3D PRINT -MATERIAL AND PROCESS MODEL AND EFFECT OF DEFECTS ON PART PERFORMANCE

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ABSTRACT

Additive Manufacturing (AM) is helping to achieve significant time and fabrication cost savings, as well as creating complex geometries and material that are otherwise impossible using conventional manufacturing processes. 3D printed "AS-Built" metal parts are exhibiting surface roughness, warping, defects, and scatter in mechanical properties (strength, stiffness). Analysis by conventional FEM does not fully account for material performance: (a) heat affected zone, (b) meltpool; (c) solidification; and (d) cooling. Path Coverage visualization using machine printing pattern and orientation can detect the formation of voids and defects, which impact mechanical properties related to the as-built part as well as associated AM process simulation. A developed software, using a multi-scale modeling approach, and combined with ABAQUS is capable of predicting: a) in-situ monitoring, b) material mechanical and fracture properties vs. temperature, including defects and roughness, c) process modeling including residual stress, damage, and defects, and d) service qualification considering scatter in geometry, material, and process. The software is able to assess sensitivity of material and parameters (i.e., laser power, speed, scan pattern, hatch distance, etc.) to build results (e.g., residual stresses) and determine optimized solution for build methodology. Virtual Design of Experiment are demonstrated for several complex parts incorporating ten design parameters for improved part quality. The methodology is validated for Titanium EBM and DMLS Powder Process for uncertainty quantification of process effect on mechanical properties. When integrated with ABAQUS FEM and the 3D print thermal-structural model, the tool offers multiple value added capabilities. The first value add capability consists of NDE-Real Time In-Situ Monitoring and Visualization based on big data processing during AM build of complex part (i.e. part to powder) and results in real time visualization of defects (void, surface roughness, heat affected zone) and calculation of material performance during heating, melting, solidification, and cooling. Here, software utilizes Terrain Micro Mapping techniques to process Camera data (example IR Thermal Camera-ThermaViz, Laser Line Scanner/Profilometer-Keyence, etc.) and visualize defects. Further, path coverage software is designed to detect the lack of material coverage while mapping the print pattern and considering bead size, scan path orientation, and non-conforming mesh at boundary. After detecting voids and anomalies, the software accounts for the As-Built condition and effect of voids on mechanical and fatigue properties, resulting in reduction of stiffness, and strength during 3D print process. The second value add capability includes Material Modeling and the Integrated Computational Material Engineering (ICME) approach, which predicts material mechanical properties (stiffness, strength, and viscosity) at different temperatures, void formation and roughness during diffusion creep, and the effect of scatter on material performance (yield, ultimate, strain). Continuing, the third value add capability supports Process Modeling combined with the ABAQUS Thermal-Structural solution to predict residual stress and warpage due to thermal induced stresses and the effect of baseline heat sink and support structures. Finally, the fourth value added capability refers to Service Loading of the As-Built 3D-printed part which supports residual strength after loading, as well as, assessment of part qualification and certification. Complex part geometry will be demonstrated based on Building-block Verification, Validation and Accreditation (VVA) strategy for part certification.

Keywords: (1) ICME, (2) Path Coverage, (3) Additive Manufacturing, (4) Manufacturing Defects, (5) Material Modeling; (6) As-Built/As-Is Part; (7) (process modeling; (8) Part qualification and Certification
1. INTRODUCTION

Additive manufacturing (AM) is a promising avenue for manufacturing geometries that are difficult or impossible to produce through normal means, such as internal channels and high resolution features [1][2], variable thickness walls, and parts already in an assembly [2]. While many geometries can be created with AM, the time variant heat transfer and cooling rates of AM processes can result in non-uniform microstructures vastly different from those found in the wrought material. Due to this, the mechanical properties of the mechanical part can vary across the geometry, leading to portions of the AM material not meeting application requirements. The most common defects are gas pores, oxidation, unfused powder, balling and swelling, void and cracking, warping, and residual stresses. The prediction of these troubling items and their input to either the AM simulation or service loading is a topic of this paper which utilizes several examples throughout to identify the key topics. The Integrated Computational Material Engineering (ICME) platform couples MCQ for material modeling, AM SIMQ for defect mapping, GENOA3DP for building the FE model, and ABAQUS as the finite element solver. The AM simulation computational platform was first established for BAAM and polymers [3], then extended to metals [4], and optimization of print builds [5].

2. MATERIAL MODELING

The process to properly model AM metal materials during simulation and service loading is shown in Figure 1. First, a user obtains the base metal material properties and stress strain curve and combines that with knowledge of the amount, shape/size/orientation, and spatial distribution of voids/defects/bald spots in the printed material. Base metal curves are typically well known. The internal defects can be (1) predicted with diffusional creep local models during the next AM print simulation, (2) be obtained from AM SimQ. In Situ monitoring and defect visualization, or (3) obtained from microscopic evaluations of the printed material. The defect information is fed into the Material Characterization and Qualification (MCQ) software to determine the printed material SS curves. Sensitivities and allowables can be generated for yield strength, ultimate strength, and % elongation can be obtained by performing design of experiment sets and feeding it into MCQ probabilistic module. The AM simulation path can be continued by using the printed material mechanical and thermal temperature dependent properties directly into the AM simulation and service loading described in the next section. If the path to qualification needs to consider fatigue life then the predicted printed material properties would be fed into MCQ metals fatigue module to predict fracture toughness versus thickness and fatigue life (da/dN versus dK). These properties can then be used in SN predictions and even further complex fatigue predictions of crack growth vs N for complex vehicle subassemblies (wings, suspension systems, …). With this in mind let us discuss in detail the in-situ monitoring and material modeling.
NDE-Real Time In-Situ Monitoring and Visualization
AM SimQ is the software that allows Non-Destructive Evaluation (NDE)-Real Time In-Situ Monitoring and Visualization of the defects during the print. The first value added capability consists of NDE-Real Time In-Situ Monitoring and Visualization based on big data processing during AM build of complex part (i.e. part to powder) and results in real time visualization of defects (void, surface roughness, heat affected zone) and calculation of material performance during heating, melting, solidification, and cooling. In Figure 2, software utilizes Terrain Micro Mapping techniques to process Camera data (example IR Thermal Camera-ThermaViz, Laser Line Scanner/Profilometer-Keyence, etc.) and visualize defects. Further, path coverage software is designed to detect the lack of material coverage while mapping the print pattern and considering bead size, scan path orientation, and non-conforming mesh at boundary. After detecting voids and anomalies, the software accounts for the As-Built condition and effect of voids on mechanical and fatigue properties, resulting in reduction of stiffness, and strength during 3D print process. Path Coverage (Figure 3) supports: 1) Quick visual assessment of printer path coverage, 2) Void ratio computation for all elements. This 2D graphics code displays one printed layer at a time. It supports quick switch (single key press) to the next or previous layer. The width and semi-circular end caps of each path are shown accurately on the part, given a user-specified bead width for the paths. This quick virtual inspection of the actual print or the print path can reveal problems in the printed part. The In Situ data, if obtained, will feed into MCQ. Path coverage should be studied before the print to change the path to reduce bald spots. Figure 2 on the left shows how delaminations (yellow/red zones) are captured from AM SimQ for one layer of an Inconel 718 NASA chamber liner and are also seen in that area in the actual part – this print was stopped due to this observation. Figure 4 shows the calculated bald spot percentages for the whole part using in situ monitoring and it is showing that one spot has a 0.22% bald spot in that local volume. This information is fed into the MCQ module to determine the local material properties due to this bald spot and mapped to the whole FE model element by element during the AM simulation. How bald spots affect the mechanical (static and fatigue) properties are discussed next for Ti6Al4V.
MCQ Modeling and the Integrated Computational Material Engineering (ICME)

MCQ predicts material mechanical properties (stiffness, strength, and viscosity) at different temperatures, void formation, melt pool, shrinkage, oxidation and roughness during diffusion creep, and the effect of scatter on material performance (yield, ultimate, strain). The current database for metals includes Titanium, Inconel, Steel, Aluminum and Magnesium and for polymers includes ABS and Ultem 1010.

MCQ was validated with Ti6Al4V to be able to predict static and fatigue DMLS printed metal properties and allowables at room and high temperature. The static properties were predicted by mixing Ti6Al4V base metal properties with bald spot percentages and compared to test [6] (Figure 5). The bald spot percentage, shape (ellipsoid shown) and aspect ratios are used as inputs to predict stiffness and strength in all directions. Depending on other options during the calculation the output can be isotropic, orthotropic, or anisotropic. The Wrought with Air Particles is the simulation curve and the LENS is the tested printed material. The SS curve was
idealized in black in the top right of Figure 6 to be able to predict fracture toughness vs thickness [7]. The plane strain fracture toughness is then fed into computations for fatigue crack growth determinations and the results of the MCQ metals prediction (FCG) are compared with test Ti6Al4V DMLS Milled. Furthermore, the da/dN vs dG curve is used as input to an FE model to determine the SN life of the part, which also accounted for additional observed surface roughness. The GENOA SN prediction matched the DMLS As Built test data which is a reduced life compared to milled specimens. Finally, room and high temperature (700°F, 371°C) allowables were generated using method discussed in [8] and are shown in Figure 7. This took us on an analytical cycle of material modeling to be used in AM simulations. The material models developed by MCQ are available as UMAT libraries in ABAQUS. There is one level above that analytical level and yet below the full blown AM process simulation which is a thermal FEM simulation and then a structural simulation. It is the local void and oxidation models and the zeroth order thermal models available in the GENOA and MCQ Suite. These are quick and close-to real time simulations that predicts voids and oxidations when local AM simulation stresses are fed into this local model (Figure 8) and that predict melt pool and heat affected zone (heating, melting, melt superheated, solidification/sintering, and cooling) when machine power is used as inputs (Figure 9). The zeroth order model computations take 0.14 seconds compared to the actual print time for the material shown 0.001s. The predictions of the melt pool shown are 120μm compared with test 150μm.

Material modeling is the key to accurate prediction of the process and service life. Now that we know all the important aspects that need to be considered in the material model we can discuss the process simulation and service loading.

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**Figure 5 3D Printing SS Curve Prediction vs. Test**

- **Input Properties** for Ti-6Al-4V and Inclusion
  - **Ti-6Al-4V**
  - **Air as Inclusion**
  - **Inclusion and Void Parameters**

- **Output**: Modulus, Strength, Longitudinal Stress-Strain

- **SS Curve Ti 6Al 4V**
- **Modulus**
- **Strength**

- **Void Volume Fraction 0.07%**
- **Void : Ellipsoid with AR=2.4**
- **Voids are all aligned in 0 direction**

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Figure 6 3D Printing Fatigue Prediction vs. Test

- **Print direction** will affect stiffness and strength properties
- **Void Shapes and Sizes** are key in determining properties
- **Scatter (COV)** prediction was performed with acceptable results for Room and High Temperature

Oxygen Level, % 0.224%

Prediction Vs. Test at RT

<table>
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<tr>
<th></th>
<th>RT YS, ksi</th>
<th>MCQ YS, ksi</th>
<th>% Diff</th>
<th>RT UTS, ksi</th>
<th>MCQ UTS, ksi</th>
<th>% Diff</th>
<th>RT El, %</th>
<th>MCQ El, %</th>
<th>% Diff</th>
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<td>COV (%)</td>
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<td>4.98</td>
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</tr>
</tbody>
</table>

Figure 7 AM Test Data Scatter Predicted (Yield, Ultimate and Strain) for Ti-6Al-4V at Room and 700F
3. PROCESS SIMULATION

The process to properly simulate the AM process is shown in Figure 10. The CAD model is used to generate a gcode and the material properties generated from the previous discussion are fed into the GENOA3DP software to produce a thermal and a structural simulation model (ABAQUS) in these examples, but the software can output other FE solvers as well. The thermal solution is obtained for the print and then the structural (residual stresses, deformation, warpage, damages) is then obtained. Critical zones can be fed into the local models already mentioned which predict oxidation, voids/bald spots, and roughness. The inputs are also the machine parameters (laser power, speed, scan pattern, hatch distance). Thermal simulation (temperatures vs time) and structural simulation (residual stresses) have already been verified and compared with test in [3] and [4].
Process Modeling combined with the ABAQUS Thermal-Structural solution

GENOA 3DP sets up the model to be solved using FE solvers using the material models previously discussed and has its own ABAQUS user material model that utilizes these micromechanical models during every step of the FE solution. A new part continues the story. This is a mount ring made of Inconel 718 simulated and printed. There were 4 builds and 3 simulations for build 1, 3, and 4. The build 1 and 3 simulation verified the software combinations ability to predict a good part and a bad part. During the simulation of build 4, the software took the lead and optimized the support structure and studied build parameters speed, laser power, and dwell time before the print and gave the ok to print a successful optimized part. The temperature distribution at the last step of the build 4 (right after the laser stops) is shown in Figure 11. The residual stresses of build 4 and those over the yield of the material are shown in Figure 12. The critical zones in red were found to be few compared to the total volume and the part was ‘pushed’ to build. This part took 11 hours for thermal and 8 hours for the structural models. The total volume of the build 3 support was 7101.242 mm³ while the total volume of build 4 support was reduced to 5643.73 mm³ (22% savings).

Figure 10 Material Modeling Flow Chart for AM Property Prediction/Material Qualification

Figure 11 Temperature distribution at the last step for new optimized support (build 4)

Figure 12 Structural Model with Critical Zones Noted in Red for build 4.
The path to a successful prediction of a good part only comes from being able to predict bad parts. The simulation of build 1 is shown in Figure 13. The first build was shown to have warping in the top right of the figure which was noted by the simulation as well. By changing the parameters for build 3 (mark speed, hatch spacing and pattern, and support thickness) the print came out as a good warp free part and the simulation showed that residual stresses were lowered by half.

**Figure 13 Path To Successful Prediction Of Good Parts**

<table>
<thead>
<tr>
<th>1st Build – Bad Part</th>
<th>3rd Build – Good Part</th>
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<tr>
<td>Warping eliminated through simulation DOE: improved support design and optimized build parameters to reduce residual stresses</td>
<td></td>
</tr>
</tbody>
</table>

*Optimized build changes:*
1. Mark speed increased
2. Hatch spacing increased
3. Hatch shifted layer to layer (avoids overlap)
4. Support thickness increased

**Figure 14**

*Service Loading of the As-Built 3D-printed part*

The service loading of the printed part can be accomplished by restarting or continuing the AM simulation with different boundary conditions and loading to determine service performance. Damages, residual stresses, and deflections if any will be carried forward from the print simulation and base plate removal to the service loading simulation. Figure 14 shows the damage initiation and propagation for the mounting ring when it is loaded up to and beyond 5,000N. The majority of the damage is in the printer z-direction as indicated by the software. The load of 5,836N is likely the max load before the tab snaps off.
5. CONCLUSIONS

An integrated solution is vital to predict AM process and it being with material modeling and ends with service loading. The ICME approach discussed showed In-Situ Monitoring and Visualization can be used to calculate of material performance during heating, melting, solidification, and cooling and can predict defects and map them to simulation models. Material modeling can predict material mechanical properties (stiffness, strength, and viscosity) at different temperatures, void formation and roughness during diffusion creep, and the effect of scatter on material performance (yield, ultimate, strain) as shown for test validated case for Ti6Al4V. Process Modeling combined with the ABAQUS Thermal-Structural solution can predict residual stress and warpage due to thermal induced stresses. Service Loading of the As-Built 3D-printed part can support residual strength during loading for the as built part. This can be used to assess part qualification and certification.

Simulations were able to guide the printing of an Inconel 718 mount ring before printing and reduce the weight by 22%. Print design parameters can be changed to improve manufacturing process: printing speed, hatch distance, intrusion distance, laser power, material temperature, ambient temperature, material type, bald spot orientation, and aspect ratio.

6. REFERENCES


