 25Cr super duplex) are used. In the context of additive manufacturing, duplex grades of stainless steel represent an interesting processing scenario, due to the fast cooling rates from selective laser melting, which ensure that a duplex structure is not created in the 'as-produced' state and post production heat treatments are required.

Herein we report research related to duplex stainless steels prepared by the selective laser melting, and the subsequent thermal treatments required to obtain a duplex structure. The microstructural evolution, mechanical and electrochemical responses of the material are discussed, as a function of the production conditions and subsequent thermal treatments.

About Anthony

Anthony Rosengren is operating as the Markforged Application Engineer for APAC. He has over 10 years experience in engineering and design across a range of industries including construction and manufacturing. Before working for Markforged, Anthony represented Formlabs in a technical capacity across APAC. Mr Rosegren has an in-depth understanding of how different AM technologies can be best applied to different applications, as well as how to design for a wide range of additive manufacturing technologies.

WHY METAL 3D PRINTING IS DISRUPTING THE WAY WE MAKE THINGS

It might still sound like something out of Star Trek, but Additive Manufacturing technology with a push of a button isn't just the way of the future; it's happening right now at manufacturing companies around the world. 23x the Strength, 50x Faster and 10x Cheaper, with Metal 3D printing, manufacturing companies experience new ways to produce products a lightning speed. Additive manufacturing is changing how make products and how they are designed.

About Markforged
Markforged was founded on the belief that there is a better way to make things. Manufacturing innovation has stagnated over the last century and the original wave of additive manufacturing driven innovation for manufacturers held a lot of promise, but fell short. These initial forays into additive technology cost too much, took too long, or used materials that yielded parts that were too fragile and short-lived to make an impact in the manufacturing environment. Founder Greg Mark's belief that a robust additive manufacturing solution could change the world is the premise on which Markforged was born in 2013.

Markforged is transforming manufacturing by addressing 3D printing as a holistic problem. Our process innovations are only possible by a combined effort in advanced cloud computing, cutting-edge materials science, and industrial design. Over our five years of existence, we've consistently pushed the boundaries of additive manufacturing—3D printing with new materials, developing novel platforms, and constantly iterating on our technology and processes. Our vision is to increase manufacturing system efficiency through better and faster ways of making functional prototypes, tools and fixtures, and end use parts—at scale.
What's the result? An end-to-end 3D printing system that rivals traditional manufacturing processes, both in speed and cost, and expands the applications for additive manufacturing with purpose-built industrial technologies and a wide range of manufacturing-ready materials. Markforged is a manufacturer of industrial 3D printers, print systems, and software, as well as an innovator in the technologies and materials that continue to define this emerging industry.

A Review on Additive Manufacturing of Metal: Surface Roughness and Surface Finishing

Shanqing Xu, Yvonne Durandet*, Dong Ruan, Xiaodong Huang, Syed Masood
Department of Mechanical Engineering and Product Design Engineering, Faculty of Science, Engineering and Technology, Swinburne University of Technology, John Street, Hawthorn, VIC 3122, Australia
*Corresponding Author: ydurandet@swin.edu.au

Additive manufacturing (AM), widely known as 3D printing, has grown tremendously in the past 30 years and attracts increasing interest in research and industry, due to its capability of creating near net shape parts, providing design freedom and shorter time to market. Various AM processes have been developed targeting engineering applications in aerospace, automotive, energy, medical and other industry sectors. However, difficulties to achieve qualified surface finish is one of the main obstacles blocking the massive applications of AM technology, especially for applications with strictly defined surface roughness. This paper presents an extensive review of the published literature on the surface roughness and surface finishing related to various AM technologies used for metals. AM technologies' pros and cons, the generation of commonly seen defects of AM parts, surface characteristics and the correlations between process parameters and surface roughness of metal AM parts, as well as surface finishing technologies and their applications to AM products are reviewed and compared.

Keywords: Additive Manufacturing, 3D printing, surface roughness, surface finishing, surface characterisation

Evaluation of In-Process Monitoring of Laser-based Powder Bed Fusion as a Tool for Qualification and Certification Processes

J.D. Miller[1], M.P. Jurg[2], D. Downing[2], M. McMillan[3], M. Leary[3], A. Molotnikov[2], and M. Brandt[3]

[1]*Defence Science & Technology Group, Fishermans Bend, 3207, Australia*

[2]*Department of Materials Science and Engineering, Monash University, Clayton, 3800, Australia*

[3]*Royal Melbourne Institute of Technology, Melbourne, 3001, Australia*

e: Jonathan.Miller@dst.defence.gov.au

Laser-based powder bed fusion has been proven as a reliable manufacturing process for aerospace hardware when conventional full-rate production statistical process control approaches are employed. However, these approaches are contrary to the agility of the additive manufacturing (AM) process and are not viable in spare-part-production scenarios considered for defence applications which require lot quantities as low as one unit. As a solution, numerous businesses and government organisations identify in-process monitoring as a critical element for the qualification and certification of additively manufactured parts in the future. This research has quantified the efficacy of multiple in-process monitoring approaches to detect both process deviations and lack-of-fusion porosity produced during laser powder bed fusion. Multiple modalities of in-process monitoring have been evaluated, including technologies based on photodiode sensors, near IR and visual-range images and optical-pyrometer videos. Spatially-registered in-situ monitoring data have been quantitatively compared to process intent information and computed tomography data. The capability of the in-situ monitoring tools and practical utility of the current approaches in terms of data size and ability to sense process deviations and lack of fusion porosity will be discussed.

A Multiphysics Model of Selective Laser Melting Process for Nickel-based Superalloy IN738LC

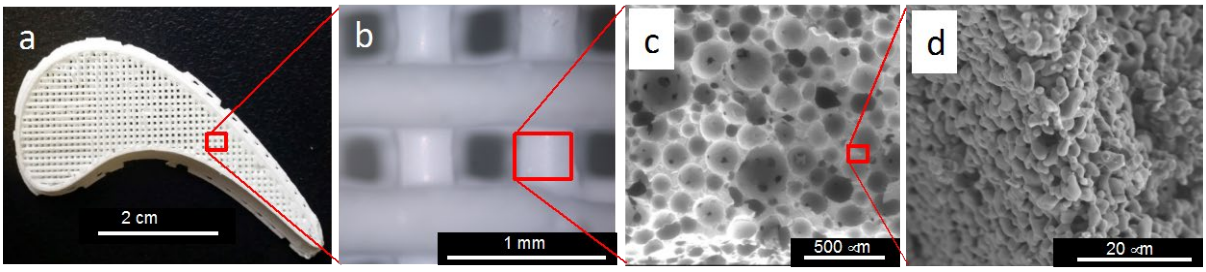
Marcus.C.Lam[1,2], Aijun Huang[1,2], Xinhua Wu[1,2]
[1]*Monash Centre of Additive Manufacturing, Monash University, Melbourne, VIC 3168, Australia*
[2]*Materials Science and Engineering, Monash University, Melbourne, VIC 3168, Australia*
e: marcus.lam@monash.edu

A mesoscale multiphysics model was developed to simulate the thermal field and solidification conditions of a Selective Laser Melting (SLM) process to explain the cracking tendency and grain texture observed in the microstructure. To increase the accuracy of the modelling, in particular the mult pool geometry that affect the solidifciation directions, the model considered the liquid flow, boiling and laser-surface interaction as well as the near-inequilibrium solidification freezing range predicted by Calculation of Phase Diagram (CALPHAD) technique. The modeled melt pool shapes and dimension agree well with the experimental result. Various SLM parameters were tested experimentally and their microstructural differences were explained by the thermal field result simulated by the multiphysics model.

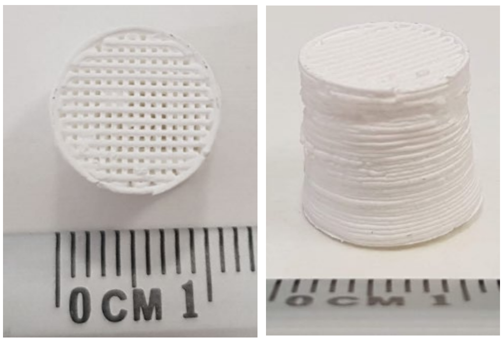
Particle-stabilized Emulsions as Pastes for 3D Printing Multiscale Porous Ceramics

Shareen S.L. Chan[1], George V. Franks[1], Mitchell L. Sesso[1,2]
[1]*Department of Chemical Engineering, Univ. of Melbourne, Parkville, Vic 3010, Au*
[2]*Department of Engineering, La Trobe University, Bundoora, Vic 3086, Au*
e: shareen.chan@student.unimelb.edu.au

We present an approach to producing multiscale porous ceramics using 3D printing. Millimeter scale porosity is created by control of the gaps between the 3D-printed scaffold strands. By using particle-stabilized emulsions of colloidal ceramic suspensions as the printing ink, 10-100 micron scale porosity is introduced by the soft templating of oil droplets. Using this approach, porous ceramic strands can be 3D printed *via* the Direct Ink Writing (DIW) technique. Micron scale porosity can also be developed by partial sintering of the ceramic. The rheological (flow) properties of the emulsion pastes must be carefully controlled to produce paste inks suitable for printing by extrusion through the needle of an extrusion-based 3D printer. A challenging part of the process is in transferring the fragile oil-filled green bodies from the printing substrate to the furnace for firing. The objects become strengthened by sintering at high temperature. Formulations and processing parameters have been developed for alumina. Complex-shaped objects can be printed and sintered into crack-free components, but distortion during drying and sintering lead to poor shape and tolerance control. X-ray tomography is used to characterize the internal structure of the printed components.



Schematic example of multiscale porous ceramic structures produced by 3D printing.



Example of sintered 3D printed cylinder with high-aspect ratio.

Investigating a closed loop ecosystem for the conversion and manufacturing of waste plastics using solar powered extrusion additive manufacturing

Mazher Iqbal Mohammed[1,2], Daniel Wilson[2], Eli Gomez-Kervin[2] and Johannes Long[2]
[1]*Deakin University, School of Medicine, Geelong, VIC 3216, Australia;*
[2] *Deakin University, School of Engineering, Geelong, VIC 3216, Australia*
e: iqy2004@hotmail.com

We present the EcoPrinting technology, a small scale pilot system which aims to realise a zero carbon footprint means of recycling waste polymers into functional products as part of a closed loop, digital manufacturing paradigm. As a proof of concept we optimize our system for the recycling of ABS plastics, a common fused filament fabrication (FFF) material, which is also found in a range of post-consumer waste. We present findings examining the use of waste ABS plastic over two recycling and manufacturing phases and document the changes in both mechanical and material properties. Results show a reduction in both the tensile and compressive strength by approximately 13-50% compared to virgin state ABS. Chemical analysis reveals an increase in carbonyl groups for increased recycling state, resulting from thermo-oxidative degradation of the polymer. However, for two times recycled ABS the strength begins to increase due to polymer hardening resulting from breakdown of the butadiene component of ABS. Ultimately, despite degradation of ABS for increased recycled state, the resulting material retained sufficient melt flow properties for FFF. The increased strength of the material may also enable several interesting possibilities with regards to closed loop industrial manufacturing of waste ABS material over multiple cycles.

Authentic Advanced Manufacturing

Steven Camilleri[1], Byron Kennedy[2], ...
[1]*CTO SPEE3D, Darwin, 0820, Australia;*
[2]*CEO SPEE3D, Melbourne, 3175, Australia;* ...
e: Steven.Camilleri@spee3d.com

Traditional manufacturing has always been about attaining the required quality at minimum total cost. As polymer and metal 3D printing technologies gradually become lower cost and higher performing, an increasing number of applications for the new technologies is emerging. These are unlocked not just by improvements in material properties and material types, but also by the cost required to attain those properties. This paper focuses on the expanding field of "Authentic AM", where traditional manufacturing methods are being displaced by more economic ways to obtain the required material and part quality using 3D printing. In the case of metal printing, new high speed / low cost techniques such as supersonic 3D deposition are opening up avenues in on-demand replacement parts and consumables where the production cost is below that of the original traditionally manufactured equivalent. A framework is described for fitting the new 3D printed substitute materials to existing compliance and logistics systems.

Solid-state transformations in TiAl during additive manufacturing by LENS

J. Jacob,[1,2]* D. Fraser,[2] G. de Looze,[2] S. Gulizia[2] and K. Xia[1]
[1]*Department of Mechanical Engineering, University of Melbourne, Victoria 3010, Australia;*
[2]*CSIRO Manufacturing, High Performance Metal Industries, Normanby Road, Clayton, Victoria 3169, Australia.*
e: jacobj1@student.unimelb.edu.

Titanium aluminide based intermetallic alloys are much lighter than nickel superalloys and possess superior mechanical properties up to ~700-800 °C. However, one of the major shortcomings of TiAl is its poor processability. Further, TiAl parts with satisfactory mechanical properties are achieved only after a series of post-processing steps including hot-isostatic pressing, ageing, annealing and hot working. Recently additive manufacturing (AM), mainly electron beam melting (EBM) and laser metal deposition (LMD) has been employed in making TiAl components possessing desired mechanical properties with minimal post-processing. In this investigation, a Ti-48Al-2Cr-2Nb alloy was successfully manufactured by laser engineered net shaping (LENS) with full density and minimum defects. Microstructures along the build direction were studied with a view to understanding the solid-state transformations caused by in-situ cyclic heating during LENS. Each solidified layer experienced a complex thermal history - a sequence of temperature cycles with peak value close to the melting point, decreasing in intensity with every additional layer. Microstructural features including lamellar colony size, lamellar thickness and phases present were characterised and correlated to AM conditions. This "in-situ heat treatment" is unique in AM and can be exploited for microstructure modification by controlling the solid-state transformations after deposition.

3D LTCC Fabrication for Wireless Sensors

Yongxiang Li[1], Hareem Khan[1], Mingsheng Ma[2], Zhifu Liu[2]

[1]*RMIT University, Melbourne, VIC 3000, Australia;*
[2]*Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai, 200050, China;*
Email: yongxiang.li@rmit.edu.au

Low-temperature co-fired ceramic (LTCC) technology has been used for many years for interconnections technology in the electronics industry. The LTCC technology enables a fast and easy fabrication of electronic devices and microsystems. LTCC technology is a three-dimensional (3D) ceramic technology for interconnection layers and electronic components. LTCC materials in the green state (called green tapes) are soft, flexible, and easily handled and mechanically shaped. The separate layers, conductor line or via sizes are of mesosize features (0.01-10 mm), and the laminated samples are co-fired at relative low temperatures (850–900°C) to form a rigid monolithic ceramic multilayer circuits (module). With the non-conventional application of LTCC technology different 3D structures, such as cantilevers, bridges, diaphragms, buried channels and cavities can be realized.

In this presentation, I will talk about different wireless sensors based on LC resonator platform for gas sensors[1], proximity sensor[2], pressure sensor with cavity inside[3], pressure and temperature dual-parameter sensor[4], and microfluidic sensor[5]. The LTCC materials processing and design and properties of the sensors will be discussed in detail. The LTCC technology as well as other additive technologies on ceramic based microsystems will be reviewed.

[1] M. Ma, H. Khan, Y. Li, *et al*., A novel wireless gas sensor based on LTCC technology, *Sensors and Actuators B*, 239 (2017) 711–717.

[2] M. Ma, Y. Wang, Y. Li, *et al*., Passive Wireless LC Proximity Sensor Based on LTCC Technology, *Sensors*, 19 (2019) 1110.

[3] L. Lin, M. Ma, Y. Li, *et al*., Fabrications and Performance of Wireless LC Pressure Sensors through LTCC Technology, *Sensors*, 18 (2018) 340.

[4] L. Lin, M. Ma, Y. Li, *et al*., Integrated passive wireless pressure and temperature dual-parameter sensor based on LTCC technology, *Ceramics International,* 44 (2018) S129–S132.

[5] Y. Liang, M. Ma, D. Wang, Y. Li, An LC Wireless Microfluidic Sensor Based on Low Temperature Co-Fired Ceramic (LTCC) Technology, *Sensors*, 19 (2019) 1189.

Additively 3D Printable High Strength Aluminum Alloys Using Cold Spray Additive Manufacturing

Q.B. Nguyen*, L. Cram*, M. Harbidge, K. Krishnan, R. Murray*

Advanced Manufacturing Alliance, Charles Darwin University, Darwin 0909, Australia

E-mail addres: Q.B. Nguyen (Bosley.nguyen@cdu.edu.au)

L. Cram (Lawrence.Cram@cdu.edu.au); R. Murray (rebecca.murray@cdu.edu.au)

Abstract

Complicated components of aluminum alloy A6061 were successfully additively fabricated using a cold spray additive manufacturing (CSAM) via a LightSPEE3D printer. Densitometry and microscopy show reasonably dense printed parts (98.15 ± 0.54 %) with strong mechanical interlocking. The as-printed samples were subsequently subjected to sintering (615^{o}C, 4hrs) and immediately solution heat treatment (550^{o}C, 10 minutes) and artificial aging at 225^{o}C for 4hrs. The mechanical strengths were 301 ± 9 MPa and 328 ± 11 MPa for 0.2% yield strength and ultimate tensile strength, respectively, with elongation of 6.4 ± 0.5 %. It is postulated that nano-aluminum oxide film on the surface of powder particles was shattered during the cold spray process due to the combination effect of high impact kinetic energy and shock wave. These nano aluminum oxide particles were diffused and well dispersed during the sintering and solution heat treatment. Good interfacial bonding between powder particles and the well distributed precipitation of nano-intermetallics and nano-Al_2O_3 particles, and small equiaxed grain structure in both the impact and transverse directions were observed under optical and scanning electron microscopy. The fractography reveals ductile features with cracks progressed along the grain boundaries as well as intra-granular. These experiments suggest that CSAM may benefit greatly from post-deposition treatment options that draw on the large body of knowledge developed for powder metallurgy of Al 6061.

Fabrication of a Cold Spray 3D Printed Component that Meets Military Specification

R.A. Murray[1], B.Saunders[2], M. Harbidge[1], M. Thorbjornsen[1], S. Camilleri[2]
[1]*Advanced Manufacturing Alliance, Charles Darwin University, Darwin, 0909, Australia;*
[2]*SPEE3D, Darwin, 0909, Australia*
e: rebecca.murray@cdu.edu.au

Cold spray metal additive manufacturing is associated with high deposition speeds and can be used with common industrial metals. This enables 3D printing to be a viable alternative for sourcing vital replacement parts either on-demand or to enhance sustainment of aging assets. Through collaboration with Defence (Patrol Boat Systems Program Office, Darwin, NT), a part was selected, a compliance plan developed, and the part manufactured and evaluated against military specifications.

An aluminium camlock hose-fitting (2” coupling, 5.5” length) was selected due to its usefulness as a replacement part and a history of previous corrosion-related failures. The replacement part was designed according to the relevant standard (MIL-C-27487/ A-A-59326), printed with 6061 aluminium on the LightSPEE3D printer and machine finished. Testing consisted of dimensional inspection, gasket compression, hydrostatic pressure (300 PSI for 3 minutes), torque-to-closure, and interchangeability. Finally, the 3D printed component was field-tested through a functional test aboard the patrol boat HMAS Broome.

The successful fabrication of a cold spray 3D printed component that meets military specification brings the future of print-on-demand components closer. Substantial work regarding establishment and testing of part validation pathways for 3D printed components is needed to ensure emerging technologies can reach their full potential and application.

Performance of a Cold Spray Additively Manufactured Water-Cooled Heat Sink

B. Katesook[1], M. Harbidge, D. Hill[1], H. Miao[1], R.A. Murray[1]
[1]*Advanced Manufacturing Alliance, Charles Darwin University, Darwin, 0909, Australia;*
e: rebecca.murray@cdu.edu.au

Cold spray (CS) metal additive manufacturing using a LightSPEE3D machine greatly increases the manufacturing speed and has different build constraints compared with other commercial fabrication methods. In this study, a bulk 3D printed pure copper block containing ~8.4mm diameter enclosed channels ($HS_{3D\text{-}Print}$) was compared to a commercially available water-cooled heat sink ($HS_{Commercial}$, Koolance® PLT-UN50F, nickel-plated copper).

Testing was performed using a custom-designed system that simulated the heat output of a processor chip and allowed total heat dissipation measurement. Using 100W power input, the total heat dissipated was 41.4±0.7kJ for $HS_{Commercial}$ and 39.7±0.4kJ for $HS_{3D\text{-}Print}$. The heat dissipation behaviour remained consistent over 25 minutes of testing at three power levels (100, 150 and 200W) with $HS_{3D\text{-}Print}$ having 3% lower heat dissipation than $HS_{Commercial}$.

The non-optimised CS 3D printed copper component performed to a similar standard as a commercially available heat sink. The commercial heat sink contained multiple interfacing metal components, a sealing o-ring, and a micro-textured internal surface whereas the 3D printed design was a solid block with simple external machining requirements. 3D printed heat sinks show promise due to strong heat dissipation alongside a streamlined design which may enable non-quantified manufacturing benefits and a possible reduction in failure mechanisms.

Dimensional Comparison of a Cold Spray Additive Manufacturing Simulation Tool

R.A. Murray[1], G. Foy[1], L. Clemon[2]
[1]*Advanced Manufacturing Alliance, Charles Darwin University, Darwin, 0909, Australia;*
[2]*Ultimo, University of Technology Sydney, Sydney, 2007*, Australia*;*
e: rebecca.murray@cdu.edu.au

High velocity particle spray greatly increases the deposition speed for metal additive manufacturing over other commercial methods. Accurate prediction and measurement of this process will enable expansion of adoption and better process control. Symmetric copper components were fabricated using cold spray additive manufacturing with a LightSPEE3D machine. The onboard software, TwinSPEE3D, generates predictions of the build geometry (.stl) given the input geometry and the build settings. Assessment of simulation accuracy is needed to enable rapid part design and print setting optimisation.

The printed part was scanned using white light 3D scanning and high-fidelity optical microscopy surface. Resultant scans are compared using hausdorf distance:

1) *Control*- repeated scans of printed object: 0.38±0.48mm, max:2.25mm
2) *Intended*- original CAD vs. scan of printed object: 1.42±1.58mm, max:6.72mm
3) *Simulation*- predicted build geometry vs. scan of printed object: 0.44±0.66mm, max:3.97mm

Discrepancies of up to 6.72 mm and asymmetric fabrication artifacts were identified. The reduction in the hausdorf distance for the *simulation* compared to the *intended,* and the larger but within error distance of the *simulation* compared to *control*, indicate the simulation tool may enable rapid optimisation given appropriate over/under spray quantification. Recommendations for better study of asymmetric fabrication artifacts and reducing over/under spray are provided.

Deep-powder-bed additive manufacturing of Ti-6Al-4V: Dependence of defect characteristics on build height and influence on tensile mechanical properties

J. Elambasseril[1,#], S. L. Lu[2,#], Y. P. Ning[2], N. Liu[2], J. Wang[2], M. Brandt[1], H. P. Tang[2,*], M. Qian[1,*]

[1] Centre for Additive Manufacturing, School of Engineering, RMIT University, Melbourne, VIC 3000, Australia.

[2] State Key Laboratory of Porous Metal Materials, Northwest Institute for Nonferrous Metal Research, Xi'an, 710016, China.

#: The first two authors contributed equally to this study.

* Corresponding authors: ma.qian@rmit.edu.au (M. Qian); hptang@c-nin.com (H. P. Tang)

ABSTRACT

A systematic study has been performed to investigate the effects of positional variation of porosity, microstructure and mechanical properties of vertically built long Ti-6Al-4V rods by selective electron beam melting (SEBM) up to the maximum building height (300 mm) of the Arcam A2 system. The as-built Ti-6Al-4V rods were characterised in detail using high-resolution micro focus X-ray computed tomography (μCT). The reconstructed three-dimensional (3D) images allowed a quantitative assessment of the sphericity, equivalent diameter and spatial distribution of pores in the rod as a function of building height. A number of new findings were made, which, together with the microstructural details and mechanical property data obtained from different segments of these long rods, are expected to improve the current understanding of the capabilities and limitations of the SEBM process for additive manufacturing of Ti-6Al-4V.

Recent developments in 3D binder jet printing of metallic materials

S.L. LU[1,2,e], G.K. Meenashisundaram[2], S.M.L. Nai[2], J. Wei[2]
[1]*Centre for Additive Manufacturing, School of Engineering, RMIT University, Melbourne, Australia, VIC 3000;*
[2]*Singapore Institute of Manufacturing Technology, A*STAR, Singapore, 637662;*
e: shenglu.lu@rmit.edu.au

3D binder jet printing (3D BJP) uses a printhead to jet binder drops into a powder bed to selectively join powder particles together to additively build the designed 3D geometries. Unlike selective laser melting and selective electron beam melting, 3D BJP proceeds at near room temperature without melting of powders. This allows 3D BJP to fabricate overhang segments without support structures and offer more freedom in geometry design. However, the as-built green parts are porous and weak. Post treatment to densify the green parts is needed. This work reported our recent research on 3D BJP of stainless steel (420 and 316), Inconel 718, TiH_2 and WC. A systematic study of the combined influence of pre-sintering and infiltration of bronze on the microstructure and mechanical properties was conducted. The shrinkage and relative density versus pre-sintering temperature were shown in this study. The powder arrangement condition in the green state and sintering evolution history were characterized by µCT and/or OM. Tensile tests were conducted after infiltration. It was found that the pre-sintering not only improved the infiltration performances but also significantly increased the tensile performances. The results of 3D BJP of Inconel 718, TiH_2 and WC were also summarized in this report.

Texture evolvement during hot isostatic pressing of selective electron beam melted Ti-6Al-4V plates and its fundamental influence on tensile performances

S.L. Lu[1], H.P. Tang[2], M. Qian[1,*]
1 Centre for Additive Manufacturing, School of Engineering, RMIT University, Melbourne, VIC 3000, Australia;
2 State Key Laboratory of Porous Metal Materials, Northwest Institute for Nonferrous Metal Research, Xi'an, 710016, China;
* Corresponding author: ma.qian@rmit.edu.au

With a better understanding the relationship between processing – microstructure – properties, selective electron beam melted (SEBM) Ti-6Al-4V components have been witnessed an increasing trend in application. However, the non-homogeneous microstructure and defect in the as-built state can cause non-consistent mechanical properties even at different segments of one single sample. Hot isostatic pressing (HIP) is proved to be effective to close the defect and render a homogeneous microstructure in a large component (300 mm high). However, it is still unclear how texture evolves and influences the tensile performances. Thin plate or strip, as a structural segment in components like impellers and rotating discs, is a basic product form of titanium. In this study, six Ti-6Al-4V plates (5mm thick, 45 mm wide, and 220 mm high) were additively manufactured and three of them were hot isostatic pressed at 920 ^{o}C for 2 hours under 100 MPa. It was found that the texture component of <0002> was intensified due to the preferential growth of primary α-laths. This significantly reduced the deformation constraint for prismatic slip, resulting into an obvious change in facture mode. The tensile properties of SEBM Ti-6Al-4V thin plates in both the as-built and HIP-processed conditions met requirements of ASTM F3001-14.

Formation and in-situ decomposition of the massive phase grains in selective electron beam melted Ti-6Al-4V

S.L. Lu[1], Z.L. Liu[2], H.P. Tang[3], M. Qian[1, *]
1 Centre for Additive Manufacturing, School of Engineering, RMIT University, Melbourne, VIC 3000, Australia;
2 College of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China
3 State Key Laboratory of Porous Metal Materials, Northwest Institute for Nonferrous Metal Research, Xi'an, 710016, China;
* Corresponding author: ma.qian@rmit.edu.au

In selective electron beam melted (SEBM) Ti-6Al-4V, the occurrences of three typical phase transformations including displacive martensitic transformation ($\beta \rightarrow \alpha'$), short-range diffusional massive transformation ($\beta \rightarrow \alpha_m$) and long-range diffusional transformation ($\beta \rightarrow \alpha + \beta_{enriched}$) were observed. Massive transformation is defined as a composition-invariant, interface-controlled diffusional phase transforamtion, involving a characteristic irregular patchy microstucture and frequent faceting and ledges but not necessarily involving lattice orientation relationships. Four types of massive grains were identified in SEBM-fabricated Ti-6Al-4V. Through the in-situ decomposition of the supersaturated α_m phase ($\alpha_m \rightarrow \alpha_{mpd} + \beta_{mpd}$, *mpd* for massive phase decomposition), a microstructure consisted of ultrafine lamellar α and β phases (100 nm wide strips) was observed. The experimentally determined orientation relationship between α_{mpd} and β_{mpd} was consistent with the prediction by edge-to-edge matching (E2EM) model, although the formation of α_m grains does not necessary obey specific orientation relationship with parent β grains. This study deepens our understanding of microstructure evolvement during additive manufacturing of Ti-6Al-4V and provides new insights into Ti alloy design with improved mechanical performances.

Digital Light Projection Printing of High Solids-Loaded Feedstocks for Military Applications: Feedstock Development Considerations

C.A. Williams[1], A. Hart[2], C. Prior[2], D. Mangos[3], D. Lewis[3].
[1]YTEK Pty Ltd, PO Box 1162, Camberwell 3124, Australia;
[2]Defence Science & Technology Group, PO Box 1500, Edinburgh 5111, Australia;
[3]Flinders University, GPO Box 2100, Adelaide 5042, Australia;

e: christopher.williams@dst.defence.gov.au

The design of energetic material charges has previously been limited by geometric constraints imposed by conventional extrusion or casting-based manufacturing techniques. Additive manufacturing stands to remove these geometric limitations, enabling for the first time the manufacture of complex, truly 3D charge designs. This affords increased tailorability over the nature of the energetic materials energy release, thus opening the door to previously unrealisable weapon concepts and levels of performance.

For military applications, energetic material charges generally contain a high proportion of solids (>60% vol) on grounds of energy density. The incorporation of such solids-loading levels presents a number of challenges for the vat-based printing of UV-curable feedstocks including: interactions between the incident light and solid particles affecting rate, extent, depth and spatial resolution of cure; affect of feedstock flow characteristics on effective print layer recoating, and; suspension stability. In addition, for energetic material applications, chemical compatibility between feedstock constituents and safe handling and processing conditions are pre-requisites for viable additive manufacturing of the same.

This paper will detail research efforts to address these challenges through a systems level approach to feedstock development, printer design and customised printing strategies for the Digital Light Projection printing technique.

Applications of additive manufacturing in a Defence Research and Development Context

T. Teske[1], J. McCarthy[2], E. Schumann[1]
[1]*Defence Science and Technology, Edinburgh, 5111, Australila*
[2]*Defence Science and Technology, Fishermans Bend, 3207, Australila*
e: timothy.teske@dst.defence.gov.au

Additive manufacturing offers unique opportunities in the Defence Research and Development (R&D) context, particularly in the design and manufacturing of bespoke hardware supporting research undertaken by scientists and engineers. Metal and polymer additive manufacturing techniques are routinely utilised alongside conventional manufacturing techniques in order to either improve product performance or reduce the reliance on technical fabrication skills. This presentation details various applications developed in the Defence R&D environment providing selected insights into the design for additive manufacture, as well as the advantages of the applications developed. Applications presented include additively manufactured jacketed vessels, heat exchangers, load transfer mechanisms, satellite mechanisms and pressure tapped wind tunnel models. With creative utilisation of additive manufacturing techniques along with conventional manufacturing techniques, hardware systems are now able to be developed which previously have not been achievable.

Digital Light Projection Printing of High Solids Loaded Feedstocks for Military Applications: Printer Design Considerations

T.J. Teske[1], A. Hart[1]
[1]*Defence Science and Technology, Edinburgh, 5111, Australila*
e: andrew.hart@dst.defence.gov.au

The ability to 3D print highly viscous, solids-loaded feedstocks has applications in the manufacture of ceramic materials, metallic materials, pharmaceuticals and energetic materials among others. Commercial 3D printing technologies such as Stereolithography (SLA) and Digital Light Processing (DLP) are generally limited to printing low viscosity feedstocks. The key element to enabling high viscosity systems to be printed is the development of effective layer recoating mechanisms and strategies, as well as the development of suitable resin systems. This presentation details aspects of the development of a bespoke 3D printer utilising the DLP 3D printing technology in order to print high viscosity feedstocks. The development of the 3D printer, along with lessons learnt and specific challenges will be discussed in this presentation. Articles successfully printed on the bespoke 3D printer demonstrates that the DLP 3D printing technology can be successfully utilised to print highly viscous feedstocks, and as such presents opportunities for DLP printing of materials for applications previously inaccessible to this printing technique.

Defect analysis in AM components and repairs

C. Wallbrink[1], B. Crawford[1], T. Harrison[1], D. Agius[2], and M. Qian[3]
[1]*Defence Science and Technology Group, Fishermans Bend, 3207, Australia;*
[2]*University of Bristol, Bristol, BS8 1QU, UK;*
[3]*RMIT University, Melbourne, 3000, Australia;*
e: Chris.Wallbrink@DST.defence.gov.au

The apparent geometric freedom of design and manufacture which additive manufacturing (AM) allows, is arguably a game changer for the sustainment of Australian Defence Force (ADF) assets. But, this new manufacturing technique also comes with new challenges and issues to overcome. One area of concern is the control, management and assessment of surface and subsurface defects resulting from this new manufacturing technique. Some of the defects observed are unique to the AM process and require a detailed understanding to determine their effects on structural performance. If AM components or repairs are to be used in structurally significant roles, a detailed assessment will be required for both certification and ongoing management. Size, orientation, material anisotropy and the distribution of defects are likely factors influencing structural performance. Traditional approaches to structural performance assessment are generally point-based approaches. This presentation details efforts by DST to develop a distributed approach (analysis at all points within a structure) to aid the assessment of known defects and evaluate their potential threat to structural performance in an in-service environment. The capability will be an integral aspect of AM material qualification and structural certification of components and repairs.

UNDERSTANDING THE STRUCTURE – PROCESS – PERFORMANCE RELATIONSHIP OF HIGH PERFORMANCE POLYMERS VIA FDM

Pejak. D[1], Bateman. S[2], Dilag. J[3], Kafi. A[4].
[1]*RMIT University, Melbourne, 3000, Australia;*
[2]*RMIT University, Melbourne, 3000, Australia;*
[3]*RMIT University, Melbourne, 3000, Australia;*
[4]*RMITUniversity, Melbourne, 3000, Australia;*
e: s3283890@student.rmit.edu.au

Fused Deposition Modelling (FDM) is a method of 3D printing that has progressed from a rapid prototyping technology to commercially viable form of additive manufacturing. Due to increasing aerospace interest in FDM, high performance polymers have been developed to produce unique parts. The technical limitations using these materials combined with the FDM process, means that mechanical properties of the bulk polymer are lost due to incomplete welding of the interlayer bond between deposited layers. While g-code optimization is valuable to improve the quality of printing, it is unclear what is occurring at the polymeric level and how the final mechanical properties are determined. This gap in understanding may be resolved through characterisation of the feedstock in terms of its rheology, microstructure and mechanical properties with respect to molecular weight (MW) and molecular weight distribution (MWD). A popular FDM engineering polymer is polyamide 12 due to its wide thermal stability range and high tensile strength. In this presentation we will discuss the influence of the molecular structure and its subsequent relationship on the printing process performance of these printed parts.

Initial Observations of Interstitial Solute Concentration in *α* and *β* Phases of Additively Manufactured Ti-based Alloys

William Davids[1,2], Hansheng Chen[1,2], Yingluo Li[1,2], Sophie Primig[3], Xiaozhou Liao[1], Sudarsanam Suresh Babu[4,5] and Simon Ringer[1,2]

[1]*School of Aerospace, Mechanical, and Mechatronic Engineering, The University of Sydney, Sydney, NSW, 2006, Australia*
[2]*Australian Centre for Microscopy and Microanalysis, The University of Sydney, NSW, 2006, Australia*
[3]*School of Materials Science and Engineering, UNSW Sydney, NSW, 2052, Australia*
[4]*Department of Mechanical, Aerospace, and Biomedical Engineering, University of Tennessee, Knoxville, Tennessee, TN, 37996, USA*
[5]*Manufacturing Demonstration Facility, Oak Ridge National Laboratory, Knoxville, TN, 37830, USA*
e: william.davids@sydney.edu.au

Ti-6Al-4V has found application in the aerospace industry due to its strength to weight ratio. Turbine blades, airframe structure and satellites all benefit from the mechanical properties of the titanium alloy. This work will report initial observations of the oxygen, carbon, nitrogen, titanium, aluminium, and vanadium concentration in hexagonal *α* and body-centred cubic *β* phases of additively manufactured Ti-6Al-4V alloys by atom probe tomography (APT). Furthermore, the segregation behaviour of these elements at *α*-*α* and *α*-*β* interfaces will be investigated. Any compositional variations with build height will be discussed. This is part of a broader AUSMURI research agenda concerned with quantifying the microstructure of AM alloy parts.

The authors acknowledge the facilities, scientific and technical assistance of the Microscopy Australia node at the University of Sydney (Sydney Microscopy & Microanalysis). The research was sponsored by the Department of Industry, Innovation and Science under the auspices of the AUSMURI program. The authors also gratefully acknowledge financial support from the Department of the Navy, Office of Naval Research under ONR award number N00014-18-1-2794. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Office of Naval Research. The research was also sponsored by the US Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office under contract DE-AC05-00OR22725 with UT-Battelle, LLC. Access to the Oak Ridge National Laboratory's (ORNL) additive manufacturing equipment at ORNL's Manufacturing Demonstration Facility (MDF) was facilitated by US Department of Energy's Strategic Partnership Projects (SPP) mechanism. More information can be found at https://science.energy.gov/lp/strategic-partnership-projects. Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

The Effects of Thermal history on Microstructural Evolution in Additively Manufactured Ti-6Al-4V

R. DeMott[1], N. Haghdadi[1], X. Liao[2], S.P. Ringer[2], S. Primig[1]
[1]*School of Materials Science and Engineering, UNSW Sydney, Sydney, 2052, Australia;*
[2]*School of Aerospace, Mechanical and Mechatronic Engineering, Australian Centre for Microscopy & Microanalysis, The University of Sydney, Sydney, 2006, Australia*
e: r.demott@unsw.edu.au

Ti-6Al-4V is frequently used in biomedical devices, aerospace components, and other applications which are uniquely suited to benefit from the advantages offered by additive manufacturing (AM) such as reduced waste, reduced density, and complex geometries. However, the complex thermal processes of AM result in microstructures that are very different from those produced by conventional methods. These microstructures are the result of multiple phase changes occurring during repeated thermal cycling and as such are highly variable and unpredictable. In this work, Ti-6Al-4V blocks were built using electron beam melting (EBM) with three different scan strategies: linear, random, and Dehoff, in order to generate different thermal histories. The microstructures were characterized using EBSD and variations in alpha lath morphology, alpha variant selection, and prior and retained beta textures were observed across the three different builds. By relating these features to the differences in thermal gradients, we will begin unraveling the complex microstructural evolution during the highly dynamic AM process.

Acknowledgements: Funding by the AUSMURI program, Department of Industry, Innovation and Science, Australia is acknowledged. Samples were provided by Prof. Suresh Babu and Miss Sabina Kumar, The University of Tennessee, Knoxville.

Direct laser deposition of eutectoid titanium-copper alloys

Dong Qiu[1], Duyao Zhang[1]
[1]*School of Engineering and Centre of additive manufacturing, RMIT Univeristy, Melbourne, VIC 3053, Australia*
e: dong.qiu2@rmit.edu.au

Titanium alloyed with a certain amount of copper is reported to have excellent anti-bacterial properties, good biocompatibility and corrosion resistance for dental applications. However, conventionally cast Ti-Cu alloys are not strong enough even after artificial aging. Given the unique advantages of very high cooling rates and multiple thermal cycles, additive manufacturing (AM) opens a new opportunity to produce high performance Ti-Cu alloys. In this study, a series of Ti-xCu binary alloys ($4 \leqslant x \leqslant 10$ wt. pct.) were produced by direct laser deposition (DLD). The effect of Cu concentration on the microstructure, porosity and mechanical properties of the AM Ti-Cu alloys has been comprehensively studied. In addition, the performance of AM Ti-Cu alloys was also compared with their cast counterparts in terms of the mechanical properties and anti-bacterial capability.

Temperature profile and residual stress investigation of Ti-6Al-4V manufactured by direct laser metal deposition

Jiexiong Wang[1], Kai Zhang[2], Xinhua Wu[2], Wenyi Yan[1]

[1]*Department of Mechanical and Aerospace Engineering, Monash University, Melbourne, VIC3800, Australia;*
[2]*Monash Centre for Additive Manufacturing, Monash University, Melbourne, VIC3800, Australia;*
e: Jiexiong.wang@monash.edu

Direct laser metal deposition (DLMD) is a well-recognized powder-feed additive manufacturing technique, which can produce a complex-shape part directly from a computer-aid design. However, its intrinsic high heating and cooling rates can induce relatively large residual stress due to the non-uniform temperature distribution as well as non-uniform plastic deformation, which leads to the compromises of geometry accuracy and mechanical performance. The residual stress may also induce crack formations, especially at the interface between the part and supporting substrate, where localised large stress occurs due to stress concentration and high cooling rate.

This project aims to investigate the effect of different substrate heating conditions on the residual stress. Proper substrate pre-heating and post-heating are considered as the key solutions to control and minimise the residual stress development by managing the initial temperature gradient and ultimate cooling rate, respectively. The temperature during the deposition process was measured in-situ by using thermocouples and the residual stress in the part-substrate system will be measured by applying both neutron diffraction and X-ray diffraction. The relationship between the temperature and residual stress will be established and the effect of the substrate heating conditions on the residual stress will be determined quantitatively.

3D printing of tuneable coloured agglomerates and strain distribution study

Jun Zhang[a], Negin Amini[a], David Morton[a] and Karen Hapgood[a]

[a] *School of Engineering, Deakin University, Geelong, Victoria 3216, Australia*

The current study presents a novel and reliable method for producing 3D printed agglomerates with different colour distributions and material properties with 2-fold aims: providing feasible and accurate control on compression of agglomerates under different compression angles, and better tracking of individual particle positions after agglomerate breakage. Multi-coloured agglomerates in cubic tetrahedral and random sphere shapes were printed. The printed agglomerates were analysed thoroughly of their surface and structural properties including surface roughness and printing accuracy. The agglomerate breakage behaviours under static compression were analysed as a function of bond strength (soft and rigid), loading rate (0.02 to 1 mm/s) and loading directions (0°, 45°, 90°, 135° and 180°), with strain distribution plotted over the random sphere agglomerate structure (Figure 1). In addition, agglomerate structures with designed internal macro-voids in different positions and sizes were also created for breakage study, in an effort to better understand parameters governing the mechanical properties of agglomerates with cavities and voids which is inevitable in particle industry but poorly understood at present.

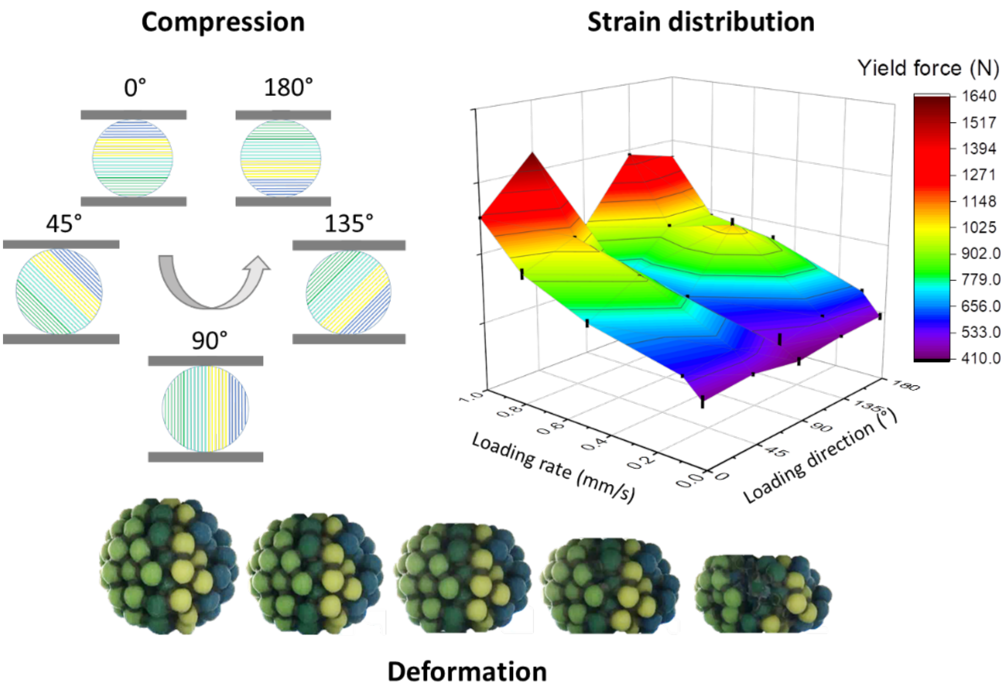


Figure 1. Schematic describing the 3D printing agglomerate breakage study.

Integrated Computational Materials Engineering of additive manufacturing – Linkage of open-source CFD and phase-field packages for process simulation & optimization of metal alloy part manufacturing

Patrick O'TOOLE[1], Milan Patel[2], Paulus Lahur[3],
Dayalan Gunasegaram[4], Anthony Murphy[5], Ivan Cole[2]

Tang Chao[6], Mingxuan Gan[6], Chee How Wong[6].

[1]*CSIRO Manufacturing, Docklands, VIC 3008, Australia*
[2]*School of Engineering, RMIT University, Melbourne, VIC 3000, Australia*
[3]*CSIRO Scientific Computing, Clayton, VIC 3169, Australia*
[4]*CSIRO Manufacturing, Clayton, VIC 3169, Australia*
[5]*CSIRO Manufacturing, Lindfield, NSW 2070, Australia*
[6]*Nanyang Technological University, Singapore, 639798, Singapore*
e: patrick.otoole@csiro.au

A 2015 TMS Roadmap study addressed implementation of the Integrated Computational Materials Engineering (ICME) paradigm in the automotive, aerospace, and maritime industries. Metal alloy additive manufacturing (MA-AM) is emerging as a key future technology for these industries. Current experimental methodologies cannot observe the *in-situ* conditions during MA-AM due to the associated extreme and highly transient conditions at solidification. MA-AM is therefore a prime target for ICME, with the aim being to reduce time (and cost) from design to market, as well as improve quality. The TMS study highlighted linking CFD and phase-field models as a key advance to relate solidification processing to final microstructure, properties, and part performance.

We present results from simulations of the Selective Laser Melting (SLM) process *via* runtime linkage of an open-source CFD library with an open-source phase-field (PF) library to compute the solidification microstructure of a hypo-eutectic Al-alloy. We couple our PF model to a linearized pseudo-binary (Al-Si) phase diagram for use in large-scale simulations and obtain interface-related quantities from molecular dynamics simulations for each crystal-liquid pair (FCC-DIAMOND-Liquid). This simulation platform demonstrates the most accurate physical treatment of SLM to date, and is an important step towards generating a real-time heuristic process model for SLM.

Direct material jetting functional surface structures onto aerospace coated substrates

T, Chen[1], J. Dilag[1], S.B. Bateman[1]
[1]*RMIT University, Melbourne, 3000, Australia;*
e: tiffany.chen@rmit.edu.au

Sharkskin inspired riblets are functional surface structures that have shown promising results in passive drag reduction. However, the limitations in the difficulty to apply the films on to surfaces and its non-durable adhesion make it unsuitable for aerospace applications. An additive manufacturing method was modified to produce these microstructures directly onto aerospace coated substrates using the material jetting technique. The spreading effects during the deposition of the photopolymer on various substrates were studied when printing the microscaled riblets. Considerations of surface chemistry such as interfacial interaction and thus adhesion of the photopolymer to the various stages of aerospace coating system were investigated. Experiments concluded that the adhesive properties is highly time dependent to the coating process due to changes in surface chemistry on the coating system. In general, better adhesion was observed when direct printing was performed within the overcoat window of the aerospace coating. Photopolymer directly deposited on topcoat coating was more adhesive than on the primer coating. The success in this method furthers the potential to large scale manufacturing of complex bioinspired surface structures directly on to surfaces in industrial applications.

Using X-ray tomography to evaluate the effect of defects on mechanical properties in metal Additive Manufacturing: a review

Anton du Plessis [1], Igor Yadroitsev [2], Ina Yadroitsava [2]
[1]*Stellenbosch University, Stellenbosch, 7602, South Africa*
[2]*Department of Mechanical Engineering, Central University of Technology, Bloemfontein, 9301, South Africa*

e: anton2@sun.ac.za

X-ray tomography has emerged as a uniquely powerful and non-destructive tool to analyze defects in metal additive manufacturing. Defects include unintended porosity, rough surfaces and deviations from design, which can have different root causes and can become better or worse due to a variety of reasons. Powder material properties, non-uniform delivery of the powder layer, deviations from optimal process-parameters caused by changes in the laser beam, the optical components and the scanning system operation, may result in keyhole pores, lack of fusion pores, metallurgical pores, etc. These different types of pores have different typical sizes, shapes and 3D distributions. The part complexity and the manufacturing and scanning strategy also may influence the porosity, resultant geometry and residual stress. All types of defects have effects on the mechanical properties of a final part. The use of X-ray tomography to visualize pores in parts (non-destructively) prior to mechanical testing allows us to build an improved understanding of the “effect of defect”, thereby providing the possibility to discriminate critical defects from harmless ones, and build confidence in additive manufacturing processes. This paper reviews the current state of knowledge with regards to the “effect of defect” in metal additive manufacturing, and highlights some relevant examples from our recent work.

Application of thermocouples to the Selective Laser Melting process

Matthew McMillan, Martin Leary, Milan Brandt
RMIT University Centre for Additive Manufacturing
e: matthew.mcmillan@rmit.edu.au

The Selective laser melting (SLM) process has two key thermal zones. A highly transient cyclical thermal zone around the bulk geometry zone which heats up throughout layer-by-layer manufacture. Process monitoring is required to understand how heat flow in the bulk geometry zone affects manufacturability and microstructure.

Non-contact surface process monitoring methods, avoid interfering with the SLM process but are limited to observing the currently exposed layer and the cyclical thermal zone. Process monitoring of the currently exposed layer enables understanding of geometric and process parameter effects on heat transfer at the surface. Process monitoring of the cyclical thermal zone investigates how process parameters affect melt pool size and stability.

This research implements novel process monitoring using thermocouples to directly measure temperatures in the bulk geometry zone. Initial results clearly demonstrate the effect of recoat period and the use of support structures on the transient heat flow.

This method provides data critical to understanding heat flow during the SLM processes leading to increased understanding of microstructural formation and the creation of more accurate numerical simulations.

Title: Industrial Applications of Additive Manufacturing Process Simulation

Authors: Erik Denlinger, Pan Michaleris, Jeff Irwin, Michael Gouge, Chao Li

Abstract:

A primary challenge for Additive Manufacturing to become an economically feasible method of component production is the warping of parts during production. Distortion is commonly mitigated by using a costly experimental trial and error approach. Finite Element Modeling can predict and mitigate build failure prior to manufacture. This work shows through simulation-experimental comparisons that simulation can be used to make timely and useful predictions of temperature, stress, and distortion for metals manufactured by either Laser Powder Bed Fusion or Directed Energy Deposition processes. It will also document the successful modeling of the secondary failure mechanisms of support structure delamination and recoater blade interference. Simulation based distortion mitigation will be demonstrated by simulating a part and compensating the build geometry to reduce deformation. Industrial use cases will be demonstrated.

Automatic reverse engineering and quality assessment of a high-speed 3D printed metal object

H.C. Harvard[1], S. Warren[1], G. Lavrov, D.J. Bone[1], G. Ranzuglia[1]
[1]*University of Technology Sydney, Ultimo, 2007, Australia;*
e: herve.harvard@uts.edu.au

Printing speed is a major limitation of most existing 3D printing technologies and is an obstacle to the wider adoption of metal 3D printing for functional part manufacturing by industry. In recent years cold-spray additive manufacturing has been used in conjunction with high-end robot arms to develop very high-speed metal 3d printing technology suitable for use by industry. This process, however, sacrifices the voxel-level accuracy achieved by lower-speed metal 3D printing processes. In Situ, automatic scanning of printed parts is therefore highly desirable and provides significant benefits. In this paper, we present a new fully automated scanning system and algorithm based on a fixed high precision 3d laser scanner and the control of an industrial robot arm. Given the 3D model of the intended part supplied to the high-speed 3d printer, our system automatically acquires the geometry of the 3d printed object and provides a reliable estimate of the error introduced during the printing process. The resulting data can then be used to optimize and improve the overall printing process.

Effect of Energy Density on the Interface Evolution of INC 625 and Stainless Steel 316L Builds Fabricated via DLD

D.R. Feenstra[1,2], A. Molotnikov[1], N. Birbilis[3]

[1]Department of Materials Science and Engineering, Monash University,
[2]Woodside Innovation Centre, Monash University, Melbourne, 3800, VIC, Australia
[3]College of Engineering & Computer Science, The Australian National University

Direct laser deposition (DLD) is an additive manufacturing (AM) technique that operates by blowing metal powder into a scanning laser using a 5~~-6~~ axis system, making it ideal for on-surface cladding operations and repair work. Another distinction of DLD from other AM processes is that it uses a multi-hopper powder system to feed in the deposited material. This multi-hopper feature gives DLD potential for the use of manufacturing of multi-metal parts. In this work DLD was used for the fabrication of Inconel 625 and Stainless steel 316L couples. The effect of input energy density on the interface evolution and on the created compositional gradient, was explored by varying the laser power for each build condition, while the other build parameters were kept constant. Columns that transitioned from Inconel 625 to stainless steel 316L were deposited onto mild steel substrates. The columns were then cross-sectioned and characterized via scanning electron microscopy (SEM). Energy-dispersive X-ray spectroscopy (EDS) mapping was collected on each dis-similar metal interface and EDS composition line profiles were measured. This was paired with microhardness and nano-scratch profiles to characterise the effect of energy density on the length and compositional distribution of the interface. Tensile specimens were built using the same conditions and the mechanical properties of each interface were characterised. The location of failure was identified with EDS fractography. It was determined that the increase of energy density had a direct effect on the remelted substrate fraction of each deposited layer and that this relationship could be quantified and correlated to be used as an effective tool for the design of functional gradients via DLD.

Mechanical response of hybrid auxetic tubes under axial compression

Krishna Prasath Logakannan[1,2], Dong Ruan[1*], Velmurugan R[2] and Jayaganthan R[3]

[1] Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

[2] Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai 60036, India

[3] Department of Engineering Design, Indian Institute of Technology Madras, Chennai 60036, India

*Corresponding author, druan@swin.edu.au

In this work, a novel hybrid auxetic tube which has an auxetic layer as an outer skin of a hollow tube have been proposed and investigated. Auxetic materials exhibit negative Poisson's ratio – they contract transversely when they are compressed axially, which is different from conventional material and other cellular structures. Therefore the presence of auxetic skin is expected to change the deformation mode of hollow tube. Numerical simulations were carried out using ABAQUS package to study the effect of auxetic layer on deformation mode and specific energy absorption of hollow tube. Simulations were conducted on a conventional tube, auxetic tube and hybrid auxetic tubes. Numerical models were verified by experimental results from literature. Preliminary simulation of hybrid tube suggested that presence of auxetics completely changed the deformation mode of hollow tube. Conventional tube exhibited oscillations in load values after the initial peak, while the oscillations in load was completely eliminated in hybrid tube. Auxetic tubes exhibited negative Poisson's ratio up to a certain strain limit but hybrid tubes did not exhibit any auxetic feature. Specific Energy absorption of hybrid tube is far better than that of auxetic tube but slightly lesser than that of the conventional tube.

Microstructural Control in Additive Manufacturing of Metal Alloys

S. P. Ringer
Australian Centre for Microscopy & Microanalysis, and
School of Aerospace, Mechanical and Mechatronic Engineering,
The University of Sydney, NSW, 2006, Australia.
E-mail: simon.ringer@sydney.edu.au

AM is a gateway to unexplored metallurgical phenomena that must be understood to open the full potential of the technology in terms of cost, design-flexibility and design-complexity. The steady-state conditions assumed during traditional manufacturing processes are not valid in AM, because of the spatial and temporal transients imposed by the abrupt, cyclical changes in energy delivery. The intrinsic microstructural heterogeneity throws new challenges at the familiar notion of a 'microstructure-property' relationship. This lecture will present recent advances in the design of structural engineering alloys and the way that the electron microscope and the atom probe microscope have enabled these developments. Recent breakthrough methodological advances in Transmission Kikuchi Diffraction, 3D-electron backscattered diffraction, aberration corrected scanning transmission electron microscopy, and atom probe microscopy will be presented in the context of how these techniques are enabling critical insights and data for AM process control.

Additive Manufacturing of Radiotherapy Phantoms in Radiation Oncology

R. Tino[1,3], M. Leary[1,3], M. Brandt[1,3], T. Kron[2,3],
[1]*RMIT Centre for Addtive Manufacture, Innovative Manufacturing Research Group, Melbourne, 3000, Australia;*
[2]*Peter MacCallum Cancer Centre, Melbourne, Australia, Melbourne, 3000, Australia;*
e: s3487718@student.rmit.edu.au
[3]*ARC Training Centre in Additive Biomanufacturing*,
www.additivebiomanufacturing.org.

In radiation oncology, commercially available anthropomorphic phantoms are utilised in the pre-treatment planning of cancer patients to validate target doses and minimise the ionising radiation effects towards adjacent healthy tissues. However, manufactured anthropomorphic phantoms through traditional moulding and casting techniques is associated with high fabrication costs and long processing times. In addition to this, they are not patient-specific in terms of individual dimensions (particularly in respect to obese patients), feature standardised tissue heterogeneity, and lack pathological features. This in contrast with the low-cost and patient-specificity of new generation phantoms enabled by AM, where manufacturing time and customisation for individual patients or radiation detectors are both improved for optimal patient treatment outcomes. Here we present the current trend of AM in Radiation oncology applications focusing on radiotherapy phantoms, their current printing workflows, and their associated printing techniques and materials.

Various Applications for 3D Printing of Particles

Negin Amini[1], Karen Hapgood[1], David Morton[1], Jun Zhang[1] and Anthony Antic[1]
[1]*School of Engineering, Deakin University, Geelong, Victoria 3216, Australia*;
e: negin.a@deakin.edu.au

3D printing can be used as a means to unlock new advances in research, particularly for particle applications. Our project investigates the photoelastic behaviour of 3D printed particle structures. The compression of simple spherical disc shapes to complex multiple stacked disc designs were carried out using a darkfield configuration. The compression of the particles at 2mm/min were video recorded. The time lapse of the compression, as shown in Figure 1, revealed stress fringes and force chains, similar to the previous conventional methods. It was found that complex structures fail sooner under heavier load. Furthermore, the effect of printing layer was found to have an effect on the photoelastic behaviour of the particle. Further work is underway to plot the exact strain distribution of the design using Digital Image Correlation (DIC) and Finite Element Analysis (FEA) to confirm the accuracy of the stress fringes.

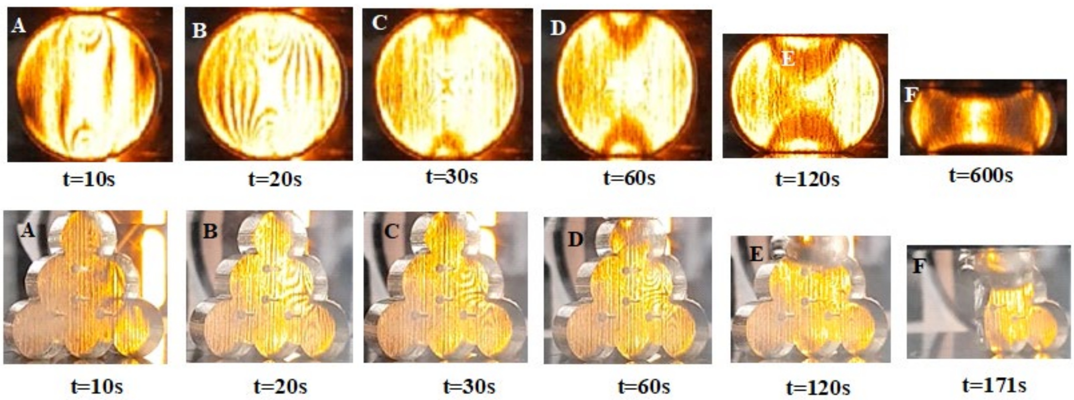


Figure 2. **<u>Top Image</u>: Compression at 2mm/min of a single 3D printed spherical disc (dimension 20x10mm) in VeroClear material. <u>Bottom Image</u>: Compression at 2mm/min of 6 stacked spherical discs (overall dimension 30x30x10mm) 3D printed in VeroClear material (Amini, Zhang, Morton, Antic & Hapgood, unpublished data, work funded by IFPRI & ARC)**

Investigation into the shear behaviour of thin walled FDM structures printed via the offset method

Thomas Romeijn[1], Dongbin Wei[2], Gavin Paul[2]
[1]*Mineral Technologies, Carrara, 4211, Australia;*
[2]*Faculty of Engineering and Information Technology, University of Technology Sydney, 2007, Australia*
e: Thomas.Romeijn@mineraltechnologies.com.au;
{Dongbin.Wei,Gavin.Paul}@uts.edu.au

Additive manufacturing techniques such as Fused Deposition Modelling (FDM) are rapidly revolutionising the manufacturing and mining sectors. In Fused Deposition Modelling (FDM) a thermoplastic filament is heated to its melting point and then, layer by layer, extruded directly on top of the previously deposited filament, which is the standard method. In this research, a new offset method has been proposed to 3D print helical gravity separation equipment to reduce the volume of cavities between deposited material. This paper presents an investigation into the shear behaviour of thin-walled FDM structures printed via the offset method. The shear properties of the samples from offset method are compared to those from the standard method via the application of ASTM D3846. Experimental results of solid (no infill) printed samples through three different nozzle sizes (0.3mm, 0.6mm and 0.9mm) have shown the newly proposed method produces an improved maximum in-plane shear stress only for the largest nozzle size (0.9mm). This intriguing lead will be the subject of future research where the nozzle size is further increased to investigate if the offset method continues to surpass the standard method regarding shear properties.

In situ Synchrotron Imaging of Additive Manufacturing

Peter D Lee [a,b], CL Alex Leung[a,b], Sam Clark[a,b], Yunhui Chen [a,b], Lorna Sinclair [a,b], Sebastian Marussi [a,b], Robert C. Atwood [c], Martyn A. Jones [d,e], Gavin J. Baxter [e]
[a] Mechanical Engineering, University College London, WC1E 7JE, UK
[b] Research Complex at Harwell, Harwell Campus, Didcot, OX11 0FA, UK
[c] Diamond Light Source Ltd, Harwell Campus, Didcot, OX11 0DE, UK
[d] University of Sheffield, Sir Robert Hadfield Building, Sheffield, S1 3JD, UK
[e] Rolls-Royce plc, PO Box 31, Derby, DE24 8BJ, UK

Laser additive manufacturing (LAM) can produce unique, high quality components for aerospace to biomedical applications. However, the solidification mechanisms controlling the formation of continuous, defect free, track are still poorly understood. During powder bed and direct energy deposition (DED) the solidification rates are 10^3 to 10^5 degrees per second, producing non-equilibrium phases that are controlled by kinetics. The solidification conditions can also lead to microstructural features (porosity, epitaxial growth) and high residual stresses that can reduce performance. We present a step change in the methodology used to characterise and optimise the solidification conditions during LAM using fast synchrotron X-ray imaging and bespoke LAM process replicators for both powder bed and DED. Using these unique in situ and operando rigs, we study a range of laser velocities and powers, developing a mechanism map for predicting when the solidification conditions are appropriate for producing high quality LAM components. Further, we capture the solidification mechanisms by which LAM fails, providing new insights into what controls additive manufacturing's process window, and how to extend it.

Effects of Cyclic Thermal Loadings during 3D Printing Processes on Local Microstructure and Mechanical Properties of a Cantor Alloy

H Wang[1], Z.G. Zhu[2], H.S. Chen[1,3], S.M.L. Nai[2], R.K. Zheng[3], S. Primig[4], S.P. Ringer[1], X.Z. Liao[1*].

[1] *School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, Sydney, NSW 2006, Australia;*

[2] *Singapore Institute of Manufacturing Technology, 73 Nanyang Drive, 637662, Singapore;*

[3] *School of Physics, The University of Sydney, Sydney, NSW 2006, Australia;*

[4] *School of Materials Science & Engineering, UNSW, Sydney, NSW 2052, Australia.*

e: xiaozhou.liao@sydney.edu.au

The 3D printing processes of metallic materials consist of cyclic rapid thermal loadings that affect significantly the microstructure and consequently the mechanical properties of materials. It has not been very clear how the number of cyclic thermal loadings introduced by the 3D printing processes affects the microstructure of materials. Here we used a FeCoCrMnNi high-entropy alloy, known as a Cantor alloy, as the model material to explore the effects of cyclic thermal loadings on local microstructure and mechanical properties. Transmission electron microscopy, in-situ straining scanning electron microscopy, and atom probe tomography were used for structural characterisation and mechanical testing. Results showed that, with the increase of the number of cyclic thermal loadings, the microstructure evolved from a nanocrystalline structure in the top layer, through coarse grains with cellular dislocation structures in a middle layer, to nanotwin and hierarchical nanotwin structures in the bottom layer. Significant Mn and Ni segregation at dislocation cell wall areas were observed. The impact of local microstructure and elemental distribution on the mechanical properties and thermal stability of the material will be discussed in detail.

Acknowledgements: The authors acknowledge gratefully support from the Department of Industry, Innovation and Science under the auspices of the AUSMURI program.

3D Printing – Exploiting profitable applications with new technologies

Prof. Dr.-Ing. C. Emmelmann
Fraunhofer IAPT
Am Schleusengraben 14
21029 Hamburg
www.iapt.fraunhofer.de

Abstract

Additive Manufacturing (AM) enables toolless conversion of digital data into three-dimensional complex, functional and nature inspired bionic components. Hence, it is a core technology for implementation of industry 4.0 by coalescing virtuality and reality. A disruption of traditional design patterns including an optimal utilization of bionic principles in product development is necessary. But not only a change in design thought patterns, but a rethinking of factory structures and production layouts leading to bionic smart factories is required. The combination of profitable bionic design and interconnected smart factories will boost leading competitive positions when 3D printing takes over further innovative applications. This is especially true with new upcoming and promising 3D printing technologies.

Additive manufacturing of complex-component alloys

Yong Liu
The State Key Laboratory of Powder Metallurgy
Central South University
Changsha 410083, P.R.China

Complex-component alloys (CCAs) with almost equal atomic ratios are a class of new metallic materials consisting of multi-elements. Compared with single-principal-element based conventional alloys, CCAs offer outstanding properties, for example, simultaneous high strength and high ductility, and high corrosion and wear resistance. This talk introduces our recent work on additive manufacturing of CCAs, and understanding of the relationship between microstructures and mechanical properties. Gas atomized CCAs powders were used for selective laser sintering (SLS). Fully dense and fine-microstructured FeCoCrNi-based CCAs can be conveniently fabricated by using SLS. The quality of CCAs is dependent on the SLS processing parameter. An increase of the SLS scanning power or a decrease of the scanning speed leads to an increase in the density of CCAs. The grain size decreased when the high scanning power or the low scanning speed was used. The carbon-doped CCAs with full density have a yield strength of 650 MPa, which nearly doubled that of the same alloy made by casting. The CCAs have unique cellular and columnar subgrain structures. The subgrain boundaries are composed of dislocation networks decorated by the segregation of Cr element and nanosized $M_{23}C_6$-type carbides, and thus, are the main strengthening factor for the C-containing CCAs The improvement of the mechanical properties of the CCAs is attributed to the solid solution strengthening, grain boundary strengthening and the homogenous microstructure, which increase the work hardening ability. SLS can be considered as a promising manufacturing route for the fabrication of large-sized and complex-shaped CCAs with high mechanical properties.

Laser Metal Deposition of Al-12Si alloy: Characterization of thin wall deposits

Jamie S. Quinton

Institute for NanoScale Science and Technology, Flinders Microscopy and Microanalysis, Flinders University, Adelaide, South Australia

Abstract

Additive manufacturing is an emerging process that is used to manufacture industrial parts layer by layer, and can produce a wide range of geometries for various applications. In this study, a gas atomized powder of a eutectic Al-12Si alloy was used as feedstock for a Laser Metal Deposition (LMD) process, which melts the metallic powders into layers of metallic beads to form a single layer wall. A numerical control system actuates the laser deposition head towards the desired printing positions. Microhardness tests on the deposited samples showed a hardness of 95 Hv. SEM analyses of the Al-12Si powders showed that the particles have an appropriate morphology for LMD processing. Further analyses on the deposited samples were able to confirm the presence of both Al rich zones and Al-Si eutectic regions. The porosity content in the samples was found to be around 2.6%. Surface roughness measurements and microstructural analysis of the samples was also performed to assess the fabricated sample in terms of roughness, porosity and distribution of Al and Al/Si eutectic phases.

Keywords: Laser metal deposition (LMD); additive manufacturing; Al-Si eutectic alloys; microstructure; surface roughness; hardness.

Influence of deposition strategy on defect evolution and fatigue life in 300M High Strength Steel following LMD Repair

Cameron J. Barr[1,3], Stephen Sun[1,3], Nicholas Orchowski[2,3], Niel Matthews[2,3], Milan Brandt[1,3]

[1] *RMIT Centre for Additive Manufacturing, 58 Cardigan St. Carlton, VIC 3083, Australia*

[2] *RUAG Australia, 836 Mountain Highway, Bayswater, VIC, 3153, Australia*

[3] *Defence Materials Technology Centre, 24 Wakefield St. Hawthorn, VIC 3122, Australia*

e: cameron.barr@rmit.edu.au

Laser metal deposition (LMD) is emerging as a vital tool for the restoration of high value aerospace components previously thought beyond repair. This is especially beneficial for 300M and other high strength steels, which are sensitive to fatigue cracking due to high static and fluctuating stresses during operation. Unlike traditional grind-out repair, where superficial damage is mechanically removed, LMD offers the ability for both geometric and structural restoration by replacing any lost material. However, the deposit must be of sufficient quality as to avoid introducing potential crack initiators. In this study, the effect of continuous and layer delay deposition strategies on microstructure and fatigue performance were investigated. Both strategies produced similar hardness profiles through in-situ tempering of as-deposited martensite. The fatigue performance also fell within a similar range for both conditions, though continuous deposition tended to show poorer results. Fracture surface observations revealed various pore types at the initiation sites, including 50 μm spherical pores, arrays of fine ~3 μm voids, and large ~200 μm irregular gas pores unique to the continuous strategy. These pores thought to originate from limited ability of local shielding to prevent oxides forming and decomposing into gas pores on subsequent deposition layers.

Effect of repair depth on the mechanical performance of 300M High Strength Steel refurbished by Laser Metal Deposition

Cameron J. Barr[1,3], Stephen Sun[1,3], Nicholas Orchowski[2,3], Niel Matthews[2,3], Milan Brandt[1,3]

[1] *RMIT Centre for Additive Manufacturing, 58 Cardigan St. Carlton, VIC 3083, Australia*

[2] *RUAG Australia, 836 Mountain Highway, Bayswater, VIC, 3153, Australia*

[3] *Defence Materials Technology Centre, 24 Wakefield St. Hawthorn, VIC 3122, Australia*

e: cameron.barr@rmit.edu.au

Laser metal deposition (LMD) is emerging as a vital tool for the restoration of high value aerospace components previously thought beyond repair. Unlike traditional grind-out repair, where superficial damage is mechanically removed, LMD offers the ability for both geometric and structural restoration by replacing any lost material. The repaired component thus becomes a hybrid of conventional and additively manufactured material. To ensure safe return to service, the limitations of LMD repair must be clearly understood. This study investigates the changes in tensile and fatigue performance as the repair depth is increased and a greater proportion of the load is shared by the deposited material. The benefits of LMD become more apparent at greater depths as the continued loss of load bearing area makes grind-out repair impossible. The yield and tensile strength of repaired samples follow typical composite type behaviour, with strength contributions from deposit, substrate and HAZ. Fatigue studies showed no significant difference in fatigue performance for deposits comprising up to 40% of the original thickness. The similar behaviour was linked to the initiation of fatigue cracks from internal defects, thus masking differences in material characteristics. Further work is continuing to eliminate these defects to further improve fatigue performance.

Materials for Defence: Opportunities for additive manufacturing

Khan Sharp
Aerospace Division
Defence Science & Technology Group
Bldg3, 506 Lorimer St, Fishermans Bend VIC 3207 Australia

Abstract

Military systems are becoming ever more complex, and so are the materials used to build them. In this context, advanced materials have sparked considerable interest as their use has the potential to significantly shape future operational effectiveness in military missions.
Advanced materials can be used in a wide range of domains and hostile environments where risks and damages can be reduced with the use of protective solutions. The most disruptive effects are expected to derive from the integration of functionalities such as energy harvesting, camouflage, structural and health monitoring, protection in ‘multi-functional’ materials for platforms and soldiers.

The major land, sea and air platforms currently in service are not expected to be retired for another two to three decades which means that the existing platforms will have to be upgraded with new materials. As a consequence, new opportunities for the implementation of new materials will most certainly arise through mid-life upgrades, incremental improvements, urgent operational needs, lifetime extension and a growing need for sovereign industry technological and material capability. These materials will make platforms and soldier systems lighter and better performing, while at the same time reducing their maintenance periods and cost. The incremental adaptations of platforms should not be the only aim as new technologies such as unmanned aerial vehicles, high speed systems, advanced sensors and emerging directed energy weapons (DEW) are maturing rapidly, and will need new materials to enhance their capabilities or to counter-measure them with new protections.

Building on AUS strong foundation of research, talented people and partners in government, academia and industry what materials S&T opportunities exist to assist Defence in the being the first to field a decisive capability. How does Defence ensure the AUS S&T community is aligned, allocated the funding and rapidly integrating the technology.

Digital Twins of Additive Manufacturing Processes: How they Add Value in an Industry 4.0 Economy

Dayalan R. GUNASEGARAM[1], Anthony B. Murphy[2], Patrick I. O'Toole[3]
[1]*CSIRO Manufacturing, Clayton, VIC 3169, Australia;*
[2]*CSIRO Manufacturing, Lindfield, NSW 2070, Australia;*
[3]*CSIRO Manufacturing, Docklands, VIC 3008, Australia*
e: dayalan.gunasegaram@csiro.au

In the end-to-end digitalisation of manufacturing expected in an Industry 4.0 economy, machines will be able to take action based on insights developed by artificial intelligence and advanced analytics using a wealth of real-time process data gathered by sensors. These cyber-physical actions will be aimed at reducing business costs by getting products and processes right every time. In order to succeed, however, process intelligence that is sufficiently in-depth is required. Such intelligence may be provided by physics-based computational models, which are called 'digital twins' of the processes. Advance knowledge derived from robust predictive capabilities of the digital twins, informed by accurate multiscale physical simulations, is especially helpful for the supervision of an additive manufacturing process which typically creates a high-value item that is a customised one-off. Such knowledge could help define an optimal processing window for a product that has not been manufactured before and assists with assuring quality in a part that is to be made for the very first time. In this talk, hurdles to the development of the digital twins for additive manufacturing processes and their integration into a smart factory will be discussed, along with potential solutions to these issues.

Laser Metal Deposition for Adding of Wear Resistant Features

Christiane Schulz[1], Thomas Schläfer[2], Colin Hall[1]
[1]*University of South Australia, Mawson Lakes, 5095, Australia*
[2]*LaserBond Ltd, Cavan, 5094, Australia*
e: christiane.schulz@unisa.edu.au

Laser Metal Deposition (LMD) may be utilised for applying a uniform cladding to a component, remanufacturing a worn part, additively manufacturing an entire component or the adding of a feature to a part. In this study a wear-resistant feature was added to a traditionally subtractively manufactured part, using NiBSi/WC as a feedstock material. This material system is considered the golden standard for high wear applications in heavy industries such as mining, oil & gas, steel and agriculture. The microstructure of the additively manufactured feature was analysed and compared to laser clad coatings of the same material deposited in a uniform layer. Especially challenging is controlling the laser power to avoid overheating and carbide dissolution.

In the present case the feature was a 25 mm rim which was added to a tube with an inner diameter of 32 mm and a wall thickness of 7 mm. The performance of the deposited feature was tested with regard to erosion resistance at high and low impingement angles according to ASTM G76. Finally, a real part was equipped with the developed wear-resistant feature and tested under real life conditions in a mining environment.

Design for Metal AM: Overcoming the Barrier to Adoption

Olaf Diegel[1]
[1]*University of Auckland, Design for AM Lab, Auckland, 1023, New Zealand;*
e: olaf.diegel@auckland.ac.nz

Many industries approach additive manufacturing (AM) as a drop-in replacement for conventional manufacturing technologies. This approach, however, does not fully utilize the unique possibilities that AM processes offer. When using AM for manufacturing it should also be noted that AM does not remove all manufacturing restrictions. It, instead, replaces them with a different set of design considerations that designers must take into account if they wish to add value to their products. Otherwise AM can easily become a slow and uneconomical way of manufacturing products or parts.

It is also of great importance to understand that, despite much of the marketing hype over the past decades, AM is not an “easy” technology that can make absolutely anything. It requires a good understanding of the different technologies and processes, and how to design for them. In fact, printing parts in metal, for example, can be downright hard, and the use of AM to manufacture metal parts should only be considered if the process truly adds value to the product.

This talk examines some of the important design considerations that can determine whether an AM part is viable or not from an economical, structural, or value-adding point of view.

A Comprehensive Model of Metal Additive Manufacturing – Progress and Obstacles

V. Nguyen[1], P.W. Cleary[2], P.S. Cook[1], S.J. Cummins[2], G.W. Delaney[2], D. Gunasegaram[1], P. Lahur[3], A.B. Murphy[4], P. I. O'Toole[1], M.J. Patel[5], M.D. Sinnott[2]

[1]*CSIRO Manufacturing, Clayton South VIC 3169, Australia;*

[2]*CSIRO Data61, Clayton South VIC 3169, Australia;*

[3]*CSIRO IM&T, Clayton South VIC 3169, Australia;*

[4]*CSIRO Manufacturing, Lindfield NSW 2070, Australia;*

[5]*School of Engineering, RMIT University, Melbourne VIC 3000, Australia*

e: tony.murphy@csiro.au

Metal additive manufacturing relies on several physical processes with length and time scales that differ by many orders of magnitude. The processes occurring in laser powder-bed fusion, for example, include raking of a bed of metal particles, their melting to form a melt pool, the formation of metallic microstructures, and residual stress development in the whole component.

Computational modelling of each process presents significant challenges and requires state-of-the-art techniques. We are using the discrete-element method to treat powder raking, computational fluid dynamics and smoothed-particle hydrodynamics for melt-pool modelling, the phase-field method and a semi-empirical approach to predict microstructure, and the finite-element method to model residual stress and distortion.

Even more challenging is linking these ‘sub-models’ together to produce a ‘digital twin’ of the complete additive manufacturing process. Difficulties include the need to model a very large number of laser passes, to transfer data produced using different computational techniques with different time steps and meshes (or in some cases no mesh), and to produce results in an acceptable time, ideally no longer than that taken to build a component.

We present results from each sub-model, and possible approaches to overcome the challenges inherent in developing a digital twin of additive manufacturing.

ADDITIVELY MANUFACTURED HIERARCHICAL HIGH-ENTROPY ALLOY WITH EXCELLENT PROPERTIES

Xianghai An,
1 School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, Sydney, NSW 2006 Australia;
e: xianghai.an@sydney.edu.au

High-entropy alloys (HEAs) are a novel class of entropy-stabilized solid solution alloys with five or more principal elements having approximately equiatomic concentrations, which open up a new avenue for the design of materials with optimized properties. The severe lattice distortion and sluggish diffusion that are induced by the mixture of multiple elements endow HEAs with exceptional structure stability and outstanding mechanical properties. However, the current preparations of HEAs rely mainly on the conventional melting or casting methods, imposing enormous limitations to produce samples with complex geometry in terms of cost and efficiency for practical applications. The additive manufacturing (AM) techniques have been recognized as a transformative technology across multiple industries. Based on their advantages of net-shape manufacturing capability and design freedom, it is feasible to harvest parts with complex geometries directly from computer-aided design (CAD) models. In this study, we applied selective laser melting (SLM) technique, which is one of the most popular AM techniques, to prepare a near-fully dense CoCrFeNiMn HEA. The as-built samples exhibit a hierarchical nanostructure, including melt pools, columnar grains, dislocations, and sub-micron cellular structures. An outstanding combination of high strength and excellent ductility compared to those fabricated by conventional methods was achieved in the as-built samples. The detailed deformation behaviour and strengthening mechanism will be discussed in this talk.

Additive Manufacturing in the Solid State by Cold Spray

Peter C. King[1], Alejandro Vargas Uscategui[1], Andrew Urban[1]
[1]*CSIRO Manufacturing, Clayton, Victoria 3168, Australia;*
e: peter.king@csiro.au

Cold spray is a solid state material deposition process that uses an inert, supersonic gas jet to accelerate metal micro-particles towards a substrate surface. Particle impact at velocities of 500 – 1000 m/s causes intense plastic deformation and bonding. Cold spray has been primarily viewed as a technique for repair of metallic structures or for coating. However, cold spray is also able to build large, free-standing parts in a variety of materials, including titanium, aluminium, ferrous alloys and metal matrix composites. It is able to achieve build rates of kilograms per hour in ambient conditions, without the need for a protective atmosphere or chamber. This talk highlights CSIRO's work building cold spray parts using dual, coordinated robots, with tool paths automatically generated from a sliced CAD file. The effect of robot motion on part geometry and build defects is discussed. An outline is presented of the necessary future developments to achieve consistent parts with reliable properties.

Measurement of Laser Absorptivity by Calibrated Melt Pool Simulation

P.S. Cook[1], D.J. Ritchie[1], A.B. Murphy[2], V. Nguyen[1]
[1]*CSIRO Manufacturing, Clayton South, 3169, Australia;*
[2]*CSIRO Manufacturing, Lindfield, 2070, Australia;*
e: peter.cook@csiro.au

In recent years there has been considerable progress in developing AM simulation capabilities aimed at process optimization, component qualification and process control. The amount of energy transferred to the part by the laser or electron beam is, of course, a critical factor. However, at least for selective laser melting (SLM), the published literature contains surprisingly little data on laser absorptivity *that apply to the actual operating conditions*.

To address this gap, we report the results of a detailed investigation of the factors affecting laser absorption by Ti-6Al-4V during SLM. By calibrating melt pool CFD simulations against single track experiments conducted over a range of energy densities, we have been able to determine the intrinsic laser absorptivity of Ti-6Al-4V during SLM. Our simulations incorporate multiple laser reflections and cover the transition from conduction to keyhole mode. We also discuss physical mechanisms that may be responsible for an increase in the effective laser absorptivity at high energy density which is observed in this and other work.

Analysis of in-situ thermal field measurements from an SLM process

D. Downing[1], J. Miller[2], M. McMillan[1], M. Brandt[1], M. Leary[1]
[1]*RMIT Centre for Additive Manufacturing, Melbourne, 3001, Australia;*
[2]*Defence Science and Technology, Fisherman's Bend, 3207, Australia;*
e: martin.leary@rmit.edu.au

Selective laser melting for metal additive manufacturing is a thermal process with a multitude of spatial and time scales. The process can produce significant variation in mechanical properties within a single part by effecting the underlying microstructure and porosity. In-situ thermal cameras can provide a wealth of information during the metal additive manufacturing process which can be used to determine the quality of the build and highlight regions of concern. This work describes how thermal data captured during the fabrication of multiple lattices and inclined cylinders was used to extract thermal field variables. Structural symmetries were utilised to collapse the field variables into various geometric regions. The collapsed data provides a summary of the build which can be analysed for trends in the field variables with geometric factors such as cross-sectional area, inclination angle and lattice location. The analysis highlights the dependence of maximum temperature upon cross-sectional area, the dependence of cooling duration upon inclination angle and identifies layers where disparate results warrant further investigation.

For APICAM 2019 - Asia-Pacific International Conference on Additive Manufacturing - June 30 to July 3 - RMIT University, Melbourne, VIC, AUSTRALIA",

In situ and *Operando* X-ray Imaging of Molten Pool Dynamics and Defect Formation Mechanism in Direct Energy Deposition Additive Manufacturing

Yunhui Chen[1,2], Samuel Clark[1,2], Lorna Sinclair[1,2], Chu Lun Alex Leung[1,2], Sebastian Marussi[1,2], Gavin Baxter[3], Martyn Jones[3,4], Thomas Connolley[5], Robert Atwood[5], Iain Todd[4], Peter D. Lee[1,2]

[1] Mechanical Engineering, University College London, Torrington Place, London, WC1E 7JE, UK

[2] Research Complex at Harwell, Harwell Campus, Oxfordshire, OX11 0FA

[3] Rolls-Royce plc, PO Box 31, Derby, DE24 8BJ

[4] University of Sheffield, Sir Robert Hadfield Building, Mappin Street, Sheffield, S1 3JD

[5] Diamond Light Source, Harwell Campus, Oxfordshire, OX11 0DE

Direct Energy Deposition (DED) Additive Manufacturing (AM) is one of the principal AM techniques for the production of larger metallic components from a computer-aided design model. However, the properties can vary due to the presence of features such as porosity, inclusions and epitaxial grain structures. This study provides new insights into the mechanisms by which some of these features form using an DED-AM machine designed to fit onto a synchrotron beamline enabling *in situ* and operando X-ray imaging and diffraction. This combination enables us to gain a fundamental understanding of the processes and phenomena that lead to feature formation and mitigation. Laser-matter interaction, melt pool dynamics, and feature formation are monitored during multi-layer build conditions. Post analysis using micro-CT and electron microscopy are used to verify the *in situ* observations. These insights reveal how the DED process parameters can be controlled to tailor and improve the mechanical properties of the final components produced.

316L Stainless Steel Microlattice Structures: Stiffer and Stronger

M. G. Rashed[1], Dhriti Bhattacharyya[2], R. A. W. Mines[3], M. Saadatfar[4], Alan Xu[2], Mahmud Ashraf[5], M. Smith[6], and Paul J. Hazell[1]

[1] SEIT, The University of New South Wales, Australia
[2] Australian Nuclear Science and Technology Organisation, Australia
[3] School of Engineering, The University of Liverpool, United Kingdom
[4] RSPE, The Australian National University, Australia
[5] School of Engineering, Deakin University, Australia
[6] AMRC, University of Sheffield, UK
e: rashed@unsw.edu.au

The versatility and easiness of producing complex geometrical forms by additive manufacturing, namely Powder-Bed Fusion (PBF) technique, compared to traditional manufacturing methods has triggered the resurgence of interest in metallic microlattice materials for achieving structural light-weightiness, albeit at the cost of having microstructural heterogeneity and discontinuity in as-built parts due to complex thermo-mechanical process in the melt pool. Built parameters optimized 316L stainless steel microlattice structures with low relative densities were manufactured using Laser-PBF process and the resulting defects were characterized using various advanced microscopy techniques. It was observed that the rapid solidification originated coincidental dislocation network and cellular substructure provide high yield stress, and enhanced twinning accompanied by dynamic recrystallization (CDRX) at high stress overcome the strength–ductility trade-off that counter balance the deleterious effect on structural performance by inherent voids. As a result, the compound response of SLM 316L stainless steel microlattice structures becomes stiffer and stronger than what it would have been by conventional manufacturing methods.

Characterisation of pharmaceutical powders for use in binder jetting printers

A. Antic[1], N. Amini[1], J. Zhang[1], D.A.V. Morton[1], K.P. Hapgood[1]
[1]*Deakin University, Waurn Ponds, VIC 3217, Australia.*
e: a.antic@deakin.edu.au

The feedstock materials available for binder-jetting printers are relatively limited. Most commercially manufactured powders mainly consist of either calcium carbonates, calcium sulphate hemihydrate or sand silica. The use of binder-jetting as an industrial manufacturing technology has not been fully exploited within the pharmaceutical industry, as there is insufficient knowledge regarding the criterion and parameter measurement techniques of a binder-jetting powder mixture. This work aims to measure the properties of commercially manufactured powders and create benchmarks to compare with common pharmaceutical excipient powders. To do this, a Freeman FT4 powder rheometer was used to measure various dynamic and bulk powder flow properties. Drop penetration studies were conducted to understand the wetting dynamics between the powder and liquid binder. Formulations were produced by low shear mixing to analyse the effect of solid powder binders when contacted with the liquid binder. To confirm this approach, several tablet designs were printed using a pharmaceutical powder blend in a 3DS Projet 460 Plus binder-jetting machine. Various quality parameters were analysed from the printed tablet constructs. Consequently, a framework surrounding the three overarching interactions, namely powder flow, powder wetting and powder binding were summarised to create a procedure for powder characterisation prior to printing.

Additive Manufacturing for improved biointerfaces

Kate Fox[1,2], Aaqil Rifai[2], Avik Sarker[1,2] Phong A Tran[3,] Nhiem Tran[4]
[1]Center for Additive Manufacturing, RMIT University, Melbourne, VIC, 3001, Australia
[2]School of Engineering, RMIT University, Melbourne, VIC, 3001, Australia
[3]Institute of Health and Biomedical Innovation, Queensland University of Technology, Kelvin Grove, QLD, Australia,
[4]School of Science, RMIT University, Melbourne, VIC, 3001, Australia
e: kate.fox@rmit.edu.au

3D printing is rapidly becoming a useful tool for orthopedic implants. Although metal implants have more commonly been produced using subtractive manufacturing processes, 3D printing of metal implants for personalized applications is gaining considerable traction. In order for these implants to be used, post-processing is commonly performed to ensure that the interface between the implant and hard tissue is suitable. Two methods to improve the interface will be discussed in this presentation, (i) the orientation of components within the printing process to control the surface of metallic components and (ii) the investigation of new materials such as diamond. We report that both methods to improve the implant interface show both increased hamster ovarian cells (CHO) viability and decreased *Staphylococcus aureus* biofilm formation compared to control substrates.

Additive Manufacturing for improved biointerfaces

Kate Fox[1,2], Aaqil Rifai[2], Avik Sarker[1,2] Phong A Tran[3,] Nhiem Tran[4]
[1]Center for Additive Manufacturing, RMIT University, Melbourne, VIC, 3001, Australia
[2]School of Engineering, RMIT University, Melbourne, VIC, 3001, Australia
[3]Institute of Health and Biomedical Innovation, Queensland University of Technology, Kelvin Grove, QLD, Australia,
[4]School of Science, RMIT University, Melbourne, VIC, 3001, Australia
e: kate.fox@rmit.edu.au

3D printing is rapidly becoming a useful tool for orthopedic implants. Although metal implants have more commonly been produced using subtractive manufacturing processes, 3D printing of metal implants for personalized applications is gaining considerable traction. In order for these implants to be used, post-processing is commonly performed to ensure that the interface between the implant and hard tissue is suitable. Two methods to improve the interface will be discussed in this presentation, (i) the orientation of components within the printing process to control the surface of metallic components and (ii) the investigation of new materials such as diamond. We report that both methods to improve the implant interface show both increased hamster ovarian cells (CHO) viability and decreased *Staphylococcus aureus* biofilm formation compared to control substrates.

Atomised powders of high temperature structural materials for additive manufacturing

Guoqing ZHANG
National Key Laboratory on Advanced High Temperature Structural Materials
Beijing Institute of Aeronautical Materials (BIAM)
Beijing 100095, China

Gas atomisation is the process where the liquid metal is disrupted by high-velocity gas and atomisation occurs by kinetic energy transfer from the gas to the metal. Argon atomised powders have been developed for high performance alloys to meet the requirements of additive manufacturing. Advances in the argon atomisation technologies of two types of high temperature structural materials, nickel based superalloys and titanium aluminides, are evaluated in this paper. The equipment, process and research results of argon atomization technology at BIAM will be presented. BIAM initiated the research and development of gas atomisation and deposition for superalloys, intermetallics and special steels in early 1990s. A serial gas atomisation and deposition plants with melt capacity of 50 to 350 kilograms have been designed, established and modified. Typical superalloys were vacuum induction melt, gas atomised, consolidated, and hot processed. Simulation and modification of the atomisation process were investigated to optimise the melting and atomising parameters to make designed and clean powders for manufacturing sound components. The results exhibit that the clean, spherical powders, with high yield and low oxygen contents, can be achieved after the optimisation of melting and atomising parameters. Argon atomised powders of Ni and TiAl based alloys with a range of particle size, oxygen contents, chemistry are utilised to produce components by additive manufacturing techniques. The metallurgical quality and mechanical properties of components produced by additive manufacturing are shown to be closely related to powder quality and character such as purity, morphology, particle size, and sphericity.

Hybrid manufacturing (HYAM) for refined DLD’d Ti-6Al-4V microstructure

Xinni Tian[1,2], Kai Zhang[1,3], Aijun Huang[1,2], Xinhua Wu[1,2]

[1]*Monash Centre of Additive Manufacturing, Notting Hill, 3168, Australia;*
[2]*Department of Materials Science and Engineering, Monash University, 3800,Australia;*
[3]*Department of Mechanical and Aerospace Engineering, Monash University, 3800, Australia;*

Ti-6Al-4V is an α + β alloy which occupied more than half of the titanium market. This both strong and ductile material has been tried to be manufactured by direct laser deposition (DLD) for numerous times. However, the typical thermal history during the process cause the formation of large columnar grain in DLD'd Ti-6Al-4V. This large scale grain (up to several centimeters) due to the instrinct directional cooling is detrimental to the tensile properties and more importantly, the fatigue properties. A convenient and economic manufacturing method (HYAM) combined with direct laser deposition (powder feed) and micro-rolling is established to break up the piror-β grain in Ti-6Al-4V formed during the DLD process. The results show that small prior-β grains with similar sizes have been achieved in the entire sample made by this hybrid manufacturing method (Fig.1). Furthermore, the tensile strength and ductility on both directions (horizontal and build directions) are improved and the anisotropy is eliminated. This hybrid manufacturing method offers an efficient way to refine the microstructures of DLD'd Ti-6Al-4V and improve its mechanical properties.

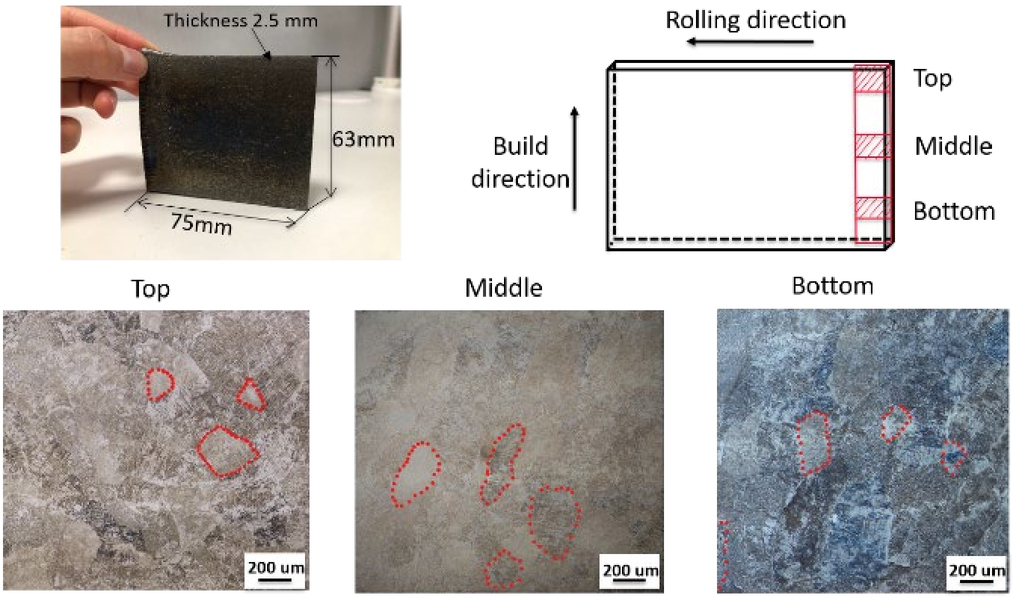


Figure 1 Optical images of the fully HYAM’d sample on the top, middle and bottom section along the building direction

Laser-based 3D printing of Cu and Cu alloys: Challenges, solutions and their typical applications

R.N. Gu[1,2] , K.S. Wong[2], M. Yan,[1*]

[1]*Department of Materials Science and Engineering, and Shenzhen Key Laboratory for Additive Manufacturing of High-performance Materials, Southern University of Science and Technology, Shenzhen 518055, China;*

[2]*Hong Kkong Univetristy of Science and Technology, The Department of Physics, Hong Kong*

Corresponding author: yanm@sustc.edu.cn (M.Yan)

So far, SLM of Cu and Cu alloys has been proved to be challenging. We have tried two methods, i.e. alloying and surface modification, to increase the absorptivity of Cu powder to laser in order to make SLM of Cu and Cu alloys possible: (a) In the alloying route, the reflectivity measurement reveals that even a small amount of alloying element can increase the absorption of Cu powder evidently, and the underlying theory was given. SLM of Cu and Cu alloys was processed and compared; the microstructures of the SLM samples were studied using optical microscope and micro-CT. The results show that printing Cu directly will result in a low relative density, which is around 85%, and a highly porous structure, but the results for alloyed Cu is better particularly when the concentration of the alloying element is high. Right now the relative density of the as-printed Cu-10Sn reaches ~99.0%; and (b) as another possible route to improve Cu's laser absorptivity, heat treatment was used to oxidize thus modify the surface structure of the Cu powder. XPS depth profile analysis was processed to reveal the surface structures of the Cu powders before and after heat treatment, and it shows that heat treatment provides an oxide layer in the outmost surface of Cu powder. The reflectivity of Cu powder after heat treatment decreases about 45%, which makes the SLM of Cu possible. Demonstrative, jewelry products are provided manufactured by using SLM.

Selective laser melting enabled additive manufacturing of Ti–22Al–25Nb intermetallic: Excellent combination of strength and ductility, and unique microstructural features associated

Y.H. Zhou[1,2], M. Yan[1,*]

[1]*Department of Materials Science and Engineering, and Shenzhen Key Laboratory for Additive Manufacturing of High-performance Materials, Southern University of Science and Technology, Shenzhen 518055, China*

[2]*School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China*

[3]*College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen 518060, China*

e: yanm@sustech.edu.cn

To realize near net-shaping of hard-to-process intermetallics is an often challenging but critical issue to their wider industrial applications. In this work, we report that an intermetallic Ti–22Al–25Nb has been successfully fabricated by selective laser melting (SLM). The as-printed samples show a high room-temperature ultimate tensile strength ~1090 MPa and excellent ductility ~22.7%; both values are higher than most conventionally fabricated Ti–22Al–25Nb intermetallic. We clarify the mechanical performance achieved by detailed microstructure analysis, including dislocation and phase constitution. It is proposed that high-density dislocation networks significantly contribute to the strength and ductility, which are further enhanced by the favorable phase constitution, including the nano-scale O phase precipitates within the disordered β phase and disappearance of the brittle α_2 phase in the microstructure. Phase evolution during solidification, particularly regarding the O phase's formation, has also been clarified using in-situ laser heating, high-temperature synchrotron X-ray diffraction and Scheil simulation. It is demonstrated that the O phase formation involves both displacive transition (B2 → B19) and chemical ordering (B19 → O). Furthermore, a demonstrative part of turbine blade has been fabricated to highlight the importance of SLM in fabricating critical structural part like the hard-to-process intermetallics.

Submicron-TiB_2 with Si decorated Al7075 alloy for selective laser melting additive manufacturing

S.Y. Zhou[a,b#], Y. Su[b,#] ,H.Wang [b, *] ,X.Y. Yao [a,], M. Yan[a,*]
[a]*Department of Materials Science and Engineering Shenzhen Key Laboratory for Additive Manufacturing of High-performance Materials, South University of Science and Technology of China, 518055 Shenzhen, China*
[b]*Guangdong Provincial Key Laboratory of Micro/Nano Optomechatronics Engineering, College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen518060, China.*
E-mail address: yanm@sustech.edu.cn

Selective laser melting (SLM) is an additive manufacturing (AM) technology used for processing casting Al alloys such as AlSi10Mg and AlSi12. In this research, SLM was used to fabricate Al-Cu-Mg-Zn alloy (Al 7075), an alloy prone to hot-cracking phenomena during the SLM process due to the high reflectivity, high conductivity and its high chemical affiliation with oxygen. The solution is to incorporate double modification agents to the Al7075, i.e. a combination of submicron-TiB_2 with Si powder. Compared to the SLMed pure Al-Cu-Mg-Zn part with microcracking and poor density, the SLMed submicron-TiB_2 shows significantly reduced microcracks by the ultrafine grain the refining effect, and exhibits increased yield strength (446 ± 4.3 MPa) and ultimate tensile strength (551 ±3.6 MPa) caused by the grain refining effect. The influences of SLM processing parameters such as volumetric energy density and laser absorptivity of powders on the densification, microstructural evolution, mechanical behavior were systematically studied. This work provides a basis for developing innovative high strength Al alloys and also new insights for Additive Manufacturing (AM).

Selective laser melting under the Ar−N2 reactive atmosphere: a convenient and efficient approach to fabricate ultrahigh strength commercially pure titanium without sacrificing ductility

Da Wei Wang, Xiyu Yao, Ming Yan*
Southern University of Science and Technology, Shenzhen, 518055, China
e: yanm@sustech.edu.cn

This study presents a novel approach for the fabrication of commercially pure titanium (CP-Ti) components. The approach conferred superb strength to CP-Ti without sacrificing its ductility. A yield strength of 807 MPa combined with 19.15% elongation was realized through selective laser melting (SLM) by using a high-power laser and incorporating solute atoms from the Ar−N_2 reactive atmosphere. Mechanical properties and microstructures of the as-printed CP-Ti were systematically investigated. Transmission electron microscopy, electron backscatter diffraction, atom probe tomography, and laser-heated *in-situ* synchrotron X-ray diffraction analysis were employed to reveal the mechanism underlying the in-situ reaction between CP-Ti and the reactive atmosphere. Results suggest that nitrogen generally dissolved in the α′-Ti matrix as interstitial solute atoms. The beneficial N content has a critical limit of ~0.43 wt.%. The ductility of CP-Ti will decrease drastically if its N content exceeds this limit. A constitutive model was developed for describing the tensile deformation behavior of the *in-situ* strengthened CP-Ti over various solute contents and grain sizes. This work demonstrates a promising methodology for the fabrication of high-performance metallic components and extends the fundamental understanding of SLM process under the reactive atmosphere.

3D printed breathable mould steel Small micrometer-sized, interconnected pores by creatively introducing foaming agent to additive manufacturing

G.H. Zeng[1,2], R.N. Gu[1], M. Yan,[1*]
[1]*Department of Materials Science and Engineering, and Shenzhen Key Laboratory for Additive Manufacturing of High-performance Materials, Southern University of Science and Technology, Shenzhen 518055, China;*
[2]*School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China;*
[3]*Centre for Additive Manufacturing, School of Engineering, RMIT University, Melbourne, VIC 3000, Australia；*
Corresponding author: yanm@sustc.edu.cn(M.Yan)

Additive manufacturing & 3D printing has almost no limitation in realizing any geometry due to its layer-by-layer manufacturing manner, while producing small-sized, interconnected pores is one of its major challenges. In this study, we report that, by creatively combining additive manufacturing with foaming agent, interconnected pores (~26 vol.% porosity) with pore size of 2–30 μm have been successfully achieved. One of the most important applications of such unique structure is for developing the so-called breathable mould steel. Breathability is rather demanding for the mould industry, since it is capable to eliminate the trapped, detrimental gas during injection moulding and therefore much improve the quality of as-injected parts. It will be revealed by the study that, due to a good selection of the foaming agent (i.e. CrNx), the as-printed breathable steel has a great combination of compressive strength (~1.3 GPa), strain (~26%), microhardness (~360 HV) and corrosion resistance, along with sufficient breathability. These mechanical properties are even superior to the commercial PM-35 breathable steel. Based on detailed microstructural characterization, the affecting factors to the pore forming are studied, and the importance of the novel approach developed by the current study has been addressed.

Selective laser melting of the hard-to-weld IN738LC superalloy: Efforts to mitigate defects and the resultant microstructural and mechanical properties

X. Zhang[1,2], H. Wang[1], Y.H. Zhou,[2] M. Yan[2,*]
[1] *Guangdong Provincial Key Laboratory of Micro/Nano Optomechatronics Engineering, College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen 518060, P. R. China;*
[2]*Department of Materials Science and Engineering, and Shenzhen Key Laboratory for Additive Manufacturing of High-performance Materials, Southern University of Science and Technology, Shenzhen 518055, P. R. China*
[3]State Key Lab for Powder Metallurgy, Central South University, Changsha 410083, P.R. China
Corresponding author: yanm@sustc.edu.cn(M.Yan)

IN738LC is an important high performance Ni-based superalloy. Its additive manufacturing via selective laser melting (SLM), however, is rather challenging due to the cracking-prone nature of the alloy whose chemical composition contains high amount of (Ti+Al) alloying elements. We address this significant problem by this study, through systematic investigations on the pre-processing, SLM optimization, and post-processing of the material, as well as using advanced analytical tools such as micro-CT. A profound process map for achieving crack-free, high-density samples (~ 99.76%) is provided. Mechanisms influencing densification, cracking and mechanical property are discussed. As a result, excellent mechanical properties have been achieved at both room temperature (895/1010 MPa as the yield and tensile strength) and elevated temperature at 850°C (720 MPa and 14.4% elongation) by the IN738LC superalloy. A demonstrative as-printed turbine blade is also presented, highlighting the capability of SLM to simultaneously achieve excellent mechanical property and good geometric integrity.

Additive manufacturing of high strength aluminium alloys

Nick Birbilis, S.K. Kairy, O. Gharbi

College of Engineering and Computer Science, The Australian National University, ACT. 2601. Australia

The additive manufacturing (AM) of high-strength aluminium alloys has not been widely explored to date. Herein, aluminium alloy AA2024 (Al-Cu-Mg) and AA7075 (Al-Zn-Mg) were additively manufactured via selective laser melting (SLM), with the resultant microstructures and corrosion properties characterised and contrast to wrought AA2024-T3 and AA7075-T6. Microstructural characterisation was carried out using transmission electron microscopy (TEM), revealing SLM produced AA2024 included a population of θ-phase (Al_2Cu) in preference to S-phase (Al_2CuMg) typical of wrought AA2024. In the case of AA7075, the as SLM produced AA7075 revealed a unique quasicrystalline nanophase, previously uncharacterised for this system. A discussion regarding the unique structures formed during solidification, and their influence on properties is provided. Additionally, the corrosion properties of such alloys were determined, indicating a significant – but beneficial - difference in the corrosion of AM prepared AA2024 and AA7075 relative to such alloys prepared conventionally in wrought form.

Invited Speaker: Dr. Ahmad Zafari

Title: Selective laser melting of Ti alloys

Abstract:

Additive manufacturing (AM) of Ti alloys has attracted increasing attention due to its capabilities of producing complex shapes tailored for individual applications. However, our understanding of microstructural evolution of the alloys during AM, in particular selective laser melting (SLM), is still premature. Hence, we systematically investigated the effects of a wide range of SLM parameters, such as point distance and exposure time, on microstructures and mechanical properties of high quality SLM products. Microstructural evolution was traced from the very first few layers deposited, and detailed analyses on tensile behaviour, including strength, work hardening rate, uniform elongation and elongation-to-fracture were conducted, leading to better understanding of the relationships between these properties and grains texture typically obtained by SLM, homogeneity of the microstructure, and interactions between phases/microstructures.

Microstructure tailoring in Electron Beam Powder Bed Fusion processing of Alloy 718 and associated mechanical properties

Arun Ramanathan Balachandramurthi[1], Jonas Olsson[1], Joakim Ålgårdh[1,2], Anders Snis[3], Johan Moverare[1,4], Robert Pederson[1]

[1]*Division of Subtractive and Additive Manufactuirng, Department of Engineering Science, University West, 461 86 Trollhättan, Sweden.*

[2]*Powder Materials & Additive Manufacturing, Swerim AB, SE-164 40 Kista, Sweden*

[3]*Arcam EBM, SE-431 37 Mölndal, Sweden*

[4]*Division of Engineering Materials, Department of Management and Engineering, Linköping University, SE-581 83 Linköping, Sweden*

email: arun.balachandramruthi@hv.se

Powder Bed Fusion (PBF) type Additive Manufacturing (AM) processes have gained a lot of traction, both in the industry and in the academia, over the last decade. Electron Beam-PBF (EB-PBF) process is being used to manufacture parts with a variety of materials such as titanium alloys, nickel superalloys, cobalt chrome alloys, steels, intermetallics and, more recently, even amorphous metals. In the present work, EB-PBF process for Alloy 718, a nickel superalloy used in gas turbine applications was investigated, using an Arcam A2X Electron Beam Melting (EBM) machine. Different melting strategies, achieved by systematically modifying the process parameters, were used to tailor the microstructure of the manufactured parts. By understanding how the processing parameters affect the solidification condition, specimens were manufactured to have either a columnar microstructure or an equiaxed microstructure. Mechanical tests were performed on specimens at 0º, 45º and 90º to the build direction, to evaluate the anisotropy in properties, in both the as-built and post-treated conditions. Metallographic investigations before and after the testing, together with Electron Back Scattering Diffraction (EBSD) were carried out to explain the differences in the observed properties.

On the Possibility of Real-Time Techniques to Enable Property Prediction in Additive Manufactured Materials

T.K. Ales[1], M. Clark[2], and P.C. Collins[1]
1: Materials Science and Engineering
Iowa State University
2: Optics and Photonics Research Group
The University of Nottingham (UK)
E-mail: pcollins@iastate.edu

A recently completed 6-year program has resulted in the demonstration of an integrated computational materials engineering (ICME) framework that has resulted in the prediction of design allowables for large-scale, electron-beam additive manufacturing (EBAM) of Ti-6Al-4V. The scale of the depositions is quite large (>650 kg), pushing the research into the realm of large structures for aerospace applications. While the ICME approach incorporates modules to predict the composition and microstructure of EBAM Ti-6Al-4V, and thus its properties, the results point to the possibility to collect relevant sensor information to predict the properties in a near-real time manner. Should such sensors be possible, it would be possible to additively manufacture a component with a "digital twin" consisting of microstructural, chemical, and defect information, along with expected performance probability distribution functions. To be successful, any sensors must collect information at a scale and rate commensurate with the additive manufacturing process. One promising technique is spatially resolved acoustic spectroscopy (SRAS) and its rough-surface equivalent. SRAS uses accurate measurements of the surface acoustic waves to characterize the local orientation of the grains and phases, providing critical microstructural information at a part length-scale. In this talk, the ICME framework will be presented, along with the emergence of the SRAS method. Possibilities and limitations of both the framework and existing sensors will be discussed. Finally, the possibility of digital twins will be discussed.

Refinement of the Microstructure in Additively Manufactured Alloys

M.A. Easton[1], D. Zhang[1], D. Qiu[1], M. Patel[1], C. Todoro[1], A. Prasad[2], M. Qian[1], D.H. StJohn[2]

[1]School of Engineering, RMIT University
[2]School of Mechanical and Mining Engineering, The University of Queensland
E-mail: mark.easton@rmit.edu.au

One of the challenges in Additive Manufacturing is that the microstructure tends to be columnar rather than equiaxed. This can lead to manufacturing defects such as hot tears/cracks and anisotropic properties. The columnar grain morphology is caused by a combination of the processing conditions, particularly the high temperature gradient and cooling rates, the choice of alloy compositions in the alloys that tend to have low solute contents and the lack of the use of grain refiners. This presentation will discuss the approaches that can be taken to generate fine equiaxed grain sizes in additive manufacturing processes. These include the use of grain refiners, modification of alloy composition, and the use of ultrasonic treatment. Furthermore the role of processing parameters will be considered using the Interdependence Model. Examples of fine equiaxed grains in additively manufactured and/or laser processed aluminium alloys, Ti-6Al-4V and other Ti alloys, and magnesium alloys will be shown.

3D Printonomics – why we need to change the current paradigm by changing the question from "what can we do with this fabrication method?" to "how can we change this fabrication process to achieve what we need".

DProfessor Dietmar W. Hutmacher
Institute of Health and Biomedical Innovation
Queensland University of Technology
E-mail: dietmar.hutmacher@qut.edu.au

In Additive manufacturing (AM) —the industrial version of 3D printing—is a revolutionary method which has tremendous potential in numerous applications areas in science and industry. AM allows rapid design and fabrication of highly customized parts e.g. it has been used to produce prototypes for engineers and designers, 3D printing for consumers and small business entrepreneurs has received a great deal of publicity recently. However, it is in manufacturing where the technology will ultimately have its most significant scientific and commercial impact. Many research challenges remain in translating the early promise of AM to industrial success in design & manufacturing of functional components and systems. Fabrication of high performance components using 3D printing is still a subject of intense research especially for multimaterial and multicomponent products and parts. Additive Biomanufacturing (ABM) is an emerging field within Advanced Manufacturing. ABM has unique technical needs and requirements in the bioprinting community combined with the quest for fundamental and translational research. As in the progression of many other emerging technologies, the greatest scientific advancements will come at the boundaries of fundamental material science, physics, engineering, chemistry, and biology. Significant research efforts are essential to expedite the transformation from random bioprinting to additive biomanufacture of innovative biomaterials that claim material flexibility, the ability to generate fine features, and high throughput. The primary take home message from this talk is that the biomedical 3D pinting community need to go beyond established single material bioprinting processes, and applications that exhibit conventional levels of functionality to move beyond the state of the art and to perform ground-breaking research to underpin multi-material and multifunctional ABM processes and design systems. Such highly innovative multi material & multifunctional ABM platforms will effectively allow the biomanufacturing (defined as first printing of cells in bioinks and then further in vitro and/or in vivo phase) of tissues that are not only optimised to have tissue-specific biochemical and physical properties but, critically, provide maximum biological functional utility to the user in a wide range of applications. It is undoubteldy this shift in perspective, I propose in this talk, that will be the key driving force behind the evolution and innovation of the field of Additive Biomanufacturing in the years to come.

Laser Additive Manufacturing of High-Performance and Multi-Function Metallic Components

Dongdong Gu
College of Materials Science and Technology
Jiangsu Provincial Engineering Laboratory for Laser Additive Manufacturing of High-Performance Metallic Components
Nanjing University of Aeronautics and Astronautics (NUAA), Yudao Street 29, Nanjing 210016, PR China
E-mail: dongdonggu@nuaa.edu.cn

This presentation summarizes our latest research progress on laser additive manufacturing of metallic components with high-performance and multi-function, including the structural optimization, material innovation, process control, performance evaluation and engineering applications. This presentation also provides some considerations in the future research and development of laser additive manufacturing technologies in the production of high-performance/multi-function metallic components and the engineering applications with high efficiency, high quality and sustainable development capability.

Low cycle fatigue behavior of Ti-6Al-4V alloy fabricated by high-power laser solid forming additive manufacturing

X. Lin, Y.M. Ren and W. D. Huang
State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, P. R. China
Key Laboratory of Metal High Performance Additive Manufacturing and Innovative Design, MIIT China
Northwestern Polytechnical University, Xi'an, Shaanxi 710072, P. R. China
E-mail: xlin@nwpu.edu.cn

The lower cycle fatigue (LCF) property is the main shortcoming for Ti-6Al-4V parts prepared by additive manufacturing (AM) on comparison with the wrought. The strong thermal input in high-power AM with high deposition efficiency induced the strong intermediate heat treatment effect in the deposition process which could improve the microstructure and mechanical properties of the deposit. Here, the LCF properties and failure mechanism of Ti-6Al-4V parts fabricated by high-power (7600 W) laser solid forming (LSF) additive manufacturing after post-fabricated solution treatment and aging (STA) were investigated. Experimental results show that the parts exhibit superior LCF lives than other AM Ti-6Al-4V in previous researches, which are comparable to that of the wrought counterparts at intermediate strain amplitudes (from 0.8% to 1.1%). These results are mainly attributed to the STA LSF Ti-6Al-4V with superior ductility (~18%), which derived from the microstructures consist of relatively coarse columnar prior-□ grains (>500μm) filled with thick α-laths (>5 μm) and fine lamellar (α_s+β) microstructures. Under the strain-controlled loading conditions, cyclic softening behaviors were found at various strain amplitudes (from 0.55% to 1.7%). A microstructure-based multistage fatigue model was used to predict their LCF lives and shows good agreement with experimental data. Finally, a two-step guideline for improvement the LCF lives of LSF Ti-6Al-4V parts was suggested, which may provides an important means to improve the LCF properties of LSF Ti-6Al-4V parts without post-fabricated hot isostatic pressing.

Additive Manufacturing *via* Thermal Spray Technologies: Transforming Science into Industrial Applications

Chris Berndt
Director SEAM: “Surface Engineering for Advanced Manufacturing”
Swinburne University of Technology
cberndt@swin.edu.au

Thermal spray (TS) coatings are manufactured by “layer-on-layer” processing and hence can be considered as part of the additive manufacturing family. Thermal spray technologies are pervasive throughout the manufacturing and industrial communities and function within adverse environments. This experience of many decades provides valuable lessons for the modern AM community.

The science and process technology of TS involves injecting a stream of particles into an intense processing zone. These particles, which may consist of metals, ceramics, polymers or mixtures of these, are propelled towards a substrate and form an additive layer-on-layer deposit. The composite like nature of TS coatings confers unique materials properties. For instance, the properties are unlike those of their bulk material counterparts that may be manufactured by pressing, sintering and rolling. Therefore, a great deal of effort has established test methods to derive engineering data that is used for design purposes. Finally, case histories will be presented where TS coatings have provided economic benefits to manufacturing and industrial applications.

Acknowledgement: This work has been sponsored by the Australian Research Council under the Industrial Transformation and Training Centre project IC180100005 titled “SEAM: Surface Engineering for Advanced Materials”.

Selective Laser Melting: Art Status and Developing Tendency

Xiaoyan ZENG, Kaiwen Wei, Zemin Wang, Xiangyou Li, Haihong Zhu,

Wuhan National Laboratory for Optoelectronics
Huazhong University of Science and Technology
Wuhan, China
E-mail: xyzeng@mail.hust.edu.cn

Selective laser melting (SLM) technique, an additive manufacturing process by powder bed, has become the first choice for complex metallic component fabrication in industry in the past years, due to its high precision, excellent performances over other techniques. However, there are still some bottlenecks before it can get wider applications in the future. In this report, the new progress and developing tendency of SLM technique and equipment developed in the past years have been reviewed. Especially, the mechanisms about how to promote the forming quality of the components by the large SLM equipment with the four laser beam scanners and the sizes of 500x500x1000 mm^3 has been discussed.

Mechanical properties of titanium alloy with cellular structures fabricated by additive manufacturing

S. J. Li, H. Wang, W. T. Hou, Y. L. Hao, R. Yang
Titanium Alloy Laboratory
Institute of Metal Research, Chinese Academy of Sciences
E-mail: shjli@imr.ac.cn

Porous titanium and its alloys have been considered as promising replacement for dense implants, as they possess low elastic modulus comparable to that of compact human bones and are capable of providing space for the in-growth of bony tissues to achieve better fixation. Recently, the additive manufacturing (AM) method has been successfully applied to fabricate cellular meshes and foams of titanium alloys. Compared with the traditional fabrication methods, the AM method offers advantages of accurate control of complex cell shapes and internal pore architectures, thus attracting extensive attention. In this talk, we focus on the mechanical properties under quasi-static and cyclic loading conditions of AM titanium alloy cellular structures aimed for use as bone substitutes and orthopaedic implants. The effects of the AM processes, material type, cell shape, graded porosity distribution and post treatments on the quasi-static mechanical properties and the fatigue behavior of AM titanium alloy cellular structures are reviewed. The processing-microstructure-property relationship of AM components is discussed in detail. The potential commercial applications of AM titanium alloy cellular structures are presented.

Mechanical properties of titanium alloy with cellular structures fabricated by additive manufacturing

S. J. Li, H. Wang, W. T. Hou, Y. L. Hao, R. Yang
Titanium Alloy Laboratory
Institute of Metal Research, Chinese Academy of Sciences
E-mail: shjli@imr.ac.cn

Porous titanium and its alloys have been considered as promising replacement for dense implants, as they possess low elastic modulus comparable to that of compact human bones and are capable of providing space for the in-growth of bony tissues to achieve better fixation. Recently, the additive manufacturing (AM) method has been successfully applied to fabricate cellular meshes and foams of titanium alloys. Compared with the traditional fabrication methods, the AM method offers advantages of accurate control of complex cell shapes and internal pore architectures, thus attracting extensive attention. In this talk, we focus on the mechanical properties under quasi-static and cyclic loading conditions of AM titanium alloy cellular structures aimed for use as bone substitutes and orthopaedic implants. The effects of the AM processes, material type, cell shape, graded porosity distribution and post treatments on the quasi-static mechanical properties and the fatigue behavior of AM titanium alloy cellular structures are reviewed. The processing-microstructure-property relationship of AM components is discussed in detail. The potential commercial applications of AM titanium alloy cellular structures are presented.

On the reliability of metallic alloys processed by additive manufacturing

T. Niendorf
Institute of Materials Engineering
University of Kassel, Germany
E-mail: niendorf@uni-kassel.de

Metal additive manufacturing (AM) has been in focus of academia and industry for several years. Due to increased productivity of the systems employed, serial production as well as manufacturing of large components at reasonable cost are feasible now. For near net-shape components mostly processes employing a powder bed are used, i.e. selective laser melting (SLM) and selective electron beam melting (EBM). For both processes in principle any metallic alloy can be applied, however, most studies report on a given number of widely used materials, i.e. stainless steel 316L, Ti-6Al-4V, Al-Si-base alloys and Ni-base superalloys such as Inconel 718. For most of these alloys solid process-microstructure relationships are established. Furthermore, evolution of microstructure and mechanical properties upon post treatment, studied under monotonic loading, have been reported numerously such that a deep knowledge allowing for monotonic strength optimization is available.
However, properties under complex in-service loading conditions contemplating residual stresses, surface conditions, fatigue strength, crack growth, creep as well as combined loadings have been only rarely addressed so far. Microstructure evolution imposed by rapid solidification and intrinsic heat treatment, however, leads to unique microstructural conditions severely affecting the alloy performance, especially under loading scenarios detailed before. For safe and reliable use of AM components in the automotive, aerospace, biomedical and other sectors, thus, the currently prevailing research gap has to be tackled. The paper presented will highlight the most important microstructural features being the basis for the performance and, thus, reliability and integrity of AM components processed by SLM and EBM. Moreover, pathways for adequate post treatments and alloy development for AM will be drawn.

Biography

Dr.-Ing. Thomas Niendorf is Full Professor at the Institute of Materials Engineering at University of Kassel (Germany) since October 2015. Dr. Niendorf studied Mechanical Engineering at University of Paderborn (Germany). In 2010 he did his doctorate. In his thesis he reported on the reliability and structural integrity of ultrafine-grained materials processed by severe plastic deformation. In 2011 he published his first work on materials processed by additive manufacturing, a work conducted in collaboration with the Direct Manufacturing Research Center at University of Paderborn.
Dr. Niendorf's research interests are in the interrelationships of process, microstructure, mechanical properties and reliability of metallic materials. Analysis of residual stresses,

microstructure evolution and fatigue performance are key aspects of research projects conducted. Materials in focus are steels, aluminum alloys, high-temperature materials, shape memory alloys as well as hybrid materials. Currently, he is supervisor of more than 20 PhD Students.
Research activities in the field of additive manufacturing (AM) comprise powder bed techniques (EBM and SLM) as well as laser metal deposition. Realization of microstructurally graded samples for improved functionality as well as thorough characterization of integrity and reliability of AM components are Dr. Niendorf's actual fields of research in AM.
Dr. Niendorf published more than 130 peer-reviewed papers in renowned journals. Furthermore, he holds several patents and has been invited speaker in many conferences. He has been scientific board member and session organizer in several European conferences focusing on AM. He will be on the Scientific Committee of the ASTM 4th Symposium on the Structural Integrity of Additive Manufactured Parts to be held in Washington DC during October 2019. For his young career achievements he received several distinguished awards, e.g. the Heinz Maier-Leibnitz-Award by German Research Foundation.

Progress in Novel Titanium Powder Processes for Additive Manufacturing

L. Prentice, S. Gulizia, K. McGregor, D. Jewell, and C. Doblin
Metal Industries Research Program
CSIRO Manufacturing
E-mail: leon.prentice@csiro.au

The metallic additive manufacturing (AM) community has an ongoing need for high-quality but low-cost powder (or wire), particularly of titanium and its alloys. Novel titanium production processes for AM seek to bypass key elements of traditional powder manufacturing, replacing one or more of the Kroll process, melt- and vacuum-refinement, alloying, forming, and atomization/spheroidisation. While many of these 'unconventional' routes have been disclosed for some time, progress to market has been slow and no convincing game-changer has yet emerged.

This review of recent developments and current status will focus on processes and chemistries designed to produce metal powders and/or structures with the most direct manufacturing methods. It will cover advances presented or patented by the key players in Australia, the United States, China, the United Kingdom, South Africa, and other countries, and provide an assessment of the technology status and time to market for the various technologies.

Key issues that hold back the introduction of new technologies will also be discussed, and approaches to mitigate these. They include process control and homogeneity; sizing, morphology, and spheroidisation; quality assurance and certification; and underlying economics and technology viability. Opportunities for the introduction of these materials into the marketplace, initially in low-cost applications, will be highlighted, as well as the path towards high-value applications.

Wire and powder manufacturing process control and defect prediction for 3D Printing

Chunguang Bai
Institute of Metal Research, Chinese Academy of Sciences, 110016 Shenyang, China
cgbai@imr.ac.cn

Arc additive manufacturing (WAAM) is an emerging technology which has great potential application to significantly reduce material usage and manufacturing time through the production of near-net-shape components with high deposition rates. Wires are the raw materials for WAAM process and take an important role for the control of mechanical properties and metallurgical qualities. One of the main problems of this process is the residual stresses and distortions of the deposited workpiece. To help understand and optimise the process, finite element models are used in this work to analyze the residual stress and distortion, and compared with the experimental results.
Key words: WAAM; FEM simulation; Residual stress; Distortion; Optimization

Carbon-Fiber Reinforced Inconel 625 by Additive Manufacturing

B.C. Zhang[1], Guijun Bi[2], Chew Youxiang[2], Pei Wang[3]
[1] *Institute for Advanced Materials and Technologies, University of Science and Technology Beijing, Beijing 100083, China;*
[2] *Joining Technology Group, Singapore Institute of Manufacturing Technology, 73 Nanyang Drive, 637662, Singapore;*
[3]*Institute of Materials Research and Engineering, 2 Fusionopolis Way. Innovis, #08-03, 138634 Singapore.*
e-mail: zhangbc@ustb.edu.cn

Carbon-fiber reinforced composites by additive manufacturing (AM) have exhibited unique superiority, which enabled producing highly customized parts with significantly improved mechanical properties. Almost all commercially available AM methods could benefit from various fiber reinforcement techniques. In our research, the microstructure and tensile properties evolution of laser deposition CNT reinforced Inconel 625 composite was studied. The research results clearly prove that the CNT structure can be completely preserved after high power effect. The SEM and EDS results showed that the CNT was distributed at columnar dendrite boundaries accompanied with precipitated of Laves and γ' phase. The addition CNT structure plays a key role of both strength and ductility improved because of microstructure refinement and fiber strengthening. The UTS and elongation of the laser deposition CNT- Inconel 625 composite can reach 1015 MPa and 22%, respectively. In comparison, the UTS and elongation of the graphite reinforced Inconel 625 are 950 MPa and 13%, respectively..

On the Applicability of Additive Manufacturing for Superhero Suit Fabrication

Craig A. Brice
Mechanical Engineering
Colorado School of Mines
E-mail: craigabrice@mines.edu

Additive manufacturing (AM) is widely gaining acceptance in a broad range of industries – from aerospace to automotive to biomedicine. The processes and materials have matured to a point where critical parts can be rate-produced and confidently adopted into demanding applications. One application area that has been largely overlooked is the fabrication of superhero suits and ancillary technology. While a niche market, the highly demanding and customized nature of this technology space is ideally suited for AM.

This presentation will detail a collaborative project among Colorado School of Mines, a major AM original equipment manufacturer, and a Hollywood production studio focused on creating an AM-fabricated superhero suit for a new television series highlighting examples of "extreme engineering." The talk will focus on a) how the 3D models developed for computer-generated imagery were converted into AM buildable parts, b) how a 3D body scan was used to fabricate an AM custom support structure for the suit tailored to the superhero's body, and c) how metal, polymer, and ceramic AM parts were incorporated into the overall design.

Development of an Integrated Clustering Analyses for Atom Probe Tomography of Additively Manufactured Alloys

Bryan Lim[1,2*], William J. Davids[1,2*], Anna Ceguerra[1,2], Xiaozhou Liao[2], Sophie Primig[3], Sudarsanam Suresh Babu[4,5] and Simon P. Ringer[1,2]

[1]*Australian Centre for Microscopy & Microanalysis, The University of Sydney, Sydney, NSW, 2006, Australia*
[2]*School of Aerospace, Mechanical & Mechatronic Engineering, The University of Sydney, Sydney, NSW, 2006, Australia*
[3]*School of Materials Science and Engineering, The University of New South Wales, Sydney, NSW, 2052, Australia*
[4]*Department of Mechanical, Aerospace, and Biomedical Engineering, University of Tennessee, Knoxville, TN, 37996, USA*
[5]*Manufacturing Demonstration Facility, Oak Ridge National Laboratory, Knoxville, TN, 37830, USA*
e: bryan.lim@sydney.edu.au & william.davids@sydney.edu.au

The analysis of solute atom clustering in metallurgical solid solutions is emerging as one of the most common applications of atom probe tomography (APT). However, the clustering analysis tools currently available in the literature suffer from several issues. Firstly, a universal analysis approach does not exist – many algorithmic designs have been developed and the literature is crowded. Secondly, clustering analyses are very time-intensive, requiring manual handling of the various stages of the computational workflow. Much of this relates to the determination of heuristics by the user to determine appropriate parameters in the multi-stage calculations. Given initial evidence that novel solute atom clustering phenomena are prevalent in additively manufactured (AM) metals, there is much interest in the development of an 'industrial grade' clustering analysis tool that enables self-consistent comparisons of the frequency distributions of atomic clusters within and between AM metals.

Here, we present outlooks for the development of a three-step process for systematic clustering analysis. We propose independent computational modules for: (1) artefact removal, (2) clustering analysis using the core-linkage algorithm, and (3) data correction to account for finite detector efficiencies. These modules may be applied in sequence or individually, providing a tool that reduces variability of outputs between users.

*These two authors contributed equally to the work.

The authors acknowledge the facilities, scientific and technical assistance of the Microscopy Australia node at the University of Sydney (Sydney Microscopy & Microanalysis). This research was sponsored by the Department of Industry, Innovation and Science under the auspices of the AUSMURI program. The authors also gratefully acknowledge financial support from the Department of the Navy, Office of Naval Research under ONR award number N00014-18-1-2794. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Office of Naval Research. The research was also sponsored by the US Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office under contract DE-AC05-00OR22725 with UT-Battelle, LLC. Access to the Oak Ridge National Laboratory's (ORNL) additive manufacturing equipment at ORNL's Manufacturing Demonstration Facility (MDF) was facilitated by US Department of Energy's Strategic Partnership Projects (SPP) mechanism. More information can be found at https://science.energy.gov/lp/strategic-partnership-projects. Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

Meta-biomaterials: additive manufacturing of impossible biomaterials

Amir A. Zadpoor
Delft University of Technology

From invisibility cloaks to materials with negative stiffness, architected materials with properties that were once considered impossible are being currently developed by a wide range of researchers from different disciplines. Meta-biomaterials are a new addition to these novel classes of metamaterials, where otherwise impossible combinations of mechanical, mass transport, and biological properties are created through complex geometrical designs as well as complex spatial distributions of material properties at multiple scales starting from macroscale and going all the way down to nanoscale. This allows for incorporation of multiple favorable functionalities into one single piece of biomaterial including improved tissue regeneration performance and minimized risk of implant-associated infections. Progress in additive manufacturing (AM) techniques is at the center of these developments, as fabrication of meta-biomaterials requires application of multi-scale and multi-material AM techniques. This talk will introduce the concept of meta-biomaterials and will present an overview of the meta-biomaterials developed in my lab during the past decade.

Additive Repair Processes for High Temperature Materials

Dipankar Banerjee[a], Dheepa Srinivasan[b], Kaustubh Bawane[c], Pooja Srinivas[d], Bhaskar Dutta[e]

[a] Materials Engineering, Indian Institute of Science, Bangalore
[b]INTECH DMLS, Pvt. Ltd., Bangalore
[c]Virginia :Polytechnic Institute and State University, , USA
[d]Indian Institute of Technology, Bombay, Mumbai
[e] DM3D Technologies, Michigan, USA

We describe examples of the development of repair technologies of high temperature materials, using additive processing (direct metals laser sintering (DMLS) and direct metal laser deposition (DMLD)). The additive repair process has been evaluated to examine the feasibility of repair and refurbishment of cast FSX414 components (a solid solution strengthened Co-based alloy extensively used in gas turbine hardware). An optimized DMLS process that eliminates HIP (hot isostatic pressing)was developed for a CoCrMo alloy, and the effect of subsequent heat treatment on microstructure and tensile properties was established. The welding of DMLS CoCrMo to cast FSX414 using Co-based Nozzalloy™ filler wire was demonstrated. We also describe a crack free build-up of directionally solidified (DS) nickel based superalloy MarM247LC via DMLD technology. MarM247LC is an extremely difficult to weld superalloy and undergoes liquation cracking or strain age cracking, during repair and refurbishment. Attempts to restore the MarM247LC structure via conventional processes such as welding and brazing have resulted in, at best, an equiaxed microstructure with cracks. In this study, the DMLD process was used to build MarM247 on a seed of cast DS MarM247LC via a systematic design of experiments, by varying the laser power, scan speed, powder feed and step over. An epitaxial growth of the DMD structure on the cast DS seed was established and columnar grains were seen to grow (with a misorientation of $< 9^{o}$ on the cast seed). Detailed characterization revealed a very fine dendritic structure in the DMD build. A detailed characterisation of the primary dendrite spacing, inter-dendritic segregation as well as precipitate size and volume fraction and tensile properties, was carried out in the as-built condition and after heat treatment.

Both examples demonstrate the ability to use additive manufacturing as a unique technology enabler for repair of high temperature superalloys. The work was carried out as part of collaborative project with GE, Power, Repair Development Center. GE, India Industrial Pvt. Ltd., Bangalore, and while DS was with GE Power, KB and PS were at the Indian Institute of Science.

Mechanical Properties of Additively Manufactured Auxetic Structures

Dong Ruan

Swinburne University of Technology, Melbourne, Australia

Abstract

Auxetic materials/structures expand laterally when stretched and contract laterally when compressed, exhibiting negative Poisson's ratio (NPR). In this study, a recently developed 2D auxetic structure with a combination of the topological features of re-entrant honeycomb and chiral honeycomb has been fabricated from Nylon-12 using Multi Jet Fusion (MJF) 3D Printing process. The external surfaces and dimensions have been examined using an optical stereomicroscope. The microscopic measurements show that MJF 3D printing process is able to produce robust parts with precise dimensions. The mechanical properties of the proposed structure under both quasi-static and dynamic loads have been investigated experimentally and numerically. A number of experimental tests have been conducted to study the load carrying capacity and Poisson's ratio of this structure under various loading velocities using different test machines such as Zwick Roell and high-speed Instron testing machine. Finite element (FE) models have been established using ABAQUS/Explicit and validated by the experimental results. Numerical simulations have been conducted in order to examine the effects of velocity and geometrical parameters of the proposed structure. The stress-strain curves, Poisson's ratio and energy absorption of this structure have been presented and compared with those of the two popular auxetic structures, re-entrant honeycomb and chiral honeycomb.

Mechanical and Fatigue Properties of Laser Metal Deposited Ti-6Al-4V with Fully Lamellar Microstructure

E.W. Lui[1,2], N. Matthews[3], M. Qian[1,2], M. Brandt[1,2]
[1]*RMIT University, Centre fror Additive Manufacturing, Melbourne, 3001, Australia;*
[2]*Innovative Manufacturing CRC Limited (IMCRC), Carlton, 3053, Australia;*
[3]*RUAG Australia Pty Ltd, Bayswater, 3153, Australia;*
e: edward.lui@rmit.edu.au

Additive manufacturing (AM) is fast establishing itself as an alternative production technology to conventional manufacturing. Recent advancement in AM enables the production of metallic parts with mechanical properties that are comparable to commercial products used in medical and aerospace applications. Strict quality requirements of these industries call for predictability of material properties under static and dynamic loading operations. To date, investigation of the high cycle fatigue properties of AM Ti-6Al-4V components have not been fully determined. Existing data shows significant spread of fatigue life as premature failures due to internal defects cannot be excluded. In this study, the mechanical and fatigue properties of laser metal deposition (LMD) manufactured Ti-6Al-4V in the as-built as well as heat treated conditions were analysed. Tensile ductility of up to 24% in the as-built state and 30% after heat treatment was achieved. The fatigue life exceeded the range of commercial Ti-6Al-4V products. The increase in fatigue endurance limit was attributed to the fine lamellar microstructure and excellent build quality. Crack initiation site and overall fatigue performance were also investigated.

Effect of Energy density on the same Titanium Alloy Product Fabricated by Select Electron Beam Additive Manufacture-Microstructure study

M.H. Tsai[1], Ta.I. Hsu[2], ...
[1] Department of Mold and Die Engineering, National Kaohsiung University of Science and Technology, Kaohsiung, 80778, Taiwan
[2] Department of Health and Beauty, Shu Zen College of Medicine and Management, Kaohsiung, 821, Taiwan
e: tmh@nkust.edu.tw

Three different energy density is commonly used in titanium medical implants with porous and solid mixing structure by using select electron beam additive manufacture (SEBAM). Most of case, high energy density and lower density on the solid and porous area respectively. Both energy density on their overlapping area. However, its effects on part properties have not been widely investigated. In this study, we employed three different line energy density (J/m) labelled high, low and overlap of Ti6Al4V plates fabricated through SEBAM were examined. Scanning Electron Microcopy (SEM) was analyzed the pores morphology and microstructure (lamella spacing, colony size of α+β mixing phase) of sintered plates. The mechanical properties and crystallographic orientations were observed using microhardness and Transmission Electron Microcopy (TEM), respectively. The result demonstrates that the similar microstructure α+β phase was observed both under high energy and overlap parameters. Lower energy density has a negative effect on the porosity of SEBAMed samples; however it has better hardness 392 HV0.5 compare to others due to high cooling rate causing α' martensite. Our study shows high energy density (0.2 J/mm) and overlap is sufficient to fabricated solid area for densification. Lower energy density on porous structure for less/without support reason.

Heat Treatment Effect on Mechanical Properties of Selective Laser Melted 17-4 Precipitation Hardened Stainless Steel

H. Eskandari [1], M. Eizadjou[1], L.Ye[1]
[1] *University of Sydney, Sydney, 2006, Australia*
hoda.eskandari@sydney.edu.au

Selective Laser Melting (SLM) as an Additive Manufacturing (AM) technique present an exceptional prospect for the fabrication of near-net-shape parts which is an area of interest in this study. However, a major problem with this kind of technique is the mechanical properties of the parts.

The effect of the SLM process on the mechanical properties and microstructural features of 17-4 Precipitation Hardening (PH) Stainless Steel (SS) parts has been studied in this research work in comparison to differences to the properties of the wrought parts.

The current study found the tensile strength of SLM parts to be lower than the wrought samples. The present results are significant in at least major two respects; the need to improve mechanical properties of as-built SLM parts in industrial applications and the impacts of the post processing.

The thermal post processing effect on SLM parts has been investigated under various standard and non-standard heat treatment procedures. The focus of the applied thermal post processing was to evaluate the effect of aging on mechanical performance with and without a prior solution heat treatment.

The tensile strength increased for the heat treatment procedures with lower ageing temperature and holding time which is attributed to the finer precipitation particles.

Mechanical Properties, Microstructure and Osteogenesis of Selective Laser Melted TiTa Alloys

Erin Brodie[1], Jess Frith[1], Andrey Molotnikov[1]
[1]*Department of Materials Science and Engineering, Monash University, Clayton, Australia*
e: erin.brodie@monash.edu

The orthopaedics industry is going through a transformation of adopting additive manufacturing (AM) as a new fabrication method for bespoke implants. This transformation is also driven by the necessity to find more suitable metallic alloys with improved mechanical and biological response. One example is the substitution of a traditional titanium alloy, Ti-6Al-4V, which contains toxic elements, such as Al and V, with titanium-tantalum (TiTa) alloys. Literature suggests that Ta possesses a better osteogenic response than Ti, and therefore TiTa alloys will likely show improved implant integration over Ti-6Al-4V. However, fabrication of TiTa alloys via selective laser melting (SLM) is notoriously difficult due to the high melting point of Ta, around 3000 °C, and better understanding of the formation of the microstructure and resulting mechanical properties of the TiTa alloy is required.

In this work, the mechanical properties, microstructure and osteogenic response of SLM fabricated Ti25wt%Ta and Ti65wt%Ta are reported. The mechanical properties are assessed via static tensile, ultrasonic modulus and fatigue testing and the microstructure is characterised via scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The osteogenic response of the alloy is tested via *in vitro* osteogenesis assays and the surface of the material assessed via X-ray photoelectron spectroscopy (XPS). The relationship between microstructure, mechanical properties and osteogenic response of Ti25wt%Ta and Ti65wt%Ta will be presented.

FABRICATION OF SCALED 3D MODEL OF BRIDGE & TERRAIN USING ADVANCED MANUFACTURING AND TRADITIONAL MANUFACTURING TECHNOLOGIES

Raju Majji[1], Dr Tosin Famakinwa[2];
[1]*Western Sydney University, Penrith Campus, 2747, Australia;*
[2]*Western Sydney University, Penrith Campus, 2747, Australia;*

e: r.majji@westernsydney.edu.au

In collaboration between Landcom and Western Sydney University, a detailed and scaled 3D printed bridge and CNC machined terrain of the future Lachlan's Line Pedestrian and Cycle Bridge in North Ryde NSW was fabricated. With a $40 million investment by the New South Wales Government at stake, a small-scale model of the proposed bridge was required for Landcom and their contractors to assess various designs and constructability approaches. Constructing this model was an excellent technical challenge for WSU's Advanced Manufacturing precinct to demonstrate the outstanding abilities of technical staff and students, and the capabilities of the latest facilities and equipment. A combination of traditional manufacturing, advanced manufacturing and hand skills were applied to achieve the final model including Stratasys J750 3D printer, CNC machine, laser and water jet cutters, and excellent hand skills of students in painting and finishing. Including eye catching (Road, lines, humans, trees and landscape) details are proportionate to design conveys concept appropriately. Not only was this project an assessment of the technical capabilities, but was another successful example of WSU collaborating in research and learning partnerships with our industrial partners.

Fatigue behaviour of Additively Manufactured Aluminium Alloy

L. Afroz[1], R. Das[1], M. Qian[1], M. Easton[1]
[1]School of Engineering, RMIT University, Melbourne, Australia
e: s3731913@student.rmit.edu.au

The aerospace and automotive industries are being drawn to Selective Laser melting (SLM), a layer-wise additive manufacturing (AM) process which can create complex net-shape geometry directly from 3D drawings in an efficient manner both technically and economically. Yet the application of AM parts in this automotive industry requires high standard static and dynamic mechanical properties to get expected service life. Fatigue and fatigue crack growth properties are imperative cyclic properties of AM parts which are often disregarded in literature compare to static one. However, the fatigue issue associated with additive manufacturing is more complex than conventional fabrication, such as casting and forging because of the multiplicity of different influencing factors like defects, microstructures and anisotropy. In the view of these aspects, the present work is aimed at investigating the fatigue properties of AlSi10Mg alloy produced by AlSi10Mg powder via selective laser melting process. High cycle fatigue test has been carried out on the machined and stress relieved samples for two different stress ratios. In addition, the effect of building orientation on the fatigue life is examined. The result enables prediction of fatigue life of additive manufactured AlSi10Mg alloy for a reliable load carrying application.

Production level Additive Manufacturing - 5 Tips for Success

Yathiraj Kasal
Asia-Pacific Leader for AddWorks
GE Additive
E-mail: yathiraj.kasal@ge.com

Metal Additive Manufacturing has matured beyond prototyping application. Organizations are increasingly accepting additive manufacturing for serial production of various components. These parts have been successfully certified for end applications. GE Aviation has successfully produced and delivered more 30,000 fuel tips as of October 2018. GE9X and Catalyst engines have significant number of components maturing towards certification. Taking additive manufacturing to production level needs change in mindset of how we design and how we collaborate. 5 tips for achieving production level success in additive manufacturing will be presented.

Biography

Mr. Yathiraj Kasal leads AddWorks team of GE Additive for Asia-Pacific region. He is an Additive Technology evangelist in Asia Pacific region. He has more than 21 years of industry experience. He has led many projects for additive parts productionization, new material development, parameter optimization, prototyping and tooling. At GE Additive, he is responsible to accelerate additive adoption for GE's customers in APAC region, which encompasses additive design, materials, industrialization consulting, low rate production, production qualification, part qualification and prototyping.

Design of titanium alloys processed using additive manufacturing for structural applications

Hamish L Fraser
Center for the Accelerated Maturation of Materials
Department of Materials Science and Engineering
The Ohio State University
Columbus, OH 43221

Additive manufacturing of components made of metallic alloys are produced using a feedstock (usually powders or wire) of conventional alloys. In the case of titanium alloy components, the application of essentially all industrially competitive techniques for additive manufacturing result in characteristic defects, being coarse columnar grains (in the direction of deposition), porosity, and residual stresses. This paper addresses the first of these, where the solution sought involves the development of modified/new alloys specifically for the given manufacturing process. The proposed solution involved the application of computational thermodynamics to identify which alloying additions to titanium alloys result in an increase in the freezing range of the given alloy base, such that a columnar to equiaxed transition (CET) may be effected. These alloying additions, mainly eutectoid formers, have been found, at critical concentrations, to cause a CET to occur, resulting in a relatively fine equiaxed microstructure. Of course, the amount of solute addition for these elements usually exceeds their solubility limit in the various titanium alloys, and, therefore, a further effort involving alloy development is required. Two types of alloys are being developed, the first with essentially identical properties as the (given) base alloy, and the second, alloys with enhanced properties. These various efforts will be described during this presentation.

Accelerate the Additive Design and Development Process

Dr.-Ing. H. Schafstall and Dr.-Ing. P. Mehmert

Simufact Engineering GmbH

Tempowerkring 19

21079 Hamburg, Germany

www.simufact.com

E-mail: hendrik.schafstall@simufact.de

Additive manufacturing (AM) processes offer great potential for many industrial applications. There are several types of AM processes, such as powder bed fusion or binder jetting, or direct energy deposition methods and in combination with other processes, so called hybrid methods. The vision and goal of the activities is a reliable, robust, fully automated, controllable process chain with the right generative design for a "first time" printable component with the right component performance and microstructure. This is only possible by linking all relevant process steps and information in the virtual and real world. The complexity of the whole process requires a complete digital transformation of the process. The focus in the presentation is on the digital process chain of metal parts for powder bed fusion processes from generative design to automated simulation and the proof-of-concept for an optimized manufacturing process and the current problems. At the end we want to have smart virtual and real processes, which are connected and an environment to store and handle all available data.

Photocurable resins for 3D printing of soft and elastic materials

Johan S. Basuki,[1] Maeva Touzard,[1] Asitha Balachandra,[1] Malsha Wickramaratna,[1] Ke Du,[1] Sean Murphy,[1] Timothy C. Hughes[1]
[1] *CSIRO Manufacturing, Clayton, Victoria, 3168, Australia*
e: tim.hughes@csiro.au

Despite the significate interest in 3D printing, there still remains a need for 3D printing resins with a wider range of properties to enable the printing of functional parts to suit end-use applications rather than just prototypes. The fabrication of soft and elastic parts by 3D printing is challenging. For instance, 3D printing of silicone or polysiloxane is very difficult to achieve, although there are needs to have silicone parts prototyped and customized in patient-specific devices. In general, soft materials are prone to plastic deformation during the 3D printing process. Moreover, the resultant 3D elastomeric object may not have sufficient mechanical properties for functional use.

Here we present our research at CSIRO on the development of new photocurable resins 3D printing designed to meet the needs of the polymer 3D printing industry. The translation of simple photocure chemistry to a DLP printer is not as straight forwards as expected. There are many factors which need to be considering when developing resins for DLP printers, namely: formulation stability, cure time for each layer, plastic deformation, successful initiation of crosslinking reactions, and inhibition of unwanted curing. Here we discuss these requirements and the interplay between them.

Application of laser additive manufacturing to high-speed train brake disc manufacturing

Hui Chen, Yong Chen, Jun Xiong, Ying Wu
School of Materials Science and Engineering, Southwest Jiaotong University, Chengdu, 610031, China
e:xnrpt@swjtu.edu.cn (H. Chen)

In order to improve service performance of the critical component in high-speed train and shorten the production cycle, the laser additive manufacturing is applied to fabricate the large complex high-performance alloy-steel brake disc. During the manufacturing process, the internal stress tends to make part deformation and cracking, thus, stress and deformation control has become an urgent problem of the technology. This work presents a detailed analysis on the mechanism of residual stress formation. Temperature gradient and phase transformation are the main reason for high-performance steel forming residual stress. And then, structure optimization, process parameters optimization, baseplate preheating and stress relieving were used for residual stress control. In addition, the densification behavior, microstructure and mechanical properties of the part were evaluated, which meets the requirement of practical application.

Additive manufacturing of tantalum lattice structures by selective electron beam melting

J. Wang, K.Yang, H.P.Tang
State Key Laboratory of Porous Metal Materials,
Northwest Institute for Nonferrous Metal Research, Xi'an 710016, China
E-mail address: jwangxjtu@163.com (J. Wang)

The medical device industry's interest in porous metallic biomaterials has increased significantly in response to the rapid development of the additive manufacturing (AM) techniques, which have enabled the commercial production of intricate devices that cannot be produced by conventional techniques. Tantalum (Ta) is a refractory metal that shows high ductility, excellent biocompatibility and high chemical resistance. The combination of these properties in a micro-architectures lattice form opens potential new applications of Ta in the medical sector. In this study, we report our recent experimental results on the additive manufacturing of solid and lattice-structured Ta selective electron beam melting (SEBM) of spherical Ta powder made by plasma rotating electrode process (PREP). Their microstructure and mechanical properties are discussed.

Characterization of plastically deformed AlSi10Mg fabricated by selective laser melting

Jiangqi Zhu[1], Yuhan Huang[1], David Ritchie[2], Sri Lathabai[2], Jian-Feng Nie[1]

[1] Department of Materials Science and Engineering, Monash University
[2] CSIRO Manufacturing
jiangqi.zhu@monash.edu

The aim of this work is to investigate how the microstructure and the crystallographic orientation of a selective laser melted AlSi10Mg alloy would change in response to the compressive loading at room temperature. To examine the microstructure evolution, scanning electron microscopy (SEM) and electron backscattered diffraction (EBSD) observations were made, before and after the deformation, on cube-shaped samples prepared from the selective laser melted parts fabricated by island scanning strategy. The EBSD results show that, after the compressive deformation, the texture becomes stronger and some of the original grains break into small grains. The SEM results show that the deformation of AlSi10Mg sample is not uniform. Strain localisation is evident at the melt pool boundaries, in the coarse-grained region of the heat affected zone. In this region, the α-Al phase within the cellular dendritic structure is seen to deform while the harder eutectic Si at the dendrite boundaries is hardly affected.

The effect of linear energy density and hot isostatic pressing on thermal conductivity of additively manufactured pure tungsten

Jinhan Chen[1], Kailun Li[2]
[1,2]*State Key Laboratory of New Ceramic and Fine Processing, School of Materials Science and Engineering, Tsinghua University, Beijing 100084, China;*
e: chenjinh17@mails.tsinghua.edu.cn

Hot isostatic pressing (HIP) process was chosen as an effective post-processing treatment to achieve thermal conductivity improvement in additively manufactured tungsten (W). Thermal properties were improved by adjusting the processing parameters. As the energy density increases, the thermal conductivity of W samples increased first and then decreased. After HIP, samples with an average thermal conductivity of 138 $W \cdot m^{-1} \cdot K^{-1}$ at room temperature (RT) were acquired, which was nearly 17% higher than that of as-built W samples (118 $W \cdot m^{-1} \cdot K^{-1}$). It was found that large grains size up to 400 μm were formed and crack healing occurred after the HIP process, which leads to a substantial improvement of the thermal conductivity of pure W produced by laser powder bed fusion (LPBF). In this work, the positive correlation between relative density and thermal conductivity of pure W was systematically analyzed. In addition, the effect of HIP treatment on crack healing behaviors and microstructure evolution of LPBFed pure W were also investigated.

Abstract/Bio for Keynote Address at APICAM 2019

Using High Energy X-Ray Diffraction to Probe Additively Manufactured Metals over a Range of Length and Time Scales

John Carpenter*, D.W. Brown*, B. Clausen*, A. Losko*, M. Strantza*, J.C. Cooley*, R. Pokharel*, E.B. Watkins*

* Los Alamos National Laboratory, Los Alamos, NM, USA 87545

Email: carpenter@lanl.gov

The last decade has seen tremendous advances in the ability of X-rays at large scale facilities to probe microstructure at unprecedented length and time scales under unique environments that simulate manufacturing conditions. Concurrently, manufacturing is undergoing a revolution as investments are made in advanced manufacturing techniques, such as additive manufacturing. It is natural that advanced manufacturing techniques should couple with advanced in-situ characterization techniques in order to accelerate the process of qualification of products for critical applications.

This talk will present our efforts to characterize the processing / microstructure / properties / performance relationship of additively manufactured materials across many length and time scales utilizing high-energy x-ray scattering techniques at the Advanced Photon Source. As an example of studying the effect of processing on microstructure, high energy x-ray diffraction has been used to monitor microstructural evolution in-situ during additive manufacture of 304L stainless steel and Ti-6Al-4V with sub-second time resolution and sub 0.1mm spatial resolution. Both material feedstocks are wire and deposited using a metal inert gas welding set-up. The intent is to study this additive technique as it pertains to the repair of existing objects. Specifically, the evolution of phase fractions, liquid and multiple solid phases, is monitored immediately following deposition, during solidification, and during cooling. This information can be utilized in current process – microstructure models in order to inform and validate the appropriate kinetics which lead to the resultant microstructure after deposition.

Advancing Manufacturing Processes

Professor Judy Schneider
University of Alabama in Huntsville

For decades, materials and manufacturing technology have been advancing at an exponential pace. Consequently, today many engineering professionals are grappling with how to incorporate many new manufacturing techniques into their businesses to become or remain competitive in the global environment. While many of these technologies are incremental and evolved from previous technologies, periodically, real game changing, “disruptive technologies” occur for which there is no prior history or infrastructure yet developed to support. These technologies are particularly challenging to embrace both for the current labor force and for academics who are responsible for training the future labor force.

Methods to quantify AM components are currently being explore both in-situ and ex-situ. In-situ technques can be used to identify spatially resolved locations of possible defects. These techniques are helpful in optimizing the build parameters and developing procedures for developing in-situ inspection techniques. These efforts are coupled with optimization of the build parameters to obtain the best build in terms of minimizing void content. However equally important to the AM development is the post-processing heat treatments. The rapidly and repeatitly melted and solidification process results in non-equilibrium microstrucures which respond differently to heat treatments than either cast or wrought materials. This presentation will summarize efforts to optimize these post processes which are needed to form the basis for standardization specifications

Corrosion Studies of Additively Manufactured Ti Alpha-Beta Alloys

K. Venkatesan[1], D. Conjan[2], D. Fraser[1], D. Ritchie[1] and S. Lathabai[1]
CSIRO Manufacturing, Clayton, 3168, Australia;
[2]*Master's student, Sigma Clermont, France*...
e: Kishore.Venkatesan@csiro.au

Two Ti alpha-beta alloys, commercially available Ti6Al4V alloy and a proprietary alloy, were additively manufactured using an electron beam additive manufacturing equipment. The alloys were tested for their corrosion performance in a 0.1 M NaCl solution. The microstructures before and after the tests were also examined. The outcome of this study will be presented in this paper.

Nitrogen Solid Solution Strengthening in AM Titanium Materials

Katsuyoshi Kondoh, Ammarueda Issariyapat and Junko Umeda

Joining and Welding Research Institute

Osaka University

E-mail: kondoh@jwri.osaka-u.ac.jp

In the previous studies, rare-metals free titanium (Ti) sintered materials with high strength and ductility were successfully developed by solid solution strengthening behavior using nitrogen and oxygen elements [1~3]. The pre-mixed Ti+TiN and Ti+TiO2 powders were employed as the starting raw materials to fabricate PM Ti-N and Ti-O materials, respectively. The additional particles of TiN and TiO2 were completely dissolved during solid-state sintering, and then nitrogen and oxygen atoms existing in α

-Ti as interstitial solution elements resulted in the significant improvement of tensile strength of PM Ti materials. When the solid solution strengthening by nitrogen atoms is applied to the additive manufactured (AMed) Ti materials, instead of the above pre-mixed Ti+TiN powder, the spherical Ti powder containing nitrogen elements (0.1~1.2 wt%), which was prepared by heat treatment at 800C (1073 K) in nitrogen gas atmosphere, was consolidated by selective lase melting (SLM) process. The surface of this Ti powder was coated by Ti2N thin layer (thickness; ~ 1 μm), and nitrogen atoms were also soluted in Ti matrix. In the matrix of AMed Ti-N materials, the nitrogen elements also existed as solid solution atoms and no titanium nitride (Ti2N and TiN) was observed because rapid solidification behavior in SLM was effective for the complete solution of nitrogen into α-Ti matrix. With increase in the nitrogen content of Ti materials, the tensile strength drastically increased, but they showed poor elongation. The increment of tensile strength was theoretically estimated by using Labusch model, and the calculation results corresponded well to the experimental data after removing the α-Ti grain refinement effect. It was concluded that nitrogen solution strengthening mechanism was also useful to improve the mechanical properties of AMed Ti-N materials as well as the conventional PM Ti-N ones.

[1] J. Shen et al., Materials Science and Engineering A, 716 (2018) 1-10.

[2] K. Kondoh et al., Int. J Powder Metallurgy, 50 3 (2014) 35-40.

[3] B. Sun et al., Materials Science and Engineering A, 563 (2013) 95-100.

Hybridisation of Microstructures by Selective Laser Melting - a New Strategy for Future Alloys

K. Xia

Department of Mechanical Engineering

The University of Melbourne

E-mail: k.xia@unimelb.edu.au

Hybridisation of Microstructures by Selective Laser Melting - a New Strategy for Future Alloys K. Xia Department of Mechanical Engineering The University of Melbourne E-mail: k.xia@unimelb.edu.au Nature is full of hybrid structures, as a result of long evolution, which are capable of sophisticated functions. It is, however, difficult to realise in metals. Among conventional engineering alloys, steels, in particular the advanced high strength steels (AHSS), come close with their comprehensive mechanisms including deformation induced transformations and twinning. In the case of metal matrix composites, the constituent phases often have very different strengths, preventing effective coordination between them. We have pioneered a new strategy for producing future alloys with significantly enhanced performances through the hybridisation of different microstructures from existing alloys to generate a composite of "microstructures" rather than phases. By selecting proper ingredient alloys and their associated microstructures in the case of mechanical applications, deformation can be effectively transferred between them, leading to coordinated behaviour of the resulting hybrid material. In this presentation, the new strategy is demonstrated by a hybrid Ti from two existing alloys produced by selective laser melting, leading to superior tensile properties. Further, individual properties can be selectively tailored, giving rise to great flexibility. This novel approach can be applied to a vast variety of metals beyond Ti, leading to unlimited choices, and contributes significantly to the coming era of microstructure-by-design.

Additive Manufacturing of a C-Mn-Cr low alloy steel by Electron Beam Melting

S. Lathabai[1], D. Fraser[1], K. Venkatesan[1], D. Ritchie[1], S. Raman[2], M. Seita[2]

[1] Metal Industries Program, CSIRO Manufacturing, Clayton, Victoria, Australia

[2] School of Materials Science and Engineering, Nanyang Technological University, Singapore

Additive Manufacturing (AM) is finding increasing applications in the aerospace and biomedical industries, where advantages offered by the technology have justified the current higher production costs. As a result, AM processes have been widely developed for materials used in these industries, such as Ti-6Al-4V and other Ti-based alloys and Ni-based alloys such as Inconel 625 and 718. Although steel alloys constitute the most extensively used materials in a variety of industrial applications, the application of AM to these materials has been limited to date partly because traditional manufacturing methods have worked efficiently in their fabrication. In this paper we examine the applicability of Electron Beam Melting to 16MnCr5, a low alloy steel with case hardening capabilities, which finds use in the automotive industry in the manufacture of drivetrain parts and gears. Process parameters that result in ~99.5% theoretical density have been determined. The resulting microstructures and mechanical properties are presented.

Design, manufacturing, mechanical and acoustic properties nature-inspired metal-water structure fabricated by selective laser melting

Lei Zhang, Bo Song, Yusheng Shi

State Key Laboratory of Materials Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan, 430074, China
e: Contact's e-mail address: zhangleizzz@hust.edu.cn

Metamaterials, also called “extreme materials”, are rationally man-made structures with abnormal physical properties which are mostly associated with negative Poisson’s ratio, negative refractive indices and negative modulus. Pentamode materials (PMs), also called as metal-water, are complex structures composed of periodic unit cells that presents effective physical properties like water or fluid ones. In this work, we designed a metal-water pentamode structure using the homogenization method, and clearly elaborated the relationship of geometrical dimensions and physical properties. The sound pressure field demonstrated that the designed metal-water has identical properties with water. Then, the optimal PM structure was manufactured with different laser power by advanced selective laser melting. The morphological characteristics of SLM-built PM samples with different laser power were evaluated by micro-CT and SEM. The influence of manufacturing accuracy on mechanical properties and acoustic properties were both studied by experiments and simulations. This work paves the way to structural design metal-water and realize the feasibility of manufacturing mater-water pentamode metamaterials using SLM.

Low-cost Polymer-based Selective Laser Sintering

Martin Mapley[1,2]; Geoffrey Tansley[1,2]; Andrew Busch[1]; Shaun D. Gregory[1,2,3]

[1] School of Engineering and Built Environment, Griffith University, Queensland, Australia
[2] Innovative Cardiovascular Engineering and Technology Laboratory, The Prince Charles Hospital, Brisbane, Queensland, Australia
[3] Department of Mechanical and Aerospace Engineering, Monash University, Melbourne, Victoria, Australia

Contact – Martin Mapley E: mmapley@gmail.com

Polymer selective laser sintering (SLS) is a powder-based additive manufacturing (AM) method which allows the production of high-density net-shaped parts from 3D model data without the need for support structures. SLS is a platform which allows the processing of pure, composite and mixed polymer-based powders to increase part mechanical, electrical, magnetic or aesthetic characteristics, however its widespread use is largely prohibitive due to the high costs associated with machine purchase.

To create a platform which could be used to experimentally process new polymer-based materials, a low-cost SLS machine was constructed from off-the-shelf parts. Optical power is supplied by a 15 W solid state diode laser which is tracked over the powder bed alleviating the requirement of expensive and complex galvometer based scanning systems. The powder bed consists of two outer pistons which increment to supply powder to the recoater and a heated center piston where the powder consolidation occurs. The machine is controlled by a PC via the parallel port which converts g-code instructions, generated by the slicing software, into motor and laser control pulses.

The capabilities of the low-cost SLS machine were tested by producing cuboids and cylinders from a powder mixture containing 38% NdFeB flakes and 62% polyamide-12 spheres. Scanning electron microscope images taken of fractured surfaces of the parts showed the NdFeB flakes suspended in the polymer matrix indicating that the laser was able to supply adequate power to perform consolidation.

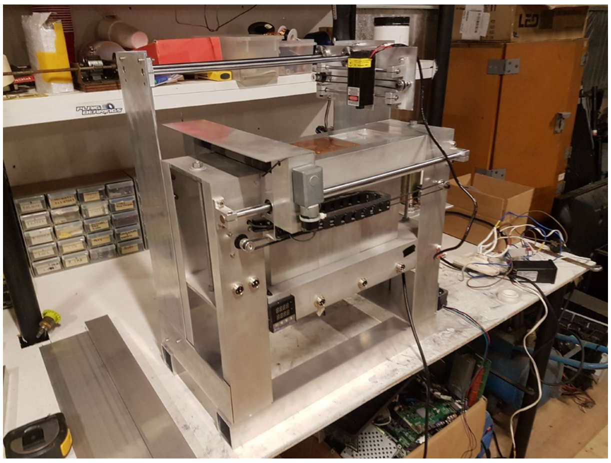


Figure 1. The assembled low-cost SLS machine

Please follow the format and style described in this template. Please use A4 (210 mm x 297 mm) paper size. **The abstract should be less than 250 words**, with page margins of 25 mm all around. Use font type **Arial**, with single spaced lines. Title of the paper (14 points, bolded) is followed by one blank line. The presenting author's name should be underlined. Author's affiliations (12 points, italic, centered) and email address of the contact person are written in separate rows. Abstract text (12 points) in paragraphs. The abstract may include one figure with the figure caption (12 points, italic, centered) underneath the figure. The abstract including figure should fit on a single page.

COMPUTATIONAL MODELLING OF STRUT DEFECTS IN SLM MANUFACTURED LATTICE STRUCTURES

Bill Lozanovski[1,2], Martin Leary[1,2], Phuong Tran[3],Darpan Shidid[1], Ma Qian[1],Peter Choong[2,4], Milan Brandt [1,2]
[1]*RMIT Centre for Additive Manufacture, RMIT University, Melbourne, 3001, Australia ;*
[2]*ARC Training Centre in Additive Biomanufacturing, www.additivebiomanufacturing.org;*
[3]*Department of Civil & Infrastructure Engineering, RMIT University, Melbourne, 3001, Australia;*
[4] *St. Vincent's Hospital, Department of Surgery, Melbourne, 3000, Australia;*
e: martin.leary@rmit.edu.au

Addition of manufacturing defects to computational models of 3D-printed lattice structures enable improved simulation accuracy. A computational model of a cellular structure based on finite element method (FEM) analysis, often starts from defect-free computer-aided design (CAD) geometries to generate discretised meshes. Such idealised CAD geometries neglect imperfections, which occur during the additive manufacturing process of lattice structures, resulting in model oversimplification. This research aims to incorporate manufacturing defects in the strut elements of a lattice structure, thereby enhancing predictive capabilities of models. In this work, a method of generating CAD AM representative strut models is proposed. The models are generated from micro-computer tomography (μCT) analysis of SLM fabricated struts. The proposed additive manufacturing (AM) representative strut FE model's axial stiffness and critical buckling load is compared to idealised- and μCT- based FE models, with significant error reduction over idealised strut models. The AM representative strut models are then used to generate full lattice FE models and compared with manufactured and idealised FE models. The AM representative FE lattice models show greater correlations toward experiment and more realistic deformation behaviours. Overall, the methodology used in this study demonstrates a novel approach to representing struts in FE models of AM fabricated lattice structures.

Ballistic performance of additively manufactured Ti-6Al-4V alloy

A. E. Medvedev[1,e], E. Lui[1], D. Edwards[2], M. Qian[1], M. Brandt[1]
[1]*Centre for Additive Manufacturing, School of Enginbeering, RMIT University, VIC 3000, Australia;*
[2]*Defence Science and Technology Group, Fisherman's Bend, VIC 3027, Australia*
e: alexander.medvedev@rmit.edu.au

Currently, steel is the material of choise for armour applications, which is due to its high mechanical properties, established production processes and low cost. In the past few decades, Ti6Al4V alloy has attracted attention as a candidate armour material primarily due to a significant weight reduction it can provide while maintaining equivalent mechanical properties compared to steel counterparts. The major drawback of titanium materials, which limits their ballistic performance, is susceptibility to adiabatic shear band (ASB) formation, which is highly dependent on their microstructure.

Recent developments in additive manufacturing (AM) of titanium alloys, including Ti6Al4V, have allowed a degree of control over various stages of processing to manipulate the microstructure of finished parts. Furthermore, AM allows a higher degree of freedom in the geometry and design of components to meet specific performance requirements. There is, therefore, a potential to use AM for a production of lighter Ti armour with tailored microstructure and complex geometry to provide better ballistic protection.

In this work, we discuss the influence of processing parameters as well as variations in microstructure on the ballistic behaviour of the Ti6Al4V alloy produced via additive manufacturing methods.

Microstructure Characteristics of Electron Beam Melted Inconel 738

Nima Haghdadi[1], Xiaozhou Liao[2], Simon Ringer[2], Edward Whitelock[1], Sophie Primig[1]

[1]School of Materials Science and Engineering, UNSW Sydney, NSW, Australia

[2]School of Aerospace, Mechanical and Mechatronic Engineering, Australian Centre for Microscopy & Microanalysis, The University of Sydney, NSW, Australia

Additive manufacturing (AM) of metals is seeing an extremely accelerated growth both in research and in industrial implementation for various critical applications. Inconel 738 is a precipitation hardened nickel-based superalloy commonly used in high temperature applications within power generation turbines and aerospace engines. Due to the difficulties associated with casting and welding of this alloy, there is now tremendous interest in using AM based techniques for fabrication of Inconel 738 parts. There have been attempts to manufacture Inconel 738 alloys through laser powder bed fusion methods. High cooling rates associated with these methods, however, inhibited the formation of desirable γ' particles, necessitating further long-time heat treatments. Slower cooling rate associated with electron beam melting might overcome this issue. No research on electron beam melting of this alloy has, however, been reported in the literature so far.

This work reports on our preliminary study of an electron beam melted Inconel 738 alloy. This alloy was successfully printed using a random deposition raster. It was found that the γ grains formed during electron beam melting were elongated vertically across the build with the grains at the top of the printed build being more elongated due to a comparably higher thermal gradient. Scanning electron microscopy analyses confirmed the presence of carbides mostly precipitated at the γ/γ grain boundaries and within the interdendritic regions. In contrast to previous work on laser based additive manufacturing of Inc738 alloy, a high-volume fraction of semi-round γ' particles were formed within the γ matrix grains during electron beam melting. This was due to the difference in thermal gradients of electron beam melting (i.e., slower cooling rate) compared to the selective laser melting. A bimodal size distribution of γ' particles was found with a first population with typical diameters of 20-40 nm while the second population was about 400-600 nm.

Acknowledgements: Funding by the AUSMURI program, Department of Industry, Innovation and Science, Australia is acknowledged. Samples were provided by Prof. Suresh Babu and Miss Sabina Kumar, The University of Tennessee, Knoxville.

Multi-Component Mesoscale Manufacturing using a Novel Tool Changing Electrospinning Platform

C.S. Deenen[1], C. Eyovge[1], A. Susarrey-Arce[1], J.G.E. Gardeniers[1]
[1]*Mesoscale Chemical Systems, MESA+ Institute for Nanotechnology, University of Twente, Enschede, 7500 AE, the Netherlands;*
e: c.s.deenen@utwente.nl

Electrospinning is an additive manufacturing technique for the fabrication of mesoscale nanofibrous structures. A conventional electrospinning setup consists of a singular electrified nozzle through which a solution is pumped. Due to electrostatic repulsion, a jet is ejected from the nozzle that solidifies as it moves towards a grounded or electrified collector, resulting in nanofiber deposition. Due to the time and labor required to either manually replace the nozzle or to flush the fluidic elements of the electrospinning setup, research in electrospinning is currently focused on single-material applications.

Mounting multiple nozzles on a rotating disc allows the inactive nozzles to be rotated out-of-plane, reducing the time required for the switching of precursor materials from minutes to seconds. Combining this concept with appropriate control of electrical voltages and fluidic flow through the different nozzles, allows the engineering of a flexible platform for fast and reliable manufacturing of multi-component materials using electrospinning.

In this work, we will demonstrate the instrumental concept and apply it to the fabrication of catalytic layers composed of TiO_2, decorated with three different metal catalyst nanoparticles (Au, Pd, Pt) which function in concert for light harvesting and efficient hydrogen production during photoelectrocatalysis.

Evolution on microstructure and mechanical properties of a novel high tungsten steel using in-situ hydride additive manufacturing

N. Kang [1], Q. Li [1], X. Lin [1], H. Liao[2], C. Coddet[2] M. El Mansori[3], W. Huang[1]
[1] Northwestern Polytechnical University
[2] University Bourgogne Franche-Comte
[3] MSMP Laboratory, EA-7350, Arts et Metiers ParisTech,
E-mail: nan.kang@nwpu.edu.cn

Selective laser melting (SLM) and hot isotropic pressing (HIPing) are considered as a set of material processing technology for obtaining defect-free metallic materials, which is defined a hydride additive manufacturing (AM) process. In this work, a new insight on microstructure and mechanical evolution of in-situ hydride AM processed high tungsten steel was proposed. The WC powder was used to in-situ induce the high tungsten content into maraging steel. The XRD analysis indicates that the hydride AM processed component presents a single ferrite phase. After the HIPing process, the high tungsten steel sample presents a large amount of θ precipitated phase. Few partial melted WC was used to investigate the interface between WC and maraging steel after hydride AM, which was determined by FIB and TEM. The results indicated a long-scale gradient structure appears in function of tungsten content. With the addition of WC and possible in-situ reaction during SLM and HIPing process, the high tungsten steel presents higher tensile strength (UTS: 1470 MPa and YS: 1025 MPa) than that of maraging steel (UTS: 1140MPa and YS: 691MPa). Meanwhile, the wear resistance of high tungsten steel is much higher than that of maraging steel component.

Keywords: hydride additive manufacturing; high tungsten steel; microstructural; wear; tensile properties.

Non-destructive scattering techniques for additive manufacturing

A.M. Paradowska*, U. Garbe, M. Reid, R. Acres

Australian Nuclear Science and Technology Organisation, Lucas Heights, NSW 2232, Australia

*E-mail: anna.paradowska@ansto.gov.au

Abstract

The OPAL research reactor at ANSTO and Australian Synchrotron has several instruments available for materials science and engineering applications. The neutron and synchrotron instruments are vital non-destructive characterisation tools for modern advance manufacturing, engineering and life extension. The instrument allows us to non-destructively determination residual stresses and texture within the interior of bulk engineering components. Imaging beamline are used to assessing defects and dimensional tolerance of internal features engineering components well suited for thick and complex's metallic and composite components.

The instruments provide valuable information that could have direct impact on optimization of modern manufacturing processes in particular additive manufacturing. They can also improve product reliability, enhanced design performance, reduced production cost, and extended life prediction on significant engineering assets (e.g. power-station utilities, gas pipelines, aircrafts, etc.).

This paper will provide a review of current techniques available and will highlight resent industry driven collaboration projects at ANSTO.

Keywords: *Additive manufacturing, Residual stress, Neutron diffraction, Neutron imaging.*

Residual Stress in Additive Manufacture

V. Nguyen[1], Y. Feng[2], S. Lathabai[1], D. Ritchie[1],G. Delooze[1], R. Wilson[1]
[1]*CSIRO Manufacturing, Clayton South, 3169, Australia*
[2]*CSIRO Mineral Resources, Clayton South, 3169, Australia*

e: vu.nguyen@csiro.au

Powder bed fusion (PBF) and Directed Energy Deposition (DED) are the two widely used Additive Manufacturing (AM) technologies. Power sources such as laser or electron beam are used for melting of powder or wire following the geometric information contained in a Computer-Aided-Design (CAD) file. In these processes, components or parts are built in a layer-by-layer manner until a fully dense 3D structure is achieved.

High thermal gradient and multiple thermal cycles are usually observed in DED and PBF processes which result in residual stress and shape distortion. Understanding of stress evolution in these processes are therefore highly desired for stress management and process improvement.

This paper presents the predicted stress occurred during DED and PBF of Ti-6Al-4V builds. The results provide an understanding of the evolution of stress during and after completion of the builds. Managing stress raiser is also discussed.

Where to From Here? A Review of the Latest Additive Manufacturing Techniques & Materials and a Look at Future Possibilities

P. A. Walls
Hitech Materials Pty Ltd, Figtree, 2525, Australia
e: philip.walls@hitechmaterials.com.au

The Additive Manufacturing scene has gone ballistic in the last few years and has shown no signs of slowing down. In fact AM processes and the types of materials they can lay down are changing almost weekly. Will this slow down? What will be the predominant technologies in ten year's time? How will materials properties be further enhanced by AM? These questions will be examined in this presentation by looking at the most recent trends and future possibilities.

Lab22 and CSIRO's Metallic AM Priorities

L. H. Prentice[1], D. East[2]
[1]*CSIRO Manufacturing, Clayton, 3168, Australia*
e: leon.prentice@csiro.au

CSIRO's Lab22 Innovation Centre was created in 2013 as a showcase and industry-accessible facility for metallic AM in Australia. Its breadth of technologies – from Cold Spray Additive to 3D Printing sand – has enabled numerous industry applications and accelerated the uptake of advanced manufacturing technologies. Over the last 5+ years CSIRO has added facilities, equipment, staff, and students to Lab22's capabilities, and has built an increasing focus on new technologies for AM. Particular focus areas that have resulted in significant industry impact have included medical devices, cold spray additive, and metal-matrix composites. This presentation will present some of these highlights, reflect on Lab22's operations to date, and present CSIRO's future vision for Lab22.

CSIRO's view is that metallic AM is now established as a multi-purpose technology, and the global emphasis is now twofold. First, the AM community is seeking to establish robust quality assurance and certification of the more mature technologies – laser-, electron-beam-, and plasma-based powder bed and wire. CSIRO is active in this area via computational modelling and non-destructive testing research. The second emphasis, and the core of Lab22's future research, is on innovative AM, particularly including novel alloys, multi-material systems, metal-matrix composites, multi-process and hybrid research.

ADDITIVE MANUFACTURING OF SOFT MAGNETIC ALLOYS

S.A. Mantri[a,c], S. Dasari[a,c], V. Chaudhary[b,d], V. Soni[a,c], R.V. Ramanujan[b], and R. Banerjee[a,c]

[a]Department of Materials Science and Engineering, University of North Texas, Denton, Texas, 76201, USA
[b]School of Materials Science and Engineering, Nanyang Technological University, Singapore 639798, Singapore
[c]Advanced Materials and Manufacturing Processes Institute, University of North Texas, Denton, Texas 76201, USA
[d]Rolls-Royce@NTU Corporate Lab, Nanyang Technological University, Singapore, 639798, Singapore

While there has been substantial effort focused on additive manufacturing (AM) of structural alloys over the past couple of decades, there have been rather limited efforts on AM of functional alloys, such as magnetic materials. The present study will focus on laser additive processing of magnetic alloys using the laser engineered shaping (LENS) process that falls under the category of directed energy deposition (DED) processes. Examples will be presented both from alloys using a feedstock consisting of a blend of elemental powders as well as pre-alloyed powders. Soft and semi-hard magnetic alloys of different types have been processed using LENS. These include those of the permalloy type, based on Fe-Ni, Ni-Fe-V and Ni-Fe-Mo compositions, as well as compositions based on Finemet, $Fe_{73.5}Si_{13.5}B_9Nb_3Cu_1$. Systematic changes in the laser-power and the travel speed have been correlated to the phase stability in the deposits of these soft magnetic alloys, and the consequent magnetic properties. The LENS technique can be effectively used to process compositionally-graded alloys by systematically varying the flow rates from individual powder hoppers that comprise the feedstock for this AM process. Influence of Fe/Co ratio on the microstructure and magnetic properties of Hiperco type soft magnetic alloys will also be discussed in this presentation. This work shows the feasibility of AM processing of soft magnetic materials.

AWBell's Additive Routes for Investment Castings in the Last Two Decades

Roger Lumley[1], Jason Barkla[2], Matthew Emery[1].

1. AWBell Pty. Ltd. 145 Abbotts Rd. Dandenong South, Victoria 3175
2. CSIRO SME Connect, Bayview Avenue, Clayton VIC 3168 Australia

AW Bell was founded in 1952 as a patternmaking business servicing the Australian foundry industry. This beginning provided the initiation of the company's depth of understanding and expertise in the metal casting and manufacturing industry. A drive for innovation and customer service has seen AW Bell successfully pass through three generations and evolve from pattern makers, to automotive supplier and today to being an integral part of aerospace, defence and biomedical device supply chains.

AW Bell today is a supplier of complex metal parts incorporating investment casting, sand casting, rapid prototyping, production machining and tier-one assembly. The company also has a number of ancillary and sub-process capabilities such as tooling design and manufacture, heat treatment, destructive and non-destructive testing, painting and finishing. AWBell was an early adaptor of additive manufacturing technologies for functional prototyping and today, has 20 years' experience in manufacturing investment castings via the additive manufacturing route using expendable patterns. An overview of the progress of the company's strategy for utilizing additive manufacturing including key learnings will be presented. The additive process via SLA patterns will be compared and contrasted with conventional investment casting via the lost wax route.

Selective Laser Melting of Zr-based Bulk Metallic Glass Composites with Nb Additon

L. Deng[1], S.H. Wang[2], L. Zhang[3], A. Funk[1], S. Pauly[1]

[1]Institute for Complex Materials, IFW Dresden, Helmholtzstraße 20, Dresden, D-01069, Germany;

[2]School of Mechanical, Electrical & Information Engineering, Shandong University (Weihai), Wenhua Xilu 180, Weihai, 264209, PR China;
[3]Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Science, 72 Wenhua Road, Shenyang, 110016, PR China.
e: l.deng@ifw-dresden.de

Selective laser melting (SLM) was applied to fabricate relatively dense $Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$ with with 2 wt. % and 10 wt. % Nb bulk metallic glass composites from mixtures of $Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$ and Nb powders. Elements diffusion happened during SLM process. We introduced micro-hardness map to show the homogeneity of the samples before and after adding Nb particles. The µ-CT reconstruction and pair distribution function (PDF) were carried out to analyse the distribution of Nb particles, which is helpful to design the material in the future work. The compressive strength decreased after adding 10 wt. % Nb. All the specimens showed no plasticity upon yielding. This work contributes to better understanding the element diffusion and the formation of microstructure during preparing bulk metallic composites by SLM.

Investigation on heat treatment induced microstructural and mechanical behavior of SLM processed AlSi10Mg

S.J. Shen, Y. Dai, S.Q. Shi, N. Kang, X. Lin and W.D. Huang
School of Materials Science and Engineering
The Northwestern Polytechnical University
E-mail: juanss@nwpu.edu.cn

Given to the high specific strength and wear resistance, AlSi10Mg alloy is widely used in aerospace, automotive and marine industry. Laser additive manufacturing is one of the most innovative manufacturing technologies, which can produce complex components while ensuring good forming quality. In this work, the nucleation and growth mechanism of the eutectic structure in the as-deposited dense AlSi10Mg is special investigated during post heat treatment. Both the microstructure and mechanical properties are characterized with novel attention on texture analysis. The microstructural analysis indicates that the as-deposited structure consists mainly of columnar α-Al dendrites growing along the deposition direction and Al-Si eutectic crystals distributed in the dendrites. Moreover, the morphology of the eutectic Si in the as-deposited state is fibrous. As the annealing temperature is raised from 200 °C to 400 °C, supersaturated Si dissolved in the Al matrix is continuously precipitated, and the precipitated Si continuously aggregates and grows. The microhardness of the as-deposited sample reaches about 130 HV, the tensile strength is 380 MPa, and the elongation is 5%. After annealing treatment, the solid solution strengthening is reduced, resulting in a decrease in tensile strength and yield strength compared to the deposited state, but the elongation is improved.

Keyword : Selective laser melting; Heat treatment; AlSi10Mg; Microstructure; tensile properties.

Additive Manufacturing of Low Alloy Steels

Sri Lathabai

Metal Industries, CSIRO Manufacturing, Clayton, Victoria, Australia

Additive Manufacturing (AM) is finding increasing applications in the aerospace and biomedical industries, where advantages offered by the technology have justified the current higher production costs. As a result, AM processes have been widely developed for materials used in these industries, such as Ti-6Al-4V and other Ti-based alloys and Ni-based alloys including Inconel 625 and 718. Although steel alloys constitute the most extensively used materials in a variety of industrial applications, the application of AM to these materials has been limited to date partly because traditional manufacturing methods have worked efficiently in their fabrication. Low cost relative to other metals and alloys used in AM, easy availability in powder form and non-reactive nature are factors which suggest that this class of materials will find increasing application as materials for AM in the next few years. this paper we examine the applicability of Electron Beam Melting to 16MnCr5, a low alloy steel with case hardening capabilities, which finds use in the automotive industry in the manufacture of drivetrain parts and gears. Process parameters that result in ~99.5% theoretical density have been determined. The resulting microstructures and mechanical properties are presented.

Structural integrity assessment of AM parts: basic concepts, applications, recent developments.

S. Beretta
Politecnico di Milano, Dipartimento di Meccanica

Abstract

Despite the disruptive benefits of Additive Manufacturing (AM), the application of this technology for safety-critical structural parts in aerospace is still far to be achieved and standardised. The necessity to comply to very strict reliability requirements is hindering this final step because of the large scatter and low re- producibility always associated to AM, especially in terms of fatigue strength.

In this regards, manufacturing defects are the most important and complex issue, but several other sources of variability have an effect as well. The AM community and the main aerospace industries involved are starting to agree that damage-tolerant approaches are necessary and that probabilistic methods are best-suited to obtain reliable but not over-constrained assessments.

In this paper the basic concepts of 'defect tolerant design' and its application will be briefly exposed, together with the probabilistic concepts of 'extreme value statistics' associated to defect sampling and the assessment of a material volume. The latest developments in terms of a novel computational framework for the probabilistic assessment and the the analysis of 'as-built' surfaces will then be discussed.

Surface Enhancement of AM Stainless Steel 316L by Abrasive Machining

1,2-AmirMahyar Khorasani, 2,1-Ian Gibson, 3-AmirHossein Ghasemi, Martin, Martin Leary4,5,6
a.khorasani@deakin.edu.au, i.gibson@utwente.nl, ah.ghasemi@grad.kashanu.ac.ir
1-School of Engineering, Deakin University, Waurn Ponds, Victoria, Australia
2- Fraunhofer Centre for Complex System Engineering, Department of Design, Production and Management, University of Twente, Enschede, The Netherlands
3- Faculty of Engineering, University of Kashan, Ravandi Bolivar, Kashan, Iran
4: RMIT Centre for Additive Manufacturing
School of Aerospace, Mechanical and Manufacturing Engineering
RMIT University, Melbourne, Australia
5: ARC Training Centre in Additive Biomanufacturing,
6: ARC Training Centre for Lightweight Automotive Structures,
RMIT University, Mill Park, 3082, Australia.

Abstract

Poor surface finish is a primary challenge to the commercial implementation of Additive Manufacturing (AM). To solve this problem, various material removal processes have been proposed such as: laser polishing, electron beam machining, hybrid work-stations, surface grinding and traditional subtractive machining; however these methods provide sub-optimal outcomes for the complex geometry enabled by AM. Abrasive Barrel Finishing (ABF) and Wet Abrasive Barrel Finishing (WABF) can provide an effective surface finishing solution method that is compatible with the geometric complexity of AM components. ABF and WABF are commercially robust processes and can economically process multiple components to polishing cavities and intricate internal geometry. Despite these opportunities, insufficient research data exists to support the commercial implementation of WABF as a formal AM surface finishing process. To overcome this deficiency, this research documents an the experimental application of WABF to polish Stainless Steel (SS) 316L, printed by Selective Laser Melting (SLM). To assess the homogeneity of the abrasive process, surface roughness was quantified in a directions parallel, vertical and at 45^0 to the laser scan direction. A Taguchi L8 experiment was devised to assess the influence of WABF parameters including rotational speed, media size and running time on the measured surface roughness. This experiment confirms that surface roughness has a non-linear correlation with increasing the rotational speed, and that enhanced surface roughness is achieved with larger media size. An important observation for commercial implementation is that increasing process provides an insignificant reduction in surface quality, implying that for commercial applications, high-throughput can be achieved without compromising quality. These experiments confirm that WABF processing improved the surface roughness for parallel, vertical and 45^0 surfaces by 62.30%, 56.33% and 56.08% respectively. This outcomes confirms the benefit of WABF for enhanced AM surface finish, and formally documents the process parameters required to achieve these outcomes in a commercial setting.

Mechanistic Models of Powder Bed Fusion and directed Energy Deposition Processes

T. DebRoy
Department of Materials Science and Engineering
The Pennsylvania State University, University Park, PA 16802, USA
debroy@psu.edu

There are three compelling reasons why the optimization of part quality in additive manufacturing (AM) cannot follow the usual trial and error testing adapted in welding: (a) building parts is much slower, (b) equipment and feedstock are orders of magnitude more expensive and (c) cooling rates and solidification parameters are strikingly sensitive to the selection of AM variants and process variables. Building and validating mechanistic models based on the numerical solution of the equations of conservation of mass, momentum and energy can provide a viable path to optimize microstructure and properties. This approach can reduce the number of expensive and time-consuming part testing and qualification, and compute the causative variables that affect microstructure, properties and defects. This presentation will discuss how heat transfer and fluid flow calculations for powder bed fusion and directed energy deposition processes, when adequately validated, can provide insight about the evolution of solidification structure, microstructure and common defects. In particular, the ability of mechanistic models in evaluating features of solidification structure, microstructure, lack of fusion defects and residual stresses and distortion will be examined. The application of these models to understand printability of different alloys will also be discussed.

$MoSi_2$ based composites by selective laser melting

Tatevik Minasyan[1], Le Liu[1], Sofiya Aydinyan[1], Irina Hussainova[1,2]
[1]*Tallinn University of Technology, Ehitajate tee 5, Tallinn, 19086 Estonia*
[2]*ITMO University, Kronverkskiy 49, St. Petersburg, 197101 Russian Federation*
tatevik.minasyan@taltech.ee

Selective laser melting (SLM) is a captivating technique allowing tailorable complex configurations to be manufactured with a minimal wastage. This is applicable to the direct production of functional components. The consolidation of high temperature ceramics has gained increasing research interest spurred by industrial requirements to produce near-full-dense parts. The compaction of $MoSi_2$ based composites by SLM can be achieved via combination of $MoSi_2$ possessing excellent mechanical properties, and metals/metalloids having suitable laser absorptivity and ductility.
In this work we report the consolidation of $MoSi_2$-metal/metalloid composite powders by SLM. The $MoSi_2$-metal/metalloid shapes with tailored geometry and mechanical properties and up to 98% relative density were produced using in combination with carefully designed powder precursors and optimized process parameters.

The feasibility study of fabricating $AlCoCrFeNi_{2.1}$ eutectic high entropy alloy using powder arc additive manufacturing

Bosheng Dong
University of Wollongong

Abstract

High entropy alloys (HEAs) have gained significant attention from researchers since they were first published by Yeh et. al in 2004 owing to their unique microstructure and promising properties. In previous research, the dominated fabrication methods of HEAs mainly relay on conventional vacuum arc melting and casting. However, the disadvantage of typical casting microstructure, columnar dendrite and serious segregation, causes serious deterioration to mechanical properties. Powder arc additive manufacturing (PAAM) having a high level of controlling local forming process and the rapid cooling rate which can reduce the segregation of material efficiently, is considered as a potential process to fabricated HEAs. Compared with laser and electron beam additive manufacturing, PAAM with higher heat input can easily produce three-dimensional metal parts with full density and highly complex shapes. In our proposed research, PAAM technology will be used to fabricate $AlCoCrFeNi_{2.1}$ eutectic HEA (EHEA). It has been found that the $AlCoCrFeNi_{2.1}$ samples show face-centered cubic (FCC)($L1_2$)/body-centered-cubic (BCC)(B2) modulated lamellar structures at the middle part of build-up wall and a remarkable combination of ultimate tensile strength (720 MPA) and ductility (31%). In general, the results have demonstrated that the PAAM process is capable of producing crack-free HEA components.

Finite Element Modeling and Ultrasound Characterization of 3D-Printed Polycarbonate-Acrylonitrile Butadiene Styrene (PC-ABS) for Aerospace Applications

With increasing practical applications of 3D-printing, structural strength and integrity of 3D-printed parts and structures have since become a major concern, especially in the case where nominal bulk properties are assumed in the design calculations and validations since 3D-printed materials are usually substantially inferior in material properties as compared with their bulk counterparts. In this paper, we present an experimental characterization methodology, finite element simulations, as well correlation studies of 3D-printed polycarbonate-acrylonitrile butadiene styrene (PC-ABS). The effect of raster angle and orientations on the elastic properties of the Fused Deposition Modelling (FDM) printed PC-ABS material is investigated. The orthotropic elastic properties of PC-ABS material were determined by conducting ultrasonic testing, which is a non-destructive test method that allows one to deduce all the anisotropic elastic constants from the bulk density and the velocities of shear and longitudinal ultrasound wave propagating along different directions. Conventional tensile tests were also carried out to validate the ultrasonic tests, and these were generally in good agreement, with less than 10% deviations. Next numerical verification was by comparing numerical finite element simulation results (using properties from ultrasonic testing) with experimental four-point bending test, where excellent correspondence between the experimental and numerical data was observed. Further, scanning electron microscopes were utilized to analyze the fracture surface to understand the effects of the raster angles and orientations on the fracture behaviour and the microstructure of the FDM printed PC-ABS. These modeling and characterizations become important in the designs of these materials for important aerospace applications.

On the reliability of metallic alloys processed by additive manufacturing

T. Niendorf
Institute of Materials Engineering
University of Kassel, Germany
E-mail: niendorf@uni-kassel.de

Metal additive manufacturing (AM) has been in focus of academia and industry for several years. Due to increased productivity of the systems employed, serial production as well as manufacturing of large components at reasonable cost are feasible now. For near net-shape components mostly processes employing a powder bed are used, i.e. selective laser melting (SLM) and selective electron beam melting (EBM). For both processes in principle any metallic alloy can be applied, however, most studies report on a given number of widely used materials, i.e. stainless steel 316L, Ti-6Al-4V, Al-Si-base alloys and Ni-base superalloys such as Inconel 718. For most of these alloys solid process-microstructure relationships are established. Furthermore, evolution of microstructure and mechanical properties upon post treatment, studied under monotonic loading, have been reported numerously such that a deep knowledge allowing for monotonic strength optimization is available.

However, properties under complex in-service loading conditions contemplating residual stresses, surface conditions, fatigue strength, crack growth, creep as well as combined loadings have been only rarely addressed so far. Microstructure evolution imposed by rapid solidification and intrinsic heat treatment, however, leads to unique microstructural conditions severely affecting the alloy performance, especially under loading scenarios detailed before. For safe and reliable use of AM components in the automotive, aerospace, biomedical and other sectors, thus, the currently prevailing research gap has to be tackled. The paper presented will highlight the most important microstructural features being the basis for the performance and, thus, reliability and integrity of AM components processed by SLM and EBM. Moreover, pathways for adequate post treatments and alloy development for AM will be drawn.

Development of novel ultra-high strength steels for selective laser melting

Timothy Murray[1], Christopher Hutchinson[1]

[1] Department of Materials Science and Engineering, Monash University, Clayton, 3800, Australia

e: timothy.murray@monash.edu

As the additive manufacturing (AM) industry moves from prototyping to serial production there is a need for new materials. In steels there are only a handful of alloys that are commonly printed. Maraging steels are one of these, which have a very low carbon content and are known for their ultra-high strength, reasonable fracture toughness and good weldability.

AISI 18-Ni 300/ MS1 maraging steel, is the most widely reported ultra-high strength steel to be produced by SLM. It achieves a high yield strengths in excess of 2 GPa, but is relatively expensive and an instability in the melt pool has also been reported. This work seeks to develop new types of maraging steels that are designed for AM and more specifically to selective laser melting (SLM). With an aim to achieve good processability and a low cost material using commodity elements.

Different strengthening precipitates have been explored, along with the formation of either a δ-ferrite or martensite BCC matrix. The formation of cracks will be discussed along with microstructural and mechanical characterisation as a function of composition. Providing new insights and design guidelines for precipitation strengthened ultra-high strength steels produced by SLM.

Titanium - Titanium Carbide graded insitu composites produced via laser engineered net shape processing.

JianSheng Wang[1], Juan Pablo Escobedo[1], Evgeny Morozov[1], Daniel East[2]
[1]*University of New South Wales, Canberra, 2610, Australia;*
[2]*CSIRO Manufacturing, Clayton, 3169, Australia;* ...
e: Daniel.east@csiro.au

Titanium – Titanium Carbide in-situ composites have been produced via Laser Engineered Net Shaping (LENS). A Nickle-coated graphite powder was added during manufacturing to the titanium melt pool. By adding carbide particles the morphology of the TiC precipitates is dendritic in nature compared to the spherical morphology that typically results when TiC particles are used. Furthermore, graded composite structures can be manufactured by controlling the rate at which the graphite powder is added to the mix. This process allows to manufacture materials with a smooth gradient in microstructure and mechanical properties. Therefore, materials can be microstructurally designed and additively manufactured that display superior performance when compared to specimens with step changes in composition. In this presentation the change in microstructure and mechanical properties that occurs through the addition of graphite particles at different rates to titanium will be presented.

Tomography Driven Diffraction novel adaptation of the method for additive manufacturing developed at ANSTO

A.M. Paradowska*, U. Garbe, M. Reid,
Australian Nuclear Science and Technology Organisation, Lucas Heights, NSW 2232, Australia

*E-mail: anna.paradowska@ansto.gov.au

Abstract
Two neutron instruments: KOWARI and DINGO at The Australian Nuclear Science and Technology Organisation (ANSTO) at Lucas Heights, are vital non-destructive characterisation tools for modern advance manufacturing, engineering and life extension. The primary function of the KOWARI instrument is the determination of residual stresses and texture within the interior of bulk engineering components. DINGO is a neutron radiography and imaging beamline used to assessing defects and dimensional tolerance of internal features engineering components well suited for thick and complex's metallic and composite components.

Using neutron tomography information to guide diffraction measurements is a relatively new concept known as Tomography Driven Diffraction that enables investigation of objects with complex internal geometry or compositional variation. The ANSTO team developed the procedure for residual stress measurement of complex's shape additively manufactured components that allows effective quick measurements with high resolution at critical locations. The procedure allows the measurement to be taken in the areas were principal directions are known, as well as at the location where full tensor analysis are required.

Keywords: Tomography Driven Diffraction, Additive manufacturing, Residual stress, Neutron diffraction, Neutron imaging.

The current study sheds light on variant selection and microstructure evolution induced by stress-accommodation and self-accommodation in additively manufactured Ti-6Al-4V via electron microscopy and ABAQUS simulations and in terms of the shape strain of martensite transformation. The pressure stress exists in the deposition direction and promotes specific variants with more frequency. In addition, primary and secondary martensite plates cluster into the hash sign morphology and triangular morphology, respectively. These two morphologies can accommodate the shear strain of the shape strain to different degrees. The thermal cycles make a difference on these microstructure evolution.

Stress Corrosion Cracking of 316L stainless steel produced by Selective Laser Melting

Victor Cruz[1,2], Nick Birbilis[1,3], Sebastian Thomas[1,2]

[1]*Department of Materials Science and Engineeriong, Monash University, Melbourne, VIC 3800, Australia*
[2]*Woodside Innovation Centre, Monash University, Melbourne, VIC 3800, Australia*
[3]*College of Engineering and Computer Science, Australian National University, Canberra, ACT 2601, Australia*
e: victor.cruzdefaria1@monash.edu

The ability to produce complex geometries of stainless steel, in net-shape, is a key feature of Selective Laser Melting (SLM). Austenitic stainless steel (SS) is corrosion-resistant alloy, widely utilised in numerous industrial applications. Although the study of stainless steels produced by SLM has been expanding recently, the numerous facets of their attendant corrosion characteristics have not yet been clarified – in particular, their environmentally assisted cracking. Herein, stress corrosion cracking behaviour of SS 316L produced by SLM was investigated. Slow strain rate test was employed in order to compare wrought, as-built (i.e. as SLM'ed), and, machined SLM specimens. A quantitative analysis was undertaken, based on reduction in plasticity and cross-sectional area attained in air and $FeCl_3$ conditions at room temperature. Furthermore, fractography was carried out using scanning electron microscopy, in order to visualise the cracking propagation pathway and seek to develop an understanding of the stress-corrosion mechanism.

Microscale plastic deformation behavior of porous titanium alloys by additive manufacturing

Hao Wang
Institute of Metal Research, Chinese Academy of Sciences, 110016 Shenyang, China
haowang@imr.ac.cn

Additive manufactured titanium alloys with porous structure exhibit a combination of superior properties, e.g., low density/modulus, high strength/ductility, compared with cast or wrought titanium alloys. These properties have both geometrical and mechanical relevance to the 3D-printed porous cellular structure. In the present work, the plastic deformation behavior of pure titanium with the porous structure is investigated with multi-scale simulation/characterization methods. Macro-scale simulation and characterization indicate significant strain concentration at the cellular corners. Molecular dynamics simulations reveal that, under such stress/strain concentration, deformation twinning is activated which contributes to both strength and ductility. In particular, as the ligament diameter of the porous cellular structure reaches several nanometers, surface dislocation nucleation becomes dominant and further enhance the mechanical property. High-resolution transmission electron microscopy observations confirm the simulation results.

Consistently Achieving Full Strength Metal 3D Printing Production Parts

Presenting Author
Downing, Warwick
RAM3D
warwick@ram3d.co.nz

Metal 3D printing is gaining traction, not only as a technology for prototyping but also production. As a service bureau, production parts account for 80% of throughput. The key to successful production parts is a close collaboration not only during the design phase to ensure the best part is developed, but also in the production phase to ensure that the parts continually meet specification.

Metal 3D printing is repeatable, however, unlike other technologies that mean once it is set up it will always run the same. The process requires constant monitoring where quality control is not just about the shape of the parts but also careful monitoring of all the variables to ensure they remain constant.

This talk will give look at a number of case studies of production parts and how they sit in the competitive market. It will also touch on the processing parameters that a commercial service provider must continually monitor in order to create parts that are only the right shape but maintain the appropriate mechanical properties.

Warwick Downing has been involved in metal 3D printing for over 10 years and together with the team at RAM3D has developed a depth of knowledge of the technology and the requirements to repeatedly deliver for the aerospace, defence, marine, consumer and industrial markets.

New AM Alloys and Metallurgical Issues for Selective Laser Melting(SLM)

Prof Xinhua Wu

Monash Centre for Additive Manufacturing (MCAM),

Monash University, Melbourne, Australia

Email: Xinhua.wu@monash.edu

This presentation highlights the SLM research activities in Monash Centre for Additive Manufacturing, in particular on process optimisation and post heat treatment development in order to achieve required mechanical properties for Ti, Ni and Al alloys. Different materials have different issues in the SLM process, due to their metallurgical and crystallographic differences. Whilst elimination of cracking and retaining high temperature properties and stability are critical for SLM Ni alloys, optimisation of post heat treatment becomes more significant for Al alloys as defined by the nature of the sensitive response of precipitates of Al alloys during heat treatment. The optimum post heat treatment of SLM'd Ti64 has found to be totally associated with the completion of martensitic transformation where ductility of 18% and yield strength of > 900MPa can be easily achieved. Extensive study has been carried out in understanding the evolution of microstructure during solidification and post heat treatment and their influence on tensile and fatigue properties. The development of a new high strength and high temperature Al alloy for SLM will also be presented, in particular its design philosophy and its outstanding properties.

The microstructures and mechanical properties of TiB_2 reinforced 2024Al composite fabricated by Laser solid forming additive manufacturing

Xiaoli Wen[1,2]*, Xin Lin[1,2], Qingzheng Wang[1,2], Nan Kang[1,2], Shang Sui[1,2], Haiou Yang[1,2], Weidong Huang[1,2]

[1] *State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, 127 Youyixilu, Xi'an, Shaanxi 710072, PR China*

[2] *Key Laboratory of Metal High Performance Additive Manufacturing and Innovative Design, MIIT China, Northwestern Polytechnical University, 127 Youyixilu, Xi'an,Shaanxi 710072, PR China*

E-mail address: wenxioli@nwpu.edu.cn (Xiaoli. Wen).

Abstract

The 2024Al alloy and 3%TiB_2 particle reinforced 2024Al composite were fabricated using laser solid forming (LSF). The effect of TiB_2 particle on the microstructures and mechanical properties were studied. Different from the LSF processed 2024Al with a large columnar grain and apparent preferential growth orientation, TiB2 reinforced 2024Al composite presents texture-less structure, consisting of the dendrite and fine equiaxed structures. Some TiB_2 particles distribute within the Al matrix, others distribute along the grain boundaries and intertwine with the Al_2Cu phase. TEM was used to analyze the TiB_2 and Al_2Cu precipitates in Al matrix. The Al_2Cu phase exhibits two morphologies, one is square block structure with the size about 300nm, and the other is the rod-like structure. The wide of the rod-like Al2Cu phase is less 50nm. Moreover, the TiB_2 reinforced 2024Al sample exhibits 284MPa high tensile strength, 163MPa yield strength, 108.5HV microhardness, and 18.7% excellent elongation. The incorporation of TiB_2 gives rise to significant grain refinement. The fine grains and the strengthening phases are the important reasons for the improvement of mechanical properties.

Selective electron beam melting (SEBM) of Ti-6Al-4V lattice medical implants: clinical and research opportunities

X.Z.Zhang[1,2,3], H.P.Tang[2], M.Leary[3], M.Qian[2,3]

[1]School of Materials Science, Northeastern University, Shenyang 110819, China
[2]State Key Laboratory of Porous Metal Materials,
Northwest Institute for Nonferrous Metal Research, Xi'an 710016, China
[3]Centre for Additive Manufacturing, School of Engineering,
RMIT University, Melbourne, VIC 3000, Australia
E-mail address: xuezhe.zhang@qq.com (X.Z. Zhang)

Abstract

Additively manufactured lattice structures display unique mechanical and biological properties by virtue of their engineered structure. These attributes enable the innovative design of patient-specific medical implants which (i) are conformal to the intended surgical geometry, (ii) mimic the mechanical properties of natural bone, and (iii) provide superior biological interaction than traditional implants. Selective electron beam melting (SEBM) is an established powder-bed fusion based metal additive manufacturing (AM) technology that enables the design and fabrication of a variety of novel intricate lattice structures. This talk will focus on the technical and clinical characteristics of SEBM fabricated Ti-6Al-4V lattice structures, including: (i) the structure of human bone and summary of reported mechanical properties; (ii) the theoretical and measured mechanical properties of Ti-6Al-4V lattice structures of various designs; (iii) the as-built microstructure of SEBM Ti-6Al-4V lattice structures and the effect of heat treatment; and (iv) the lattice manufacturability and associated geometric errors.

Keywords: Additive manufacture, Ti-6Al-4V, SEBM, lattice structure, medical implants, biomimetic.

Laser welding of electron beam melted Ti-6Al-4V to wrought Ti-6Al-4V: effect of welding angle on microstructure and mechanical properties

Y.Y. Sun[1], P. Wang[1*], S.L. Lu[1], L.Q. Li[2], M. L. S. Nai[1], J. Wei[1]
[1]Singapore Institute of Manufacturing Technology, 73 Nanyang Drive, 638075, Singapore
[2]State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, 92 West Dazhi Street, Harbin 150001, PR China

Electron beam melting (EBM) is an established powder-bed additive manufacturing process for small-to-medium-sized components of Ti-6Al-4V. For further employing EBM on fabricating large-scale components, an effort has been made by joining EBM-built Ti-6Al-4V plates to wrought counterparts using laser welding, and the welding angles between EBM build direction and weld bead were chosen as 0^o, 30^o and 45^o. The influence of the welding angles on the microstructure, microhardness of base metals, fusion zone, and heat-affected zones, as well as the macro tensile test have been characterized. The microhardness of each zone is determined by the local microstructure, and the macro tensile properties largely depend on the EBM base metal due to the internal defects generated during the EBM process. The effect of welding angles on tensile strengths is not significant, while the elongation drops from 9.4% to 5.8% as the welding angle increases. The mechanism of stress during uniaxial tension on EBM base metal is investigated based on the stress state of columnar grains and the internal defects.

The Electrochemical Responses of Ti-6Al-4V Alloy Manufactured by Seven Different Processes including SEBM in Hank's Solution at 37°C

Y.Y. Sun[1], S. Gulizia[2], C.H. Oh[2], D. Fraser[2], M. Leary[1], M. Qian[1]

[1]*RMIT University, School of Engineering, Centre for Additive Manufacturing, Melbourne, VIC 3000, Australia*

[2] *Commonwealth Scientific and Industrial Research Organisation (CSIRO), Manufacturing Flagship, Clayton, Melbourne, VIC 3168, Australia*

Contact: M. Qian (ma.qian@rmit.edu.au)

This work presents the results for the effect of different manufacturing methods on the electrochemical responses of Ti-6Al-4V alloy in Hank's solution at 37°C. The manufacturing methods included SEBM, SEBM + HIP, SLM, SLM + HIP, casting, spark plasma sintering (SPS) and mill-annealing. The different manufacturing processes resulted in retainment of a wide range of microstructure with varying spatial dimensions and morphologies of elongated/equiaxed grains/phases, as a result of which different electrochemical responses were observed. The order of the corrosion resistance of samples is: SLM > Mill-annealed > SLM + HIP > SEBM > SEBM + HIP ≫ Cast ≫ SPS. The point defect model and element partitioning were effectively applied to explain these differences.

Title Residual stress predicting in selective laser melting of high strength steel considering solid-state phase transformation

Yong Chen, Ying Wu, Hui Chen*, JingQing Chen, Jun Xiong, Yi Shuai Jiang, Wei Yi
School of Materials Science and Engineering, Southwest Jiaotong University, Chengdu, 610031, China
e:yognchen@my.swjtu.edu.cn

The complex metallurgical processes of high strength steel makes it difficult to accurately predict the residual stress in laser additive manufacturing. In order to solve this problem, a 3D finite-element thermo-mechanical model considering solid-state phase transformation (SSPT) is developed to predict temperature field and residual stress field for the multi-track multi-layer selective laser melting process of AISI H13 tool steel. The temperature cycle and thermal behavior are analyzed, and the effects of mechanical properties changes, volume change and transformation induced plasticity (TRIP) on residual stress are discussed in detail. The results show that the phase transformation has a significant effect on the evolution of residual stress, considering the influence of phase transformation can effectively reduce tensile residual stress and increase compressive residual stress. The residual stress component in the scanning direction is larger than the other two stress components. Compared with the experimental data, taking phase transformation into consideration can assure a better accuracy in predicting the residual stresses.

Selective Laser Melting of Aluminum with TiC Heterogeneous Nucleation Site Particles

Yoshimi Watanabe[1], Hiroyuki Sugano[1], Tadachika Chiba[1], Hisashi Sato[1], Naoko Sato[2] and Shizuka Nakano[2]
[1]*Nagoya Institute of Technology, Nagoya, 466-8555, Japan;*
[2]*National Institute of Advanced Industrial S c ience and Technology (AIST), Tsukuba, 305-8564, Japan; Tsukuba, 305-8564, Japan;* ...
e: yoshimi@nitech.ac.jp

Grain refinement plays a vital role in cast and wrought aluminum alloys. Al–Ti–B alloys containing Al_3Ti and TiB_2 particles are used as grain refiners in the casting of aluminum alloys, since Al_3Ti and TiB_2 show a good lattice registry with a solidified aluminum. It is also known that TiC particles can become favorable heterogeneous nucleation sites for the aluminum cast. In this study, effects of TiC heterogeneous nucleation site particles on microstructure of selective laser melted (SLMed) aluminum samples were studied. SLM experiments were carried out under vacuum or Argon gas atmosphere. It is found that the addition of TiC particles decreases the grain size of SLMed aluminum samples, since the lattice matching between TiC and aluminum is good. It is also found that the hardness of SLMed aluminum samples could be increased by addition of TiC particles. It can be concluded that addition of heterogeneous nucleation site particles is one of key technologies to achieve better microstructure and higher mechanical properties for SLMed aluminum products.

This study was supported by Japan Science and Technology Agency (JST) under Industry-Academia Collaborative R&D Program "Heterogeneous Structure Control: Towards Innovative Development of Metallic Structural Materials" and by the Amada foundation.

Application of selective laser melting ferrous lattice as copper matrix composite reinforcement

Zhenhua Li*, Rui Yang, Huiyan Xu, Baoren Teng, Bo Ren
School of Materials Science and Engineering, Kunming University of Science and Technology, Kunming, 650093, China
e: lzhkust@sina.com

Ferrous lattice with different cell sizes of 5mm, 3.75mm, 2.75mm, 1.75 mm, 0.75 mm were prepared by selective laser melting. The lattices were used as reinforcements for copper matrix composites. Copper melt solidified with the lattices under pressure of squeeze casting process, and was combined with lattices to get composites. Microstructure and properties of the composites are controlled effectively using this novel method. Wear tests of the composites were investigated by pin-on-disk procedure, and the microstructure and wear morphology of samples were observed and analyzed. The results indicate that ferrous lattices and copper matrix combined properly, and the lattices performed a key role to improve and control the properties of the composites. The composite with lattice of 0.75mm cell size shows the highest hardness and best wear resistance. The hardness of it reaches 120HB, which is 1.71 times of the Cu matrix's. The wear volume loss of it is 35.4mm3, which is 58% less than that of the Cu matrix. The wear mechanism of the composite is abrasive wear, which is different from the adhesive wear of the Cu matrix, due to reinforcement of the lattice.

The Strategy for Fabricating Wire Structure Parts Using Robotic Wire and Arc Based Additive Manufacturing

Ziping Yu[1], Huijun Li[1], Zengxi Pan[1]
[1]*University of Wollongong, Wollongong, 2522, Australia;*
Zy755@uowmail.edu.au

Wire arc additive manufacturing (WAAM) is the advanced technology which deposits materials layer by layer with the low buy-to-fly ratio and rapid prototyping. Robotic WAAM brings significant advantages for producing large-size metallic solid structures or thin-walled structure, and it is also gradually interested in the manufacture of wire print structures that have been used to make everything from fine decoration to home furnishings to large skeleton objects, making it an integral part of artists and architects.

This paper develops the manufacturing strategy for wire structure part. It starts with the establishment of the bead modelling, followed by investigating the acceptable selection boundary of various welding parameters. Then a second-degree regression model is established to predict the bead geometry from optimal welding parameters input accurately. A control system that uses the voltage variation during the welding process to adjust the height increase and reslice layer height of the wire structure is also established. Based on the above research, this paper developed the three-dimensional collision-free path planning algorithm for various branches and intersections of wire print. Finally, two case studies are presented to demonstrate this manufacturing strategy is efficiency and precision in processing wire print.