

**SFF SYMPOSIUM MANUSCRIPTS APPEARING IN THE  
MARCH 2018 ISSUE OF *JOM***

Ten materials-related manuscripts from the 2017 SFF Symposium were selected by the Organizing Committee for publication in the TMS journal *JOM* (March 2018). Papers may appear in only one publication, or they must be substantially revised and improved for submission to *JOM*, or they may be split into two articles. The titles and abstracts appear here so readers will know that the papers have appeared in print.

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**The following authors chose to publish their manuscript only in *JOM*, so their papers do not appear in this proceedings.**

**Qualification of DMLS Ti6Al4V (ELI) Alloy for Biomedical Applications**

Igor Yadroitsev<sup>1</sup>; P. Krakhmalev<sup>2</sup>; I. Yadroitsava<sup>1</sup>; A. Du Plessis<sup>3</sup>;

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Ti6Al4V (ELI) samples were manufactured by Direct Metal Laser Sintering (DMLS) in vertical and horizontal directions and subjected to various heat treatment. Detailed analysis of porosity, microstructure, residual stress, tensile properties, fatigue and fractured surfaces was done based on computed tomography scans, scanning electron microscope and X-ray diffraction methods. Types of fractures and tensile fracture mechanisms in DMLS Ti6Al4V (ELI) alloy were studied at pre-strained samples. Peculiarities of the microstructure and corresponding mechanical properties were compared with standard specification for conventional Ti6Al4V alloy (grade 5 and grade 23) for surgical implant applications. Conclusions regarding mechanical properties and heat treatment of DMLS Ti6Al4V (ELI) for biomedical applications were made.

**Using Laser Ultrasonic Testing to Detect Sub-surface Defects in Metal Laser Powder Bed Fusion Components**

Sarah Everton<sup>1</sup>; Phill Dickens<sup>1</sup>; Chris Tuck<sup>1</sup>; Ben Dutton<sup>2</sup>;

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Laser powder bed fusion offers many advantages over conventional manufacturing methods, such as the integration of multiple parts which can result in significant weight-savings. The increased design freedom that layerwise manufacture allows has also been seen to enhance component performance at little or no added cost. However, in order for such benefits to be realised, the material quality must first be assured. Laser ultrasonic testing is a non-contact inspection technique which has been proposed as suitable for in-situ monitoring of metal additive manufacturing processes. This paper explores the current capability of this technique to detect manufactured and seeded sub-surface defects in Ti-6Al-4V samples. The results are compared with x-ray computed tomography reconstructions and validated using destructive testing methods.

### **Selective Laser Melting of Pure Copper**

Toshi-Taka Ikeshoji<sup>1</sup>; Kazuya Nakamura<sup>2</sup>; Makiko Yonehara<sup>1</sup>; Ken Imai<sup>1</sup>; Hideki Kyogoku<sup>1</sup>;  
<sup>1</sup>Kindai University; <sup>2</sup>TRAFAM

For the selective laser melting for 99.9% pure copper powder, the suitable building parameters was searched at relatively high laser power, 800 W with variation in hatch pitch, 0.025 – 0.12 mm. The highest relative density of the built material was 99.6% for the hatch pitch of 0.10 mm. The building conditions was also searched using the transient heat analysis by FEM with liquidation and solidification of powder. The estimated melt pool length and width was comparable with the values obtained by the observation through thermoviewer. The tendency of melt pool width values width to the hatch pitch met with the experiment.

### **Effect of Bed Temperature on the on the Laser Energy Required to Sinter Copper Nanoparticles**

Nilabh Roy<sup>1</sup>; Obehi Dibua<sup>1</sup>; Michael Cullinan<sup>1</sup>; <sup>1</sup>The University of Texas at Austin

Copper nanoparticles (NPs) due to their high electrical conductivity, low cost, and easy availability provide an excellent alternative to other metal NPs such as gold, silver and aluminum in applications ranging from direct printing of conductive patterns on metal and flexible substrates for printed electronics applications to making three dimensional freeform structures for interconnect fabrication for chip packaging applications. Lack of research on identification of optimum sintering parameters such as fluence/irradiance requirements for sintering of Cu NPs serves as the primary motivation for this study. This paper focuses on the identification of good sintering irradiance window for Cu NPs on aluminum substrate using Continuous wave (CW) laser. The study also includes the comparison of CW laser sintering irradiance windows obtained with substrates at different initial temperatures. The irradiance requirements for sintering of Cu NPs with substrate at 150-200 °C were found to be 5-17times smaller than the irradiance requirements for sintering with substrate at room temperature. These findings have also been compared against the results obtained with a nanosecond (ns) laser and a femtosecond (fs) laser.

### **Long-Term Effects of Temperature Exposure on SLM 304L Stainless Steel**

Tarak Amine<sup>1</sup>; Caitlin Kriewall<sup>1</sup>; Joseph Newkirk<sup>1</sup>; <sup>1</sup>Missouri University of Science and Technology

Austenitic stainless steel is extensively used in industries that operate at elevated temperatures. This work investigates the high temperature microstructure stability as well as the elevated temperature properties of 304L stainless steel fabricated with the selective laser melting (SLM) process. Significant microstructural changes were seen after a 400 °C aging process for as little as 25 hours. This dramatic change in the microstructure would not be expected based on the ferrite decomposition studied in conventional 304L materials. The as-built additively manufactured alloy has a much faster kinetic response to the heat treatment at 400 °C. An investigation of the structures which occur, the kinetics of the various transformations and the mechanical properties will be presented. The impact of this on the application of SLM 304L will be discussed.

## **Achieving Functionally-graded Material Composition through Bicontinuous Mesostructural Geometry in Material Extrusion Additive Manufacturing**

Brant Stoner<sup>1</sup>; Joseph Bartolai<sup>1</sup>; Dorcas Kaweesa<sup>1</sup>; Nicholas Meisel<sup>1</sup>; Timothy Simpson<sup>1</sup>;  
<sup>1</sup>Pennsylvania State University

Functionally-graded materials (FGMs) gradually change composition throughout their volume, allowing for areas of a part to be optimized for specific performance requirements. While additive manufacturing (AM) process types such as material jetting and directed energy deposition are capable of creating FGMs, design guidelines for varying the material composition in a FGM do not exist. This paper presents a novel design solution for FGMs: creating the material gradient by varying the mesostructural size and thickness of bicontinuous, multi-material geometries. By using a bicontinuous structure, such as Schoen's gyroid surface or Schwarz's P and D surfaces, each component material exists as a continuous discrete structure, which allows FGMs to be fabricated by a wider range of AM processes. The gradient is created by varying the volume fraction occupied by the surface structure inside the part volume. This paper explores the use of this technique to create FGMs with material extrusion AM. Properties of these bicontinuous structures are experimentally characterized and shown to outperform typical material extrusion FGMs.

## **Adjustment of Part Properties for an Elastomeric Laser Sintering Material:**

Andreas Wegner<sup>1</sup>; Timur Ünlü<sup>2</sup>; <sup>1</sup>University of Duisburg-Essen; <sup>2</sup>ROWAK AG

Laser sintering of polymers gets more and more importance for small series production. In most cases parts are build up using polyamide 12. However, other materials are available for laser sintering, too. Elastomeric, rubber like materials are some of those alternative materials. These enable for the production of flexible parts like e.g. sealings, flexible tubes or shoe soles. They offer high part ductility and low hardness. At the chair for manufacturing technology one of these materials was developed and commercialized by a spin-off. Aim of the presented study was to analyze the properties of this new elastomeric laser sintering material. It was found, that Shore hardness can be modified by variation of parameter settings. Therefore, the correlation between process parameters, energy input, Shore hardness and other part properties like mechanical properties were analyzed. Basing on these results suitable parameter sets were established which enable for the production of parts with different Shore hardnesses.

## **Supportability of a High-Yield-Stress Slurry in a New Stereolithography-based Ceramic Fabrication Process:**

Li He<sup>1</sup>; Xuan Song<sup>1</sup>; <sup>1</sup>University of Iowa

In recent years, ceramic fabrication using stereolithography (SLA) is gaining popularity due to relatively high accuracy and density that can be achieved in final part production. One of the main challenges in ceramic SLA is that support structures are required for building overhanging features, whereas removing these support structures without damaging the components is extremely difficult. In this research, a Suspension-Enclosing Projection-Stereolithography (SEPS) process is developed to overcome this challenge. This process uses a high-yield-stress ceramic slurry as the feedstock material and exploits the elastic force of the material to support overhanging features without the need for building additional support structures. Ceramic slurries with different solid loadings are studied to identify the rheological properties most suitable for supporting overhanging features. An analytical model of a double doctor-blade module is established to obtain uniform and thin recoating layers from a high-yield-stress slurry. Several test cases highlight the feasibility of using a high-yield-stress slurry to support overhanging features in SLA.

**Substantially Improved: Included in both *JOM* and the *SFF Symposium Proceedings*:  
Mechanical Properties and Color of TPE Parts as Function of Temperature Histories  
During Selective Laser Sintering**

C. Kummert<sup>1</sup>, S. Josupeit<sup>1</sup>, H.-J. Schmid<sup>1</sup>; <sup>1</sup>Direct Manufacturing Research Center (DMRC) and Particle Technology Group, University of Paderborn, Germany

The influence of laser sintering (SLS) parameters on PA12 part properties is well known, but research on other materials is rare. One alternative material is a thermoplastic elastomer (TPE) called PrimePart ST which is more elastic and became available recently by EOS. It shows a quite distinct SLS processing behavior. In former research, a temperature measurement system which allows temperature measurements inside the part cake, was developed at the Particle Technology Group, part of the Direct Manufacturing Research Center at the University of Paderborn. This system is applied to TPE in the present work. The temperature history at different positions within the part cake is recorded during the whole build and cooling process. Position-dependent temperature histories are directly correlated with the color and mechanical properties of built parts and is in very good agreement with artificial heat treatment in a furnace. Furthermore, it is clearly shown that the yellowish discoloration of parts in different intensities has no influence on mechanical part properties.

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**Split into Two Manuscripts:  
One part to *JOM* and one part to the *SFF Symposium Proceedings*:**

**Competing Influence of Porosity and Microstructure on the Fatigue Property of  
Laser Powder Bed Fusion Stainless Steel 316L**

Meng Zhang<sup>1</sup>, Chen-Nan Sun<sup>2</sup>, Xiang Zhang<sup>3</sup>, Phoi Chin Goh<sup>4</sup>, Jun Wei<sup>2</sup>, Hua Li<sup>1</sup>, David Hardacre<sup>4</sup>  
<sup>1</sup>Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University; <sup>2</sup>Singapore Institute of Manufacturing Technology, A\*STAR; <sup>3</sup>Faculty of Engineering & Computing, Coventry University; <sup>4</sup>Lloyd's Register Global Technology Centre

Crack initiation constitutes a large portion of the total life for parts under high cycle fatigue loading. Materials made by the laser powder bed fusion (L-PBF) process contain unavoidable process-induced porosity whose effect on the mechanical properties needs to be considered for fatigue applications. Results from this work show that not all pores in L-PBF parts promote fatigue crack initiation. The length scale of local microstructure defects, i.e. grain boundary, could be larger than the pores and in such cases they are the primary cause for crack initiation. Samples were produced in this work to demonstrate the critical defect size responsible for the transition between the porosity-driven and microstructure-driven failure modes. The competition between porosity and microstructure was also found to influence the monotonic tensile properties. For near fully dense parts, tensile strength correlates well with fatigue strength, whereas for parts containing a large amount of porosity, ductility is the more representative parameter of fatigue strength.

**SFF SYMPOSIUM MANUSCRIPTS APPEARING  
IN A FUTURE ISSUE OF *Virtual and Physical Prototyping***

Six materials-related manuscripts from the 2017 SFF Symposium were selected by the Organizing Committee for publication in Issue 1 of 2018 of the *Virtual and Physical Prototyping* journal. Papers may appear in only one publication, or they must be substantially revised and improved for submission to *Virtual and Physical Prototyping*.

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These authors chose to publish their manuscript only in *Virtual and Physical Prototyping*, so their papers do not appear in this proceedings. The titles and abstracts appear here so readers will know that the papers have appeared in print.

**Using Multi-Axis Material Extrusion to Improve Mechanical Properties through Surface Reinforcement**

Kubalak, Joseph; Wicks, Alfred; Williams, Christopher

Due to the layer stacking inherent in traditional three-axis material extrusion (ME) additive manufacturing processes, a part's mechanical strength is limited in the print direction due to weaker interlayer bond strength. Often, this requires compromise in part design through either adding material in critical areas of the part, reducing end-use loads, or forgoing ME as a manufacturing option. To address this limitation, the authors propose a multi-axis deposition technique that deposits material along a part's surface to improve mechanical performance. Specifically, the authors employ a custom 6 degree of freedom robotic arm ME system to create a surface reinforcing 'skin', similar to composite layup, in a single manufacturing process. In this paper, vertical tensile bars are fabricated through stacked XY-layers, followed by depositing material directly onto the printed surface to evaluate the effect of the skinning approach on mechanical properties. Experimental results demonstrate surface-reinforced interlayer bonds provide increased yield strength.

**Assessment of Optical Emission Analysis for In Process Monitoring of Powder Bed Fusion Additive Manufacturing**

Dunbar, Alexander; Nassar, Abdalla

Developing methods which allow real-time monitoring of Powder Bed Fusion Additive Manufacturing (PBFAM) processes is key to enabling in situ assessments of build quality (e.g. lack of fusion and porosity). Here, we investigate the use of optical emission spectroscopy and high-speed (100 kHz) measurement of select wavelength emissions, based on a line-to-continuum approach, to determine if a correlation between PBFAM process inputs, sensor outputs, and build quality exists. Using an open protocol system interfaced with a 3D Systems ProX 200 machine, sensor data was synchronized with the scanner position and the laser state during buildup of Inconel-718 components under varying powers, scan speeds, and hatch spacing parameters. Sensor measurements were then compared against post-build computed tomography scans. We show evidence that sensor data, when combined with appropriate analyses, are related to both processing conditions and build quality.

### **The Three-Prong Method: A Novel Assessment of Residual Stress in Laser Powder Bed Fusion**

Sillars, Stuart; Sutcliffe, Chris; Philo, Adam; Brown, Stephen; Sienz, Johann; Lavery, Nicholas

Residual stress is a problem for laser-powder bed fusion components, which can be reduced by appropriate build planning and post-process heat treatments. However, it is not always avoidable and can lead to build failures due to distortion, cracking or baseplate delamination. Accurate measurement of residual stress levels can be difficult due to high equipment set-up costs and long processing times. This paper introduces a simple but novel method of measuring residual stresses, utilising 3 adjoined cantilever beams. Previous methods have only included measurements in 2-dimensions, in some cases, this can cause an under-estimation of peak stress.

### **Surface Integrity of Inconel 718 by Hybrid Selective Laser Melting and Milling**

Brown, D.; Li, C.; Liu, Z.Y.; Fang, X.Y.; Guo, Y.B.

While selective laser melting (SLM) offers design freedom of metal parts with much less material consumption, there exist several limitations including high surface roughness, low dimensional accuracy, and high tensile residual stresses. To make functional parts with high form accuracy and superior surface integrity, an as-SLM part needs finishing to remove the deposited surface material. The integration of machining and SLM creates a hybrid manufacturing route to overcome the inherited limitations of SLM. However, little study has been done to characterize surface integrity of an as-SLM part followed by machining (e.g., hybrid SLM-milling). In this paper, surface integrity including surface roughness, microstructure, and microhardness have been characterized for IN718 samples processed by the hybrid process. It has been found that microhardness varies with the scan direction and the use of coolant in the subsequent milling, and surface integrity can be significantly improved by the hybrid SLM-milling route.

**These authors chose both to publish their manuscripts in both this proceedings and to publish a substantially improved paper in in *Virtual and Physical Prototyping*:**

**Infrared Thermal Imaging for Melt Pool Analysis in SLM: A Feasibility Investigation**

Cheng, Bo; Lydon, James; Cooper, Kenneth; Cole, Vernon; Northrop, Paul; Chou, Kevin

Melt pool dimension can help to relate process parameters and build part quality in selective laser melting (SLM) process. In this study, a near infrared (IR) thermal imager (about 670 nm spectral range) was employed to collect powder layer thermal signal in SLM machine using nickel-based alloy as raw powder material. Radiant temperature distribution at different build heights has been acquired and melt pool sizes have been analyzed. The major findings are as follows. (1) It is possible to estimate melt pool dimension based on the identified radiant liquidus temperature and appropriate thermal imager setting, but it is difficult to obtain true temperature. (2) At nominal process conditions of 600 mm/s beam speed and 180 W beam power for Inconel 718 powder, the melt pool has a length of about 0.36 mm and a width of about 0.21 mm. Build height seems to have little effect on melt pool dimensions.

**An Implicit Slicing Method for Additive Manufacturing Processes**

Dunbar, Alexander; Nassar, Abdalla

All additive manufacturing processes involve a distinct pre-processing stage whereby the part geometry is translated into a process specific printing plan. This plan is developed in layers or slices of the original part geometry by a set of algorithms collectively known as a slicer. Most commercial slicing programs generate tool paths explicitly, and do not consider the impact of resulting geometric part features (e.g. thin walls, small corners, round profiles) which can result in critical voids leading to part failure. Recent work into an implicit slicing algorithm allows for an infinite set of functionally-defined infill patterns to be defined. When these patterns are overlaid onto each part layer, the mechanical properties of the part and the presence undesirable voids and flaws can be reduced or eliminated. The variation of part properties is demonstrated with tensile tests of dog bone specimens with different infill patterns to determine their resulting mechanical properties.

