

Validation of a Generic Metallurgical Phase Transformation Framework Applied to Additive Manufacturing Processes

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Abstract: *While significant progress has been made in the last few years, the reliability of AM manufactured parts is often questionable as they suffer from manufacturing defects and hence subpar strength/fatigue life. Like in many other fields before, numerical methods are sought to provide insight into the process and help accelerate progress in raising the quality of AM parts, including predicting thermal evolutions, part distortions and residual stresses. In metal applications, assessing the amount of unfused powder, melt pool volumes, grain growth, and metallurgical phase transformations are often of interest. Ultimately, process-controlled microstructures can lead to superior designs and desirable mechanical properties. In previous work, a highly customizable general simulation framework was demonstrated and validated for a wide spectrum of additive manufacturing processes (laser and electron beam powder bed fabrication, direct energy deposition, arc welding, polymer extrusion, ink jetting) as implemented on the Dassault Systemes 3DX Platform based on new FE technology implemented in Abaqus. The framework allows for: 1) arbitrary meshes of CAD representations; 2) exact specification in time and space of processing conditions (e.g., powder addition, laser trajectories, dwell times, etc.); 3) precise tracking of the progressive raw material addition to each element in the mesh via complex geometric computations; 4) precise integration of the moving energy sources (e.g., laser, electron beams, arc welds, high temperature polymer extrusion) and; 5) automatic computation of the continuously evolving convection and radiation surfaces. In the current work, in conjunction with the general simulation framework above, we are introducing a generic metallurgical*

Keywords: *Additive Manufacturing, Metallurgical Model, Process Simulation, Selective Laser Melting*

1. Introduction

Recapture the abstract.

2. Experimental Programme

To provide calibration and validation data, an experimental test program involving SLM processing, metallographic examination, and mechanical testing was undertaken. For the purpose of this activity, two, Ti-6Al-4V (Grade 23) cruciform parts were manufactured using a special-purpose Renishaw AM250 machine. The cruciform parts had a 4mm wall thickness, 140mm end-to-end span and a 40mm build height. The SLM process parameters were as follows:

- 100°C substrate temperature and a 60µm layer thickness.
- A scan strategy comprising parallel, alternating scan lines for the infill and four boundary contours.
- Infill: 200W power, 70µs exposure time, 60µm point distance and 95µm hatch spacing.
- Boundary contours: 160W power, 30µs exposure time, and 20µm point distance.

Figure 1 shows the as-built cruciform parts whilst attached to the build plate including the naming and labelling convention. The cruciform parts were removed from the build plate using EDM wire cutting. One cruciform (CRUC1) was left in the as-built condition whilst the other cruciform (CRUC2) was heat treated at 700°C for 4 hours.

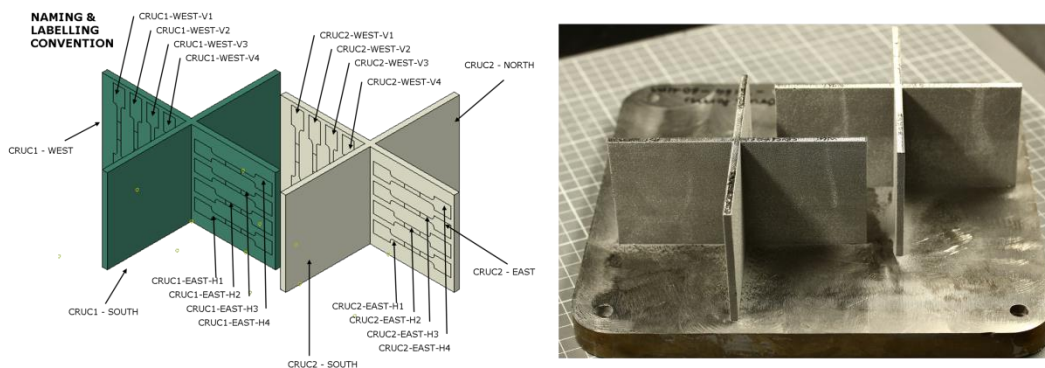


Figure 1. Stress-strain curves for tensile specimens from the cruciform builds.

Tensile specimens were then machined from each cruciform: four in the horizontal orientation (parallel to the build plate) and four in the vertical orientation (parallel to the build direction). Tensile testing was then performed on each specimen and the resulting engineering stress-strain curves are shown in Figure 2. For three of the specimens in the as-built condition, fracture occurred within the vicinity of the shoulder radius, invalidating the test results. The stress-strain curves demonstrate the following features:

- Whilst SLM processing is known to introduce anisotropy and texture, the stress-strain curves show only small differences in the yield and hardening behaviour for horizontal and vertical orientation specimens in the same condition (as-built or heat treated).
- The heat treated specimens exhibit a lower yield point and ultimate tensile strength compared with the as-built specimens, as expected.
- The horizontal specimens, in general, exhibit larger fracture strains (and uniform elongation limits) than the vertical specimens.

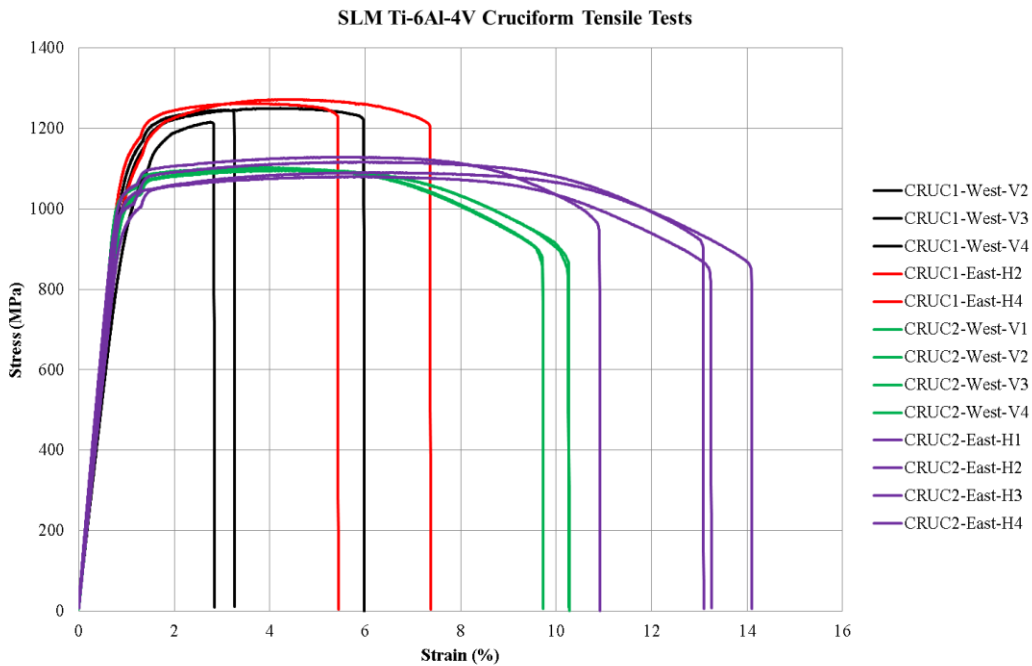


Figure 2. Stress-strain curves for tensile specimens from the cruciform builds.

Following tensile testing, the remaining plates from the cruciform parts (in addition to the gripped and unstrained portions of the tensile specimens) were subjected to metallographic examination. Figure 3 shows an EBSD map for the heat treated condition. This image clearly shows the growth of grain boundary α phase that was not observed in the as-built condition. In addition, the clear presence of globular, primary α phase can be seen. The characteristic grain size (in this case, the width of the martensite laths) is $X\mu\text{m}$.

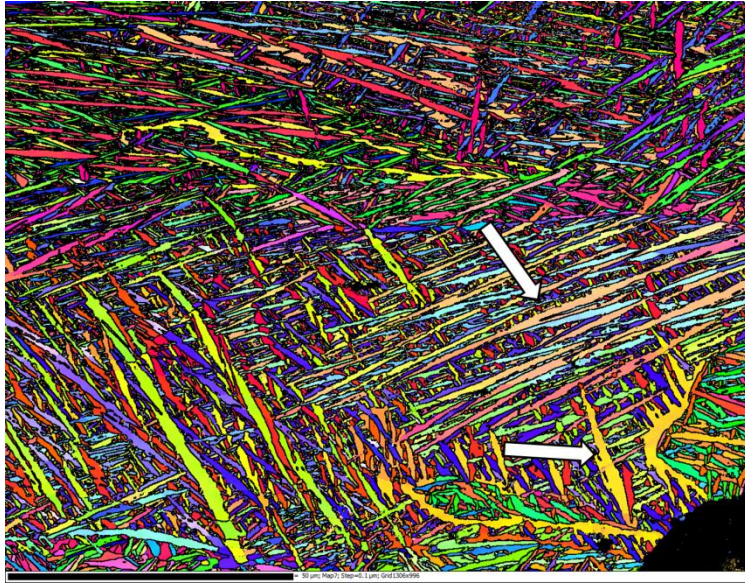


Figure 3. EBSD map from the heat treated condition highlighting grain boundary α .

3. Finite Element Modelling

[Input from Victor]

4. Microstructure-Property Relationships

[Discussion on hall-petch and nano-hardness results linking Young's modulus to phase content; linking yield strength to inverse square of grain size; linking UTS to linear relationship with grain size; similar for elongation]

5. Results

[comparison of model predictions to mechanical properties]

6. References

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