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A Multiscale Multiphysics Integrated Computational Materials Engineering Approach for Layered Deposition Processes of Novel Materials

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The purpose of this document is to describe the progress of the NRL 6.1 Core new challenge project titled "The Science of Layer Deposition Processes of Novel Materials". This program attempts to lay the scientific foundations of mass and energy deposition processes for creating novel materials with unique features and enhanced functional performance previously unattainable via traditional processes. Emphasis will be given to Navy relevant alloys, such as 316L SS, for providing customized functional performance, such as mechanical and fatigue response, corrosion passivation and acousto-elastic response. This project focused on developing a Multiscale Multiphysics Integrated Computational Materials Engineering (MM-ICME) framework for addressing several aspects of layered deposition processes associated with the Aditive Manufacturing (AM) of novel materials.

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EXECUTIVE SUMMARY

The purpose of this document is to describe the progress of the NRL 6.1 Core new challenge project titled “The Science of Layer Deposition Processes of Novel Materials”. This program attempts to lay the scientific foundations of mass and energy deposition processes for creating novel materials with unique features and enhanced functional performance previously unattainable via traditional processes. Emphasis will be given to Navy relevant alloys, such as 316L SS, for providing customized functional performance, such as mechanical and fatigue response, corrosion passivation and acousto-elastic response. This project focused on developing a Multiscale Multiphysics Integrated Computational Materials Engineering (MM-ICME) framework for addressing several aspects of layered deposition processes associated with the Aditive Manufacturing (AM) of novel materials.

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A MULTISCALE MULTIPHYSICS INTEGRATED COMPUTATIONAL MATERIALS ENGINEERING APPROACH FOR LAYERED DEPOSITION PROCESSES OF NOVEL MATERIALS

1. ACHIEVED PROGRESS

1.1 Summary of the technical progress achieved

We developed a Multiscale Multiphysics Integrated Computational Materials Engineering (MM-ICME) framework for addressing several aspects of layered deposition processes associated with the Additive Manufacturing (AM) of novel materials. We developed a definition o f s pecification re quirements for Additive Manufacturing of representative parts to determine the multiscale properties of AM produced materials and compare to standard materials. We defined t hermo-mechanical, c orrosion, a nd acoustic performance specifications f or r elevant c ase-study s cenarios. W e d eveloped c omputational multiphysics modeling infrastructure simulating AM processes under an MM-ICME methodology involving multiple approaches. We characterized specimens from two Direct Energy Deposition (FED) and several Laser Powder Bed Fusion (LPBF) builds for mechanical, corrosion and microstructural properties and functional performance. We produced several sets of parameter excursions on single pass powder bed builds on NRL's GE/Concept Laser M2 system and performed their characterization in an effort t o i dentify t he o rigins of the cellular structures appearing of the sub-grain level that appear to be related to the increase of yield and ultimate strengths of 316L specimens when they are produced by LPBF AM. Furthermore, we studied and documented the fatigue performance of AM materials and introduced and deployed a qualification and certification framework for AM m aterials. Several computational tools were developed in support of these activities and transitioned to other projects within and outside US-NRL.

1.2 Technical progress for each of the technical areas

The efforts of this project have focused on several technical a reas. There are the c ore M M-ICME, the electrochemical testing activities, the acoustics related activities and the space sciences related activities.

1.2.1 Multiscale Multiphysics Integrated Computational Material Engineering

Below are the major developments under the MM-ICME technical area performed by the members of Code 6394.

Multiphysics Additive Manufacturing Discrete Element Method (NAMMDEM) Framework

Developed Multiphysics Additive Manufacturing Discrete Element Method (NAMMDEM) Framework. Our effort to address the needs of linking of process parameters to performance parameters in a computationally elegant and at the same time physically realistic manner, we evolved our finite element solutions of the partial differential equations encoding the conservation principles, the enriched analytical solution methods and the NRL Additive Manufacturing Multiphysics Discrete Element Method (NAMMDEM) extended to incorporate thermal, and thermo-structural physics. The NAMMDEM was utilized to demonstrate porosity and surface texture predictions.

Manuscript approved December 29, 2021.

Physics Informed Implicit Slicer

Developed the physics informed implicit slicer algorithm and is computational Implementation. We developed a physics-informed implicit slicing algorithm capable of computing toolpaths derived from the level sets of arbitrary heuristics-based or physics-based fields defined over the input geometry. In particular, the scale-independent capability that makes this slicer useful regardless of the size of the manufactured part was tested for extrusion-based systems used for large structures and it s functionality was verified for corrugated large structures. The slicer software was also interfaced with the GE/CL M2 system by exploiting its Common Layer Interface. The first prints by using CLI demonstrated that additional parameter exploration is required for using the CLI deterministically. Demonstration of this capability has led to multiple publications.

Residual Fields Predictor

Developed a computational process for residual fields prediction via finite element method for the thermo-elasto-plastic response of the material during and after AM processes. The computational infrastructure developed to incorporate phase transformation and residual stress evolution with domain activation and true thermo-elasto-plasticity via a finite element-based approach to lay the groundwork for full-scale, fully coupled simulations of entire parts. Demonstrated that the method works very well for simulating building of full parts and was validated against CHESS collected experimental data of residual strains.

Enriched Analytical Solutions Method

We developed an enriched analytical solutions methodology and computational implementation (of the heat conduction partial differential equation), describing the energetics of AM processes. In addition to generalized heat flux form, temperature-dependent properties and capability for finite domain applicability we have further enhanced the solutions with the ability to account for phase transformation of the material due to melting and solidification even more than last year and have initiated the effort to add enrichment that predict the mechanical fields of thermally driven displacement, strains and stresses. Extended this EASM approach to include the solutions of the momentum equation for describing the thermo-elasto-plastic fields such as displacements, strains and stresses in a manner that accounts for the thermal history. Furthermore, the enriched analytical solution method has been transitioned to a python framework to reduce runtime. Demonstration of this capability has led to multiple publications.

Synthetic Microstructure Simulator

We developed a computational infrastructure for predicting the multi-grain solidification behavior of multi-element systems. A multi-phase-field model for predicting the microstructural evolution was created for ternary alloy systems. Demonstration of this capability has led to multiple publications.

Multiscale Generalized Anisotropic Multiphysics Topology Optimizer

We developed a computational infrastructure enabling multiscale generalized anisotropic multiphysics topology optimization for the purpose of tailoring the functional performance of AM produced parts. The framework was also extended to account for material anisotropy in the plastic region. Demonstration of this capability has led to multiple publications.

Cellular Substructure Formation and Evolution

Several investigators have associated the presence of cellular substructure in AM-produced SS316L with significantly improved yield and ultimate strength. To understand the factors and the process of their formation in an effort to control their tailored formation we have embarked to a series of activities as follows:

1. Additional selectively laser melted (SLM) "single-track" experiments were continued in order to isolate the intrinsic processes associated with rapid melt/solidification without the complexities associated with heat/re-heat and melt/re-melt cycles linked to additional build layers.
2. Additional follow-on characterizations of single tracks were conducted via SEM, TEM, EDS, EBSD, and optical microscopy. These characterizations led to added evidence that the dominant theory for cellular formation, i.e. cellular solidification followed by dislocation pinning, was inconsistent with our observations.
3. Additional collaborative efforts have also continued with both Johns Hopkins University in order to develop data-driven discrete dislocation dynamics simulations, as well as Georgia Tech to examine the implications of these cellular structures on the follow-on inelastic response of this material via crystal plasticity model development.
4. EBSD-based thermomechanical simulations of single tracks have also been developed in support for our hypothesis that the observed cellular structures are actually due to solid-state diffusion occurring after solidification, as opposed to at the advancing solid/liquid interface during solidification.
5. Further effects of cellular structure on the mechanical response have been identified via nanoindentation studies, revealing a hierarchical set of size effects stemming from indenter tip size effects, cell size effects and grain size effects that all act in a simultaneous fashion.

Surrogate Modeling

Developed Constitutive and Surrogate Modeling (utilizing machine learning) Encapsulating Microstructural Features Induced by Powder Additive Manufacturing and associated Validation. Also developed crystal plasticity-based models, which considered microstructural features such as grain size and aspect ratio.

In particular, a data-driven surrogate model of the crystal plasticity finite element model, developed in the previous year, has been created. This model uses individual grain morphology to predict stress and strain then averages this over a representative volume element to predict overall stress-strain. The surrogate model can make predictions in seconds rather than hours/days like the finite element model and could additionally be used for model calibration in the future.

Additional improvements are the generation of data to train a machine learning model. The machine learning model relates AM process parameters to output thermal history for a representative volume element nearly instantaneously. This history is used to create a microstructure, such as the cellular automata code being developed at NRL, and then into the surrogate crystal plasticity model. The goal is to demonstrate to process-structure-property linkages in near real-time and determine appropriate process parameters to produce parts with optimal performance.

Experimental Validation

The idealized single bead width spray deposition AM samples, have been evaluated in tensile testing and microhardness testing validate the simulation process. Data from these tests have also been used to relate process modeling, grain formation and growth modeling with crystal plasticity-based prediction of constitutive models. The results of these tests provided a six-way validation between a) process modeling and prediction, b) grain growth simulation, c) crystal plasticity-based constitutive model development, d) microstructural features, e) multiscale mechanical properties assessment, and f) corrosion performance. This combination of computational modeling and experimental validation is key to an ICME framework for metal AM processes.

A second set of idealized single bead-width spray deposition AM samples have been fabricated to produce smaller samples to explore the evolution of microstructure and strain mapping in uniaxial tensile testing. The objective of this study, jointly with Clarkson University, was to determine the role of various microstructural features on the mechanical properties of 316L stainless steel samples manufactured by AM processes and consists of two major tasks. In the first task, the goal was to determine the mechanical characteristics of individual features by obtaining their response to nanoindentation. In this task, the goal was to characterize the influence of the microstructural features on local plastic deformation.

In the first task, a new method to perform indentation in the vicinity of optically identified features was developed. A new method that relies on post-indentation etching followed by digital mapping of the indentation locations was developed. This new method ensures that the roughness introduced by chemical etching does not influence the nanoindentation characterization data. In the second task, a uniaxial, tensile micro-testing system equipped with a microscope that can track the formation of slip planes and shear bands in-situ as well as determine the barriers introduced by the microstructural features. The characterization activities have been verified using conventionally manufactured 316L stainless steel samples, as well as AM samples produced earlier and not carefully manufactured as in this program. The characterization process was completed in FY21.

Tension specimens from both powder bed and powder jet builds have been tested. Results from these tests have been compiled and analyzed. A statistical analysis of the tension results has been conducted.

Surrogate Models for Residual Fields

Developed a surrogate modeling framework, which is based on Non-Uniform Rational B-Splines (NURBs) and K-cluster Interpolants for computing residual stresses with 3 to 4 orders of magnitude speedup performance without loss of accuracy. This effort was transitioned to Technical Data Analysis Inc. and the US Army for missile applications via a Small Business Innovative Research (SBIR) project that was a transition outgrowth of our efforts on this topic that has now won a Phase II.

Rapid AM Part Qualification Framework

We have developed a qualification methodology for AM produced parts in terms of their mechanical performance. The concept of performance signature was extended and used as a consequence of this effort. The methodology was applied for a Fused Deposition Model of an Orion P-3C aircraft bracket connecting the inner with the outer wing in collaboration with NAVAIR. Additional evaluation of the proposed approach indicated very promising results especially if performance signatures if AM-produced parts are compared to performance signatures of conventionally manufactured parts. The design and initial assembly of a new prototype multiaxial fatigue-enabled loader has beeen completed to facilitate the qualification testing loading emulating in service loading conditions applied on AM-produced parts. The development pf the control algorithms for displacement and load-control of such system has been initiated.

Assessment of Fatigue Behavior of AM-produced Parts

In an effort to establish an understanding of the state of affairs on the effects of AM processing and post-processing into the fatigue behavior of AM-produced part we have explored a large amount of experimental data present in the bibliography. We have established that the Hartman-Schijve variant of the NASGRO crack growth equation enables a generalized comparison of the crack growth behavior of various processes and Post-processes for various alloys used by AM methods. This approach enabled us to rank AM processes and post-processes relative to their fatigue performance and the results were published in several publications.

Stochastic Modeling of Constitutive Response

In an effort to develop an infrastructure capable of assessing the stochastic nature of the AM process parameters and the associated randomness introduced by the AM processes, we developed an infrastructure for inversely characterizing material constitutive response when random spatial variability modulates bulk properties in materials. This approach was applied for realistic AM built parts.

In-situ Experimental Capabilities

To enable feedback control of AM processes we have acquired two in-situ measurement systems 1. We installed and verified the functionality a sensor capturing spectral information from the volume of the melt pool created by our direct energy deposition system. We also have acquired a high frame rate dual-wavelength infrared camera for capturing the in-situ temperature signature during AM processes in a manner that does not depend on the variability of emissivity due to phase transformation.

Material Analysis and Characterization

Characterized 316L AM microstructures as a function of post-processing conditions and correlating the observed variations to changes in a variety of mechanical and corrosion properties by the members of Code 6356. This program focused on wrapping up a study on the effect of post-processing on microstructures and corrosion susceptibility and supporting a separate program examining the impact of those microstructures changes on corrosion, toughness, tensile, and fatigue properties.

Because of the COVID restrictions, this past year was spent primarily on research areas related to the additive manufacturing of 316L stainless steel that had started in previous years, namely i) crystallographic orientation of fine cellular structures, ii) distortion and porosity measurements in an additively manufactured pressure vessel, and iii) the mechanical and corrosion behavior of post-processed builds. This work resulted in four presentations presented virtually at conferences and significant progress towards two publications, all of which are listed below.

For the crystallographic orientation of fine cellular structures program, trace analysis was conducted on the cellular features on 2D sections to determine their crystallographic orientation in 3D. An earlier study of about 50 traces showed that the cells appeared to be oriented along the 001 direction. That result was partially obscured by the background noise generated from the 23 (out of 24) incorrect orientation variants used in the calculation. The updated study expanded on that earlier study by correlating the 2D orientation of cell structures at 1118 points to their crystallographic orientation as revealed by electron backscatter diffraction imaging. The results demonstrate a strong alignment with the cell structures to the 001 direction–93.4% of all traces were oriented within 10° of 001 with no other orientations exhibiting a correlation. More recent work suggests that the sub-grain boundaries formed during fabrication and highlighted with deformation recovery may also adhere to 001 planes, which will be the subject of research in the next year.

The additively manufactured pressure vessel contains cylindrical walls that range from vertical to horizontal which are associated with different microstructures and porosity contents. The amount of porosity and its distribution from the surface (both inner and outer) was measured and correlated to the underlying microstructure. The outer surface (where new material is being deposited directly on previously-deposited layers) exhibited a layer of higher porosity below the surface at depths that depended on the inclination of that surface. The maximum porosity was located at a distance from the surface that contained the lower portion of the melt pool. The porosity consisted primarily of large, near-spherical pores that were identified as keyhole porosity associated with the higher laser power border passes. The inner wall (where deposition extended out beyond the previously deposited material) typically exhibited a similar high density of pores at a corresponding location, but also contained a region with a lower density of pores that have an irregular morphology located further from the surface. The location of these additional pores indicates that they are lack or fusion porosity formed at the interface between the fill and bordering passes of the build.

Considerable work has been done to track down, organize, and analyze the data from a collaborative effort with code 6130 on a Cross-Platform Systems Development program. This program examined the microstructures, mechanical properties, and corrosion behavior of four characteristic microstructures that are typical of as-built and post-processed AM 316L stainless steel. This program revealed the microstructural characteristics associated with these four characteristic microstructures: 1) the as-built condition, 2) an annealed condition that removes the fine cellular structures but preserves the original grain structure, 3) a recrystallized condition that changes the grain structure to an equiaxed structure and removes most of the orientation gradients within each grain, and 4) a hot isostatically pressed condition that exposes the AM build to high temperatures for a longer dwell time while subjecting the sample to high isostatic pressures. These microstructural characteristics were used to explain the observed changes in tensile properties, fatigue properties, Charpy toughness, potentiodynamic polarization testing, and crevice corrosion testing.

1.2.2 Electrochemical Testing Activities

Electrochemical Polarization testing has been conducted on the preliminary material for the Grand Challenge Program by the members of code 6130. The results indicate the corrosion resistance of the AM316L material meet or exceed that of traditional wrought product 316L materials, for both the initial and final layers of the build, and exceed the results of earlier AM316L materials from other programs. These are very encouraging data, as it shows the material is relatively consistent as a function of deposition history. Focused on SEM/EDS to determine the onset of pitting sites, and EBSD to interrogate the effects (if any) of grain structure on electrochemical performance

A major accomplishment was the contribution to the 316L post-processing paper and a literature study to help support the paper and future work.

1.2.3 Acoustics related activities

Acoustical research thrusts were in the following areas have been performed by the members of code 7160.

- Inversion of acoustical properties of metal foams using Bayesian methods.
- Experimental characterization of metallic membrane resonance variation as a function of 3D printed build direction.
- Analysis of novel 3D printed materials called bi-anisotropic acoustic reflectors and structurally anisotropic lattice structures.

Three-dimensional printing offers a novel means of creating custom metallic foams with designed acoustical properties. Joint work between NRL and the Jet Propulsion Laboratory (JPL) have investigated the acoustical properties of metal foams made using Powder Bed Fusion. Samples fabricated by JPL were examined using the NRL air-impedance tube. The effective medium description of the foam was the multi-parameter Johnson-Champoux-Allard-Lafarge (JCAL) model. NRL obtained inverted parameter distributions for 6 variable porosity metal foams using Bayesian inversion methods. This article was published in the Journal of the Acoustical Society of America (2021). [NRL/JA/7160-20-0077; NRL/OP/7160–21-0093; NRL/JA/7160–20-0045]

Metallic membrane resonators fabricated using 3D printing were investigated due to their strong resonant coupling with fluid environments and structural acoustic architectures. Furthermore, metallic membranes are used as thin-walled, truss-like components in many elastodynamic metamaterial designs, particularly those intended for aqueous coupling such as Pentamode structures. Cantilever and disk membrane geometries were additively manufactured using two different approaches: building thin-wall geometries directly, and using a wire EDM to slice thin sections off of thicker pieces. Characterization using acoustic coupling in impedance tubes and laser-doppler vibrometry (LDV) demonstrated that the resonant response of these geometries could not be explained by an isotropic elastic material model.

Asymmetry in the path dynamics of powder bed printers such as the GE Additive M2 Cusing SLM system introduces a material anisotropy in the vertical build direction. We demonstrated that a transversely isotropic elastic model can account for this anisotropy when characterizing membranes manufactured using different print orientations (vertical vs parallel to the powder bed). The anisotropic elastic tensor components of thin-plate resonators (both disks and rectangles) can be determined by considering the frequency response over a hierarchy of resonant modes. The discovery that additively-manufactured, thin-walled metallic structures are anisotropic has important implications for acousto-elastic device fabrication, where the anisotropy must be taken into accounted when considering propagation through complex structural acoustic architectures. Results from this study are have been presented at several scientific conferences including Phononics, ASA, and the International Materials Research Congress. This work was performed cooperatively with Code 6394. [NRL/AN/7160–19-0054; NRL/JA/7160–19-0112; NRL/AP/7160–19-0067; NRL/AP/7160–19-0069]

We have continued the aqueous analysis of novel 3D printed materials called bi-anisotropic acoustic reflectors and structurally anisotropic lattice structures. SLM has enabled the construction of these system for underwater use, because of the relatively high acoustic impedance between printed SS316L and water and the complex nature of the printed structures. The characterization of the acoustic reflection from bi-anisotropic Willis coupled surfaces was presented at two international conferences. One of these was an invited presentation at the Acoustical Society of America's December meeting in Coranado, CA. In collaboration with MIT, Duke University, and UT Austin we provided test structures for controlling underwater acoustic propagation with anisotropic lattices. This work is currently being prepared for publication in Advanced Engineering Materials.

Through the collaborative efforts of Code 6390, NRL has joined the Acceleration of Large Scale Additive Manufacturing (ALSAM) working group of America Makes. Through this program, NRL is working towards installation to an "Open M2" additive manufacturing architecture. This approach will retrofit our current GE Additive M2 Cusing SLM system with an additional fully open system for research-level control of all printing parameters.

1.2.4 Space Sciences Progress

We focused on achieving the printing and qualification of multimaterial space application relevant parts.

2. FUTURE PLANS

This project has generated a multitude of areas that could be benefited by additional efforts.

2.1 Potential Opportunities

Here we describe areas fo potential extension of our work some of which we have already begun pursuing under other projects. We are describing them in a manner that matches the areas of activities where the progress for this project were presented earlier.

2.1.1 Multiscale Multiphysics

Below are potential opportunities under the MM-ICME technical area.

Multiphysics Additive Manufacturing Discrete Element Method (MAMDEM) Framework

The NAMDEM technology can be further extended to account for DED processes in addition to the LPBF ones for which it is currently formulated. Another potential area for its extension are the cold-spray processes. More detailed models for process chamber gas flow and denudation can be also added.

Physics Informed Implicit Slicer

The Pii-Slicer technology can be extended to account for multiple physics fields so the generated parts exhibit optimal performance for multiple physics. Another extension of this technology can be for large scale AM required in construction engineering for concrete and polymer extrusion systems that account for reinforcement and maximize the continuous path capability instead of the segmented paths available now. The ARmy Core of Engineers has already contacted us and we are pursuing this extension.

Enriched Analytical Solutions Method

The EASM approach can further be extended to include the prediction of the thermo-mechanical fields in and effort to predict analytically the residual displacement, strain and stress fields.

Synthetic Microstructure Simulator

The SMS can be further extended for the case of multi-element alloys in a manner that not only predicts nucleated microstructure, but also for cases for epitaxial growth related to AM processes as well as for the case of grain growth during post development heat treatment of materials for stress relief.

Multiscale Generalized Anisotropic Multiphysics Topology Optimizer

The multiscale GAMTO technology can be further extended to account for more physical fields and additional properties anisotropy related to multi functional applications such as conformal pressure vessels and antennas. This effort has already been initiated in a follow-up program funded by ONR under the title of “Agile ICME toolkit”.

Surrogate Models for Residual Fields

The developed technology can be further extended with additional physics-agnostic algebraic and machine learning based technology for achieving even faster computational performance.

Rapid AM Part Qualification Framework

The rapid AM part qualification framework, can be further extended for not only quasi-static loading but also for cyclic loading associated with fatigue conditions, as well as electromagnetic, thermal and corrosion conditions.

Assessment of Fatigue Behavior of AM-produced Parts

In addition to the Hartman-Schijve variant of the NASGRO crack growth equation for modeling the fatigue behavior of AM parts, a computational infrastructure automating the process for identifying the model parameters from experimental data can be achieved. Special optimization techniques capable of dealing with the asymptotic behavior of the crack extension graphs can be developed and extended to be useful for many other models in addition to the Hartman-Schijve. Parameterization of surface roughness and porosity metrics can be also added to achieve higher generalization of such models.

Stochastic Modeling of Constitutive Response

The inverse characterization methodology we developed when random spatial variability modulates bulk properties in materials, can be further extended for additional functional requirements of the parts beyond those of its mechanical performance.

In-situ Experimental Capabilities

To enable real-time feedback loop control for feed-forward control additional in-situ measurement technologies can be added beyond the sensor capturing spectral information from the volume of the melt pool and the high frame rate dual-wavelength infrared camera for capturing the in-situ temperature signature during AM processes in a manner that does not depend on the variability of emissivity due to phase transformation can be added. These include post re-coater geometric surface characterization instrumentation, dynamic laser beam ellipticity control, localized inert gas flow control etc.

2.1.2 Electrochemical Testing Activities

In addition to 316L SS other alloys can be characterized in order to establish the connection between the AM process porosity and their respective electrochemical response as it related to their corrosion behavior and corrosion mitigation.

2.1.3 Acoustics related activities

Underwater applications of acoustic meta-materials and parts created by AM for tailored band-pass performance as well as sonar reflection obfuscation are very promising directions for the future.

2.1.4 Space Sciences Progress

Using AM for multi-material parts for multi-functional applications can be extended for multi-functional requirements and part count reduction.

3. PEER REVIEWED PUBLICATIONS

The publications produced under this project are listed below.

1. A. Birnbaum, J. Michopoulos, and A. Iliopoulos, "Simulating Geometric and Thermal Aspects of Powder-Jet Laser Additive Manufacturing," Proceedings of the ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Paper DETC/CIE2016–59644, volume 01 (American Society of Mechanical Engineers, ASME), 2016, pp. V01AT02A034–V01AT02A034.

2. A. Iliopoulos and J. G. Michopoulos, "On the feasibility of crack propagation tracking and full field strain imaging via a strain compatibility functional and the Direct Strain Imaging method," *International Journal of Impact Engineering* **87**, 186 – 197 (2016), ISSN 0734-743X, doi:http://dx.doi.org/10.1016/j.ijimpeng.2015.03.006. URL `http://www.sciencedirect.com/science/article/pii/S0734743X15000391`, SI: Experimental Testing and Computational Modeling of Dynamic Fracture.

3. J. Steuben, A. Iliopoulos, and M. J., "On Multiphysics Discrete Element Modeling of Powder-Based Additive Manufacturing," Proceedings of the Proceedings of the ASME 2016 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Charlotte, NC, August 21–24 2016.

4. J. Steuben, A. Iliopoulos, and M. J., "Implicit Slicing for Functionally Tailored Additive Manufacturing," Proceedings of the Proceedings of the ASME 2016 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, number DETC2016–59638, Charlotte, NC, August 21–24 2016.

5. A. Iliopoulos, J. Steuben, J. Michopoulos, T. Baxevanis, T. Kirk, and D. Lagoudas, "On the thermomechanical behavior of Ni60Ti40 coupons via high performance full field experiments," Proceedings of the Proceedings of the ASME 2016 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, number DETC–CIE2016–59880, Charlotte, NC, August 21–24 2016.

6. J. Michopoulos, A. Birnbaum, and I. A., "Effect of Temperature Dependent Properties On The Applicability of the Heat Conduction Equations for Rapid Heat Deposition Applications," Proceedings of the Proceedings of the ASME 2016 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, number DETC–CIE2016–59631, Charlotte, NC, August 21–24 2016.

7. A. Iliopooulos, J. Michopoulos, and S. Lambrakos, "Reduced Order Modeling for Inverse Parameter Identification of Ti-5111 Friction Stir Welding," Proceedings of the Proceedings of the ASME 2016 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, number DETC–CIE2016–59890, Charlotte, NC, August 21–24 2016.

8. J. C. Steuben, A. P. Iliopoulos, and J. G. Michopoulos, "Implicit slicing for functionally tailored additive manufacturing," *Computer-Aided Design* **77**(Supplement C), 107 – 119 (2016), ISSN 0010-4485, doi:https://doi.org/10.1016/j.cad.2016.04.003. URL `http://www.sciencedirect.com/science/article/pii/S001044851630015X`.

9. J. C. Steuben, A. P. Iliopoulos, and J. G. Michopoulos, "Discrete element modeling of particle-based additive manufacturing processes," *Computer Methods in Applied Mechanics and Engineering* **305**, 537 – 561 (2016), ISSN 0045-7825, doi:https://doi.org/10.1016/j.cma.2016.02.023. URL `http://www.sciencedirect.com/science/article/pii/S0045782516300536`.

10. Y. Fu, J. G. Michopoulos, and J. H. Song, "On Investigating the Thermomechanical Properties of Cross-linked Epoxy Via Molecular Dynamics Analysis," *Nanoscale and Microscale Thermophysical Engineering* **21**(1), 8–25 (2017), doi:10.1080/15567265.2016.1263696. URL `http://dx.doi.org/10.1080/15567265.2016.1263696`.

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