Preliminary Technical Program

WORKSHOP ON MECHANICAL BEHAVIOR OF ADDITIVE MANUFACTURED COMPONENTS

Sponsored by ASTM Committee E08 on Fatigue and Fracture in conjunction with the National Institute of Standards and Technology (NIST).

May 4-5, 2016
Grand Hyatt San Antonio
San Antonio, TX

Workshop Organizers: Steve Daniewicz, Mississippi State University
Nima Shamsaei, Mississippi State University
Nik Hrabe, NIST

WEDNESDAY, MAY 4, 2016
***separate registration is required for Wednesday and Thursday**

8:00 AM
Opening Remarks
Steve Daniewicz, Mississippi State University

8:15 AM
Additive Manufacturing in the Context of Structural Integrity
Michael Gorelik, FAA

8:45 AM
Effect of build orientation on axial/torsional fatigue life of laser sintered Ti-6Al-4V ELI
Matthew Di Prima, FDA

9:15 AM
Ti-6Al-4V for Orthopaedic Implants in Fatigue
Mukesh Kumar, Zimmer-Biomet

9:45 AM BREAK

10:15 AM
Fracture Mechanics and Nondestructive Evaluation Modeling to Support Rapid Qualification of Additively Manufactured Parts
Craig McClung, Southwest Research Institute (SWRI)

10:45 AM
Extreme value analysis of defects on AM parts
Steffano Beretta, Politecnico di Milano

11:15 AM
Fatigue Life Manipulation of SLM® Parts
Richard Grylls, SLM Solutions

11:45 AM LUNCH

1:15 PM
Advanced Characterization of Additively Manufactured Materials, including Synchrotron–based 3D X-rays
Anthony Rollett, Carnegie Mellon University

1:45 PM
Effects of HIP Processing on Additively Manufactured, Titanium Materials Produced Using an Electron Beam – Directed Energy Deposition Process
Hank Phelps, Lockheed Martin Aeronautics

2:15 PM
Reliability of Mechanical Behavior in Metallic Additively Manufactured Parts Used in Critical Applications
Doug Wells, NASA Marshall

2:45 PM BREAK

3:00 PM
Presentation of NEEDS and BARRIERS from pre-workshop survey
Nik Hrabe, NIST

3:30 PM
Expert Panel leads discussion of NEEDS and BARRIERS
Expert Panelists:
Bob Klein, Stryker
John Slotwinski, Johns Hopkins Applied Physics Laboratory (APL)
Gautam Gupta, 3D Systems
More TBD

4:30 PM
Entire group prioritizes NEEDS and BARRIERS

5:00 PM CLOSE 1st Day

THURSDAY, MAY 5, 2016
***separate registration is required for Wednesday and Thursday**

8:00 AM
Opening Remarks
Nik Hrabe, NIST

8:15 AM
Metal Additive Manufacturing: A Review of Mechanical Properties
John Lewandowski, Case Western University

8:45 AM
Breakout Sessions generate STRATEGIES for identified NEEDS and BARRIERS

10:00 AM BREAK

10:30 AM
Breakout Sessions prepare summaries of their discussions

11:00 AM
Breakout Sessions present summaries

11:45 AM
Closing Remarks
Steve Daniewicz, Mississippi State University

12:00 PM CLOSE Workshop

ABSTRACTS
***in chronological order**

Additive Manufacturing in the Context of Structural Integrity
Michael Gorelik, Federal Aviation Administration (FAA)

Additive Manufacturing (AM) applications are poised to rapidly expand in aviation, driven by a significant number of business and technical benefits that are extensively covered elsewhere. Due to its inherent flexibility, AM is being considered for a variety of application domains that span new parts, repairs and aftermarket. At the same time, there is a number of implementation challenges identified by multiple researchers and organizations, including complexity of manufacturing process controls, questionable applicability of conventional NDI inspection methods, lack of industry standards and design allowables, etc. These technical challenges are further exacerbated by the current lack of field experience and full-scale production experience, at least in commercial aviation applications, that may result in additional implementation risks. Analysis of historical lessons learned for introduction of new material technologies suggests that appropriate application of fracture mechanics-based damage tolerance (DT) principles can offer an effective risk mitigation mechanism against the inherent material flaws, as well as manufacturing and service-induced defects. This presentation outlines a DT framework for AM parts based on probabilistic fracture mechanics approach. The proposed methodology is discussed in the context of the “system-level” approach to structural integrity of AM components, and is compared and contrasted with established risk mitigation frameworks for other material systems, such as the use of casting factors for cast aircraft components, or probabilistic life prediction systems for powder metallurgy (PM) turbine engine components. Potential implications for regulatory guidance and certification criteria, including linkage between the DT criteria and levels of parts criticality are briefly discussed as well.

Effect of build orientation on axial/torsional fatigue life of laser sintered Ti-6Al-4V ELI

Matthew Di Prima, US Food and Drug Administration (FDA)

Additive manufacturing enables the production of very complex parts as well as products that can be easily individualized to a specific patient. This is the result of the layer-by-layer assembly inherent in additive manufacturing processes; however this same layer-by-layer assembly can lead to anisotropy in the built part. In medical devices, there is a concern that this anisotropy could lead to reduced dynamic performance of load bearing devices; especially in devices that undergo complex loading. The concern with comples loading is compounded by the use of complex porous structures and patched matched design which can complicate the effort to ensure device loading is not affected by anisotropy. Therefore, to evaluate the effect of print orientation on the fatigue life of Ti-6Al-4V ELI; axial, torsional, and axial-torsional fatigue tests per ASTM E2207 were conducted on laser sintered parts whose print orientation varied from 0, 45, and 90 degrees from axis of the test specimen. While fatigue life was the primary endpoint of the study; fracture and microstructure analysis were also performed on the test specimens to further illuminate the effect of the build orientation on fatigue performance. These findings will be pooled with a larger study that varied the additive manufacturing method to help the FDA assess devices the effect of print direction on the fatigue performance of additively manufactured medical devices.

Ti-6Al-4V for Orthopaedic Implants in Fatigue

Mukesh Kumar, Zimmer-Biomet

A few concurrent events have brought about Additive Manufacturing to mainstream usage in the orthopaedic community. Advancements in computing power now able to take patient image and manipulate this data to generate CAD models of the patient's anatomy and the necessary instruments. In fact, this aspect is considered so precise that surfaces can be generated that mirror details of bone anatomy well enough to help create precise fitting jigs. Today jigs can be printed with registration surfaces that help seat the orthopaedic implant correctly to achieve biomechanical alignment. Even though the implant is often generic, this simple act of providing a patient specific jig that removes any guess work on the part of the operating surgeon has the potential of making the outcome of the surgery much better. However, this advancement is just a step in the multiple iterations to make the surgery truly patient specific. With better imaging capability and Additive Manufacturing, today there is the possibility of making implants that are specific to a given patient. But the orthopaedic industry is cautious - so far its forage in this space is limited to patient specific jigs and instruments but not much has happened with patient specific implants that are fatigue sensitive. Another reason for quick adoption of additive manufacturing by the orthopaedic industry is the potential of designing potentially better bone ingrowth porous surface. The technology has proven itself in acetabular shells which is not fatigue prone. However, implant manufactures are still exploring if the technology is robust enough to manufacture implants that can sustain the rigours of high fatigue loading conditions.

In general, a hip stem is designed to survive potential fretting corrosion at the taper junctions and loading conditions that can exceed 6-8 times body weight of the patient for sustained periods. Though fatigue property is a design input, and an implant could be tailored to fit this input, a major constraint in adopting this design philosophy is the dimensions of the receiving bone. To make things easier for design engineers and regulatory bodies, the fatigue properties of additive manufactured implants must be at least as high as that obtained from wrought material. However, materials like titanium are notch sensitive and hip stems necessarily have two features that play a role in reducing the fatigue strength of the implant - a taper junction that could potentially show fretting corrosion and thus weakening the implant and the porous structure that could act as regions of stress riser. Current hip stems have a porous structure where the coating is applied over the machined surface, with little or no metallurgical bonding, so a fatigue crack originating in the coating may not penetrate into the substrate. In the case of additive manufactured hip stem with porous structure, this region would be metallurgically contiguous to the underlying solid region - thus potentially creating a notch situation.

Recognizing that the orthopaedic community needs implants that would have sections where there is no machining to achieve smooth surfaces and most likely, these sections have the porous ingrowth surface, the adoption of AM technology to produce patient specific parts would be greatly facilitated if the following is well understood and answered for Ti6Al4V alloy
(a) what heat treatment regimen can provide fatigue properties in excess of wrought material?
(b) how does the fatigue property change if there is semi-sintered loose powder on the "as built" surface? Is there a way to simulate the decrease in fatigue from the presence of such semi-sintered surface particle clusters and thus help define acceptance criteria for such clusters?
(d) design rules - recognizing that porous structures are essential features in orthopaedic implants, but the presence of porous structures create stress risers and reduce fatigue properties, what design rules such as minimum curvatures between porous and solid substrate could be followed to help create a higher fatigue strength implant
(e) standards - introduce such concepts as standards that would allow easier regulatory path

If the above is well addressed, it would be revolutionary for the orthopaedic space as patient specific fatigue prone implants and organic design of the same would become common place.

Fracture Mechanics and Nondestructive Evaluation Modeling to Support Rapid Qualification of Additively Manufactured Parts

Craig McClung, Southwest Research Institute (SWRI)

Additive Manufacturing (AM) offers the prospect of substantial reductions in the time and cost required to design and produce new parts under certain conditions. However, as with any manufacturing process, AM can create defects. For AM processes, potential defects include incomplete fusion, gas porosity, and quench cracking. It is essential that any defects produced that would compromise the integrity of the part can be found by appropriate nondestructive evaluation (NDE) methods. However, brute force, trial-and-error NDE qualification could compromise the cost-effectiveness of the AM process. A pilot study has recently been completed to confirm the feasibility of combining NDE modeling with fracture mechanics modeling to address this challenge. NDE simulations are used to determine the probability of detection of defects at various locations in a complex three-dimensional part produced by direct metal laser sintering (DMLS) and inspected by X-ray methods. Fatigue crack growth simulations are used to determine critical initial defect sizes (to determine what needs to be found) and also to determine the probability that an undetected defect would grow to fracture during the service lifetime of the part. The joint NDE-fracture modeling system could be used to optimize both the design of the part and the design of the NDE inspection plan. Research is underway to develop the modeling system further.

Extreme value analysis of defects on AM parts

Steffano Beretta, Politecnico di Milano

The estimation of fatigue strength and, especially, the quality control of components containing defects and inhomogeneities are very important problems, which have found a complete solution only in the mid 80's. The experimental evidence by by Murakami and co-workers [1] have shown that non-propagating cracks are always at the tip of defects and micro-notches at stress levels near the fatigue limit.

The similitude between defects and cracks near the fatigue limit implies that the estimation of fatigue strength can be successfully performed with the models (Murakami-Endo or $\sqrt{area}$, Tanaka and Akiniwa, El-Haddad et al. models [2]) able to describe the different regions of the so-called Kitagawa diagram.

When the defects become the fracture origin, it is well recognized that in a given volume of material subjected to the same cyclic stress, the fatigue failure occurs at the largest defect or inhomogeinity that is present in the volume. Consequently, the fatigue strength is then controlled by extreme values of the population of defects rather than the average dimension of inhomogeneities. So the estimation of fatigue strength in presence of defects needs the estimate of the prospective size of maximum defect in a given material volume (or batch of components) [3].

This analysis can be carried out adopting the concepts of statistics of extremes [4, 5]. A series of papers ([1] and [6] provide a summary of these studies) have shown the successful application of statistics of extremes for estimating the size of the maximum defect at the fracture origin when there is a single type of defect in the material. However, due to the presence of multiple defects types [7, 8], there is a minimum material volume to be inspected in order to find the detrimental defects that will be then responsible for fatigue failure. This is the critical point for a correct sampling and statistical analysis of defect size.

Application to AM

In this presentation we will summarise a cooperative activity, between ESA and PoliMi, aimed at verifying the possibility to estimate extreme defects in components made by AM. In detail, the measurements of inhomogeneities and volumetric defects that were present in the gage length of 6 fatigue samples have been carried out by CT scan. The defect volumes have then been analysed with the statics of extremes in order to estimate the maximum defect present in a given material volume.

Results have then been compared with the CT measurements on the entire specimen volume (gage length + grips) and the fractographies of the defects at the fracture origin, by discussing the effects of shape and clusters on the predicted maximum defect.

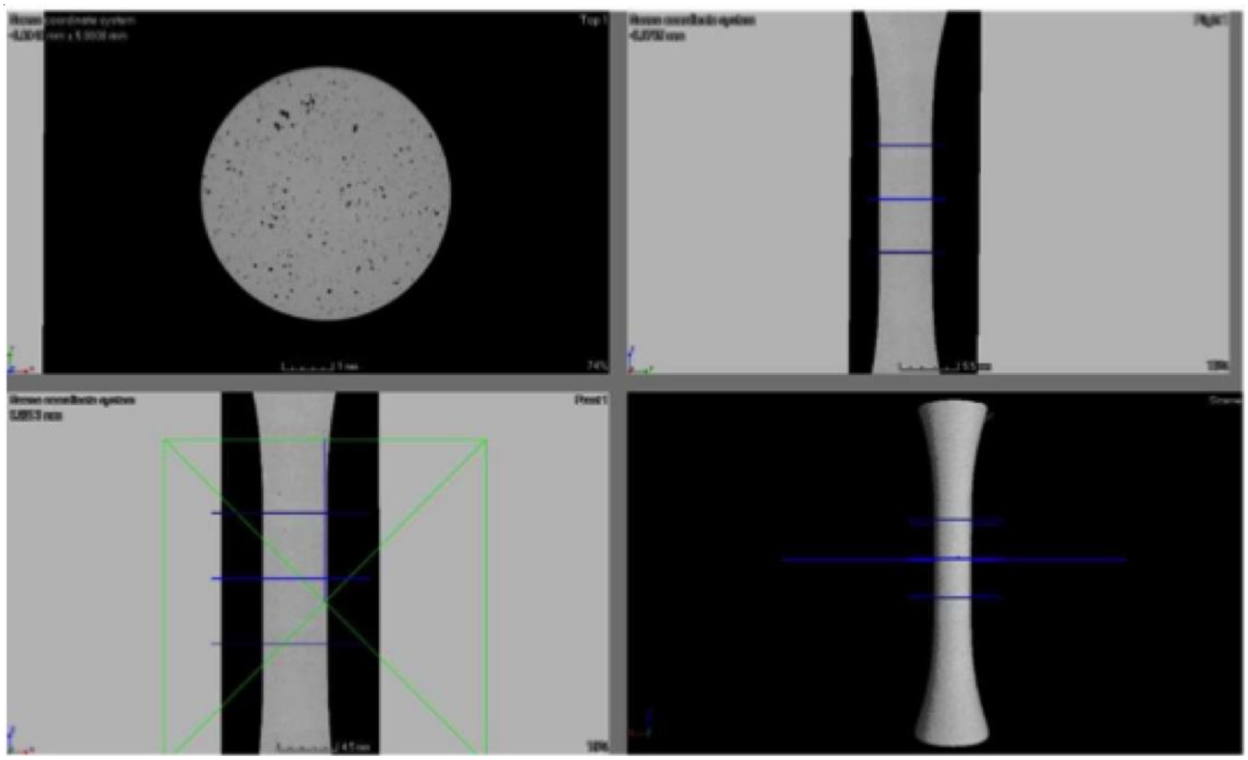

Figure 1: Example of CT scan of the defects in a fatigue specimen

References

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[4] S. Coles. An Introduction to Statistical Modeling of Extreme Values. Springer, London, 2001.
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Fatigue Life Manipulation of SLM® Parts

Richard Grylls, SLM Solutions

Selective Laser Melting (SLM®), a new innovative additive manufacturing (AM) technology, allows for manufacturing of geometrically complex metallic parts directly on the basis of 3D-CAD data. In this current work, the selective laser melting manufacturing systems SLM®250^{HL} and SLM®280^{HL} are presented with additional technical background information and specifications. At these systems manufactured SLM® parts are used for fatigue life investigation. At this point the effect of different notch geometries in the crack path, which are responsible for crack deflection, crack retardation, crack arrest, crack initiation, as well as the exchange between the crack initiation and the crack growth phase (Figure 1) are in focus. Figure 1 shows the effect of notches on the lifetime during crack initiation and crack propagation. The reason for the difference in life time can be found in the crack growth behavior during initiation. The holes positioned in the crack path lead to a new crack initiation at each notch. The significantly higher number of load cycles within the crack initiation period (compared to the number of cycles during crack propagation) will be used to manipulate the total life time. The experimental results and the impacts of the fatigue life manipulation are shown on selected specimens made of titanium alloy Ti-6-4.

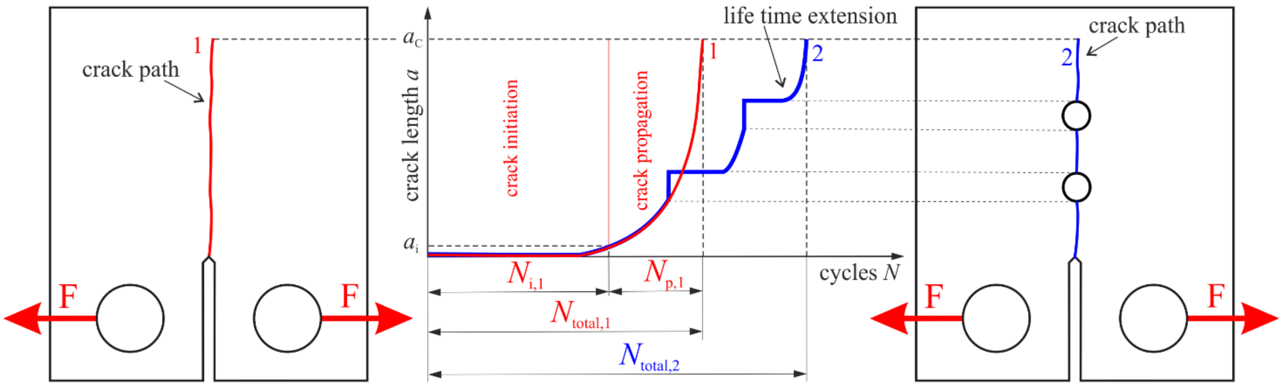

Figure 1 Manipulation of life time caused by notches - schematic illustration

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Effects of HIP Processing on Additively Manufactured, Titanium Materials Produced Using an Electron Beam – Directed Energy Deposition Process

Hank Phelps, Lockheed Martin Aeronautics

Hot Isostatic Pressing (HIP) uses high temperatures and pressures to close and diffusion bond porosity and Lack-of-Fusion (LOF) defects to achieve parent metal properties in titanium castings and powder bed Additive Manufacturing (AM) processes. More recently the process has been evaluated for application of large scale metallic AM processes, such as Electron Beam – Directed Energy Deposition (EB-DED). This presentation will cover the impact on internal quality and mechanical properties of Ti-6Al-4V titanium alloy materials deposited using a wire feed, EB-DED process subjected to HIP processing and a conventional processing route. The results showed a significant improvement in internal quality without detrimental effects on static or fatigue properties.

Reliability of Mechanical Behavior in Metallic Additively Manufactured Parts Used in Critical Applications

Doug Wells, NASA Marshall

Assuring the reliable mechanical performance of additively manufactured parts is a key challenge in the pursuit of certifying their use in safety-critical applications. A methodology is presented for the development of statistically reliable mechanical design properties and the necessary process control sampling needed to ensure the process maintains the expected performance. All aspects of the additive manufacturing process play a role, from control of feedstock to the education of the technical staff executing the additive builds. Known challenges to quality assurance such as the limitations of machine feedback to the limitations of non-destructive evaluation are discussed.

Advanced Characterization of Additively Manufactured Materials, including Synchrotron–based 3D X-rays

Anthony Rollett, Carnegie Mellon University

It is important to understand the microstructure and, in particular, porosity in additively manufactured metallic parts as well as the powders used in many of the machines. Absent manufacturing defects, pores are the primary origin of fatigue failures under cyclic loading. The morphology and location of these pores can help indicate their cause; lack of fusion or keyholing pores with irregular shapes can usually be linked to incorrect processing parameters, while spherical pores suggest trapped gas. Synchrotron-based 3D X-ray microtomography was performed at the APS on additively manufactured samples of Ti-6Al-4V using electron beam powder bed and Al-10Si-1Mg using laser powder bed. The spatial and size distributions of the porosity over a range of processing conditions were determined. Five Ti-6Al-4V samples were fabricated with parameters varied to produce a range of melt pool areas. Imaging samples were sectioned from the bulk and the contour-bulk interface. Similarly, three samples of Al-10Si-1Mg were made with varying process conditions. Marked variations in the type and amount of porosity were observed as a function of the melt pool area.

Beyond measurements of porosity, 3-D printed parts are known to have residual stress as a consequence of the shrinkage that occurs on solidification as well thermal contraction. Thanks to recent advances in high-energy (synchrotron) x-ray methods, a combination of near-field and far-field high energy diffraction microscopy (HEDM) enables the mapping of both 3-D grain structure and the lattice strains. Preliminary measurement results are presented for printed Ti-6Al-4V. Once such data are available, the impact of microstructure on properties has to be evaluated. The application of image-based methods for calculating the micro-mechanical response is described, where the measured image is used as direct input.

Metal Additive Manufacturing: A Review of Mechanical Properties

John Lewandowski and Mohsen Seifi, Case Western University

This presentation reviews published data from over 200 papers, including those of the authors, on the mechanical properties of additively manufactured metallic materials, and is taken from an Annual Review of Materials Research review paper prepared by the authors. The additive manufacturing techniques utilized to generate samples covered in this review include Powder Bed Fusion (e.g. EBM, SLM, DMLS, etc.) and Directed Energy Deposition (e.g. LENS, EBF^3, etc.). While only a limited number of metallic alloy systems are currently available for additive manufacturing (e.g. Ti-6Al-4V, TiAl, Stainless Steel, Inconel 625/718 and Al-Si-10Mg), the bulk of the published mechanical properties information has been generated on Ti-6Al-4V. Individual summaries and/or key figures will be provided for published mechanical properties for each of the alloys listed above, grouped by the additive technique utilized to generate the data. Published mechanical properties obtained from hardness, tension/compression, fracture toughness, fatigue crack growth, and high cycle fatigue are included for as-built, heat treated and/or HIPped conditions in the presentation in order to capture the key observations. The effects of test orientation/build direction on properties are also provided, when available, along with discussion of potential source(s) (e.g. texture, microstructure changes, defects, etc.) of anisotropy in properties. Recommendations for additional work are also provided.