Solid Freeform Fabrication 2022: Proceedings of the 33rd Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

COMPARISON OF MULTIPLE HEAT TREATMENTS BY OBSERVING MECHANICAL PROPERTIES AND MICROSTRUCTURE OF LPBF FABRICATED ALUMINUM F357

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Abstract

In this paper, Aluminum F357 (AlSi7Mg), a material which is widely used in the automotive, aerospace, and additive manufacturing industries, will be analyzed after performing several heat treatments to enhance the properties of the material. However, there is currently no standard for the usage and heat treating of F357 alloy; for that reason, ASTM F3318 standard will be followed for heat treating it. Having a comprehensive study on the performance of 3D-printed F357 benefits the automotive, military and aerospace industries due to the numerous casted components already in service and many becoming legacy components. This work presents mechanical and microstructural properties of F357 specimens fabricated with SLM technology and subjected to heat treatments; as-built, stress-relief, T6, hot isostatic pressing (HIP), and HIP+T6 heat treatments were applied. Furthermore, with the interest of the alloy performance in-service conditions, the specimens were subjected to artificial thermal aging.

Introduction

As additive manufacturing evolves into a more viable option for manufacturing components, more materials are being studied. F357 is one of those materials that still needs to be studied more into depth so that it can be used where suitable since it has been mainly used for casting applications[1]. Aluminum F357 is anti-corrosive, and lightweight[2][3]. These characteristics make this material ideal for aerospace, military, and automobile applications[4].

This study was performed using a Selective Laser Melting (SLM) M280 machine. SLM is a Laser Powder Bed Fusion (LPBF) AM technology which uses a laser beam to melt layers of metal powder to then form a part. This technology can build complex geometry components with good mechanical properties, comparable to the ones achieved with traditional manufacturing processes[5]. Aside from this, LPBF is also capable of delivering high density parts with high dimensional accuracy[6]. It is common to apply heat treatment to the manufactured samples in order to enhance the properties of the material[7]. In general, heat treatments are a common post processing step for most metal AM technologies given that by applying a heat treatment, most of the residual stresses formed in the printing process can be released/eliminated as well as the porosity induced by either the printing process or the nature of the atomized powder[8]. In particular, SLM can induce certain stresses due to the high temperature gradient while in the printing process[9]. Given that this material has no specific standard for heat treatment, ASTM F3318 – 18 standard was followed and several heat treatments were applied; as-built, stress-relief, T6, hot isostatic pressing (HIP), and HIP+T6. After applying these heat treatments, the specimens were aged at different temperatures and aging times (0hr, 100hr, 1000hr at 285 °F and 385 °F). Later they were tested and analyzed to observe their mechanical performance and microstructure.

Materials and Methods

Powder Feedstock

The material used for this study is atomized F357 (AlSi7Mg) powder, obtained from Valimet, AM 357C. A Retsch Camsizer X2 machine was used to characterize this powder. This characterization process showed that the powder had a particle size distribution of D10: 24.4 µm, D50: 39.3 µm, and D90: 60.4 µm. Figures 1 & 2 show SEM images of the powder particles; as it can be seen, the particles seem to be mostly spherical.

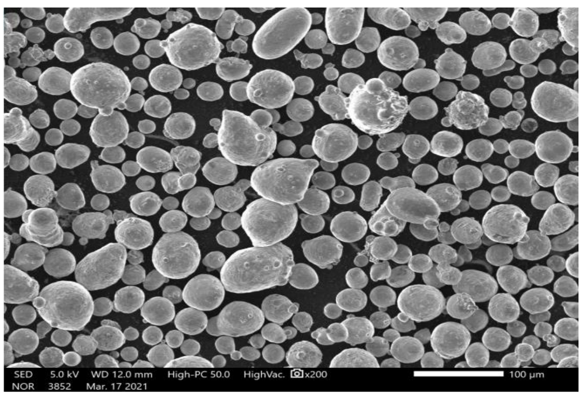

Figure1: SEM Powder Particles

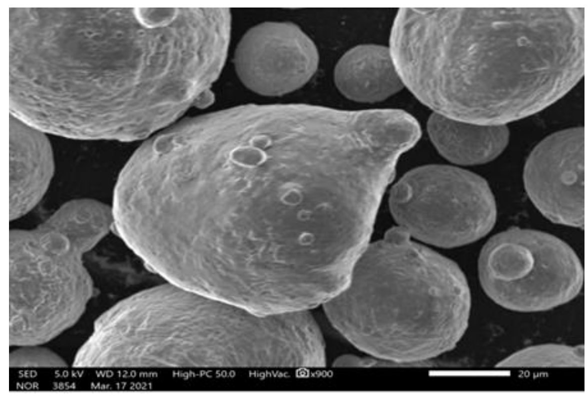

Figure 2: SEM Particles (Higher Magnification)

Laser Powder Bed Fusion (LPBF)

This technology additively manufactures components by melting layer by layer of metal powder with a laser. This process occurs in an inert atmosphere such as in an argon gas environment which allows this to be a clean process. It is mostly suitable for rapid prototyping but can also be used for low & high volume production. As AM has grown during the past decades, this technology has evolved and become one of the primary technologies for metal AM and can now print a wide variety of materials. As the printing layer thickness is considerably small, the resulting surface finish of the printed components is of high quality. As mentioned above, LPBF has high dimensional accuracy and can produce highly dense parts. Although it is common for the parts to go through a heat treatment after printing due to residual stresses created in the process, this technology has shown it can deliver components with desirable microstructure and mechanical performance. Figure 3 shows the machine in which all samples were printed.

Figure 3: SLM M280

Heat Treatments and Thermal Aging

As mentioned before, several heat treatments were applied to the printed specimens (all as per ASTM F3318 – 18):

SR1: parts shall be stress relieved or partially annealed in accordance with AMS 2771 except that the temperature shall be 285 °C (±14 °C), held for 120 min (15±) and cooled at a rate equal to air cooling or faster. Refer to AMS 2771 for soaking time and furnace class requirements.

T6: parts shall be solution heat treated in accordance with AMS 2771 except the temperature shall be 530 °C (±6 °C) held for 360 min minimum, quenched in water or glycol as agreed upon by the part supplier and purchaser and aged at 160 °C (±6 °C) for 360 min minimum. Refer to AMS 2771 for soaking time and furnace type requirements.

HIP+T6: product shall be hot isostatically pressed (HIP) under an inert atmosphere at 100 MPa minimum within the range 510 °C - 520 °C, held at the selected temperature within ±14 °C for 180 ±60 min and cooled under inert atmosphere to below (93 °C). HIP should be followed be Condition T6 processing. Refer to AMS 2771 for soaking time and furnace class requirements.

As-Built (NHT): no heat treat required. Parts are supplied in the as-built condition.

In addition to the heat treatments, artificial thermal aging will be applied to the specimens to further analyze the behavior of the material and simulate its performance under service conditions. The aging is divided into two temperatures, 285 °F and 350 °F, held at three different times (0 h, 100 h and 1000 h).

Tensile Testing (Uniaxial Monotonic Tensile Load)

After applying the proper heat treatment to samples, each of them were then machined into tensile coupons to then perform a tensile test as per ASTM E8 Standard Test Methods for Tension Testing of Metallic Materials. This test was performed in an MTS Landmark machine. When the test was performed, this machine would obtain the mechanical properties such as Yield Strength, Elongation at Fracture, and Ultimate Tensile Strength among others.

Figure 4: MTS Landmark; Tensile Test

Density Measurements

A selected section was cut from the tested tensile coupons to then analyze it in an Accupyc II 1340 Pycnometer, shown in Figure 5, to obtain density measurements. The process involves gas displacement. After weighing the sectioned piece, the density measurements can then be obtained by performing a calculation with the mass and volume values obtained from the weighing apparatus and pycnometer system respectively.

Figure 5: Accupyc II 1340 Pycnometer

Microstructure Characterization

The previous section used for density measurements was again cut in the X, Y, and Z plane direction to later be mounted in epoxy to then be grinded and polished with the use of an ATM SAPHIR 530 machine. Several pictures of the different planes were taken at multiple magnifications using an Olympus GX53 microscope. Later, the same mounted samples would be etched and analyzed using the same microscope to observe the melt pools.

Figure 6: Mounted Samples

Figure 7: Grinding & Polishing SAPHIR 530

Results and Discussion

Microstructure Analysis

Density for the material used in this study is 2.67 g/cm^3; all density measurements taken shall be compared to this density.

Process	Density (%)
As-Built	99.2
SR1	99.6
HIP	99.5
T6	98.3
HIP+T6	99.8

Table 1: Density

After taking images of the as polished microstructure of the different samples, it can be observed that the as-built samples show some porosity and almost no sign of precipitates. Light precipitate density can be shown in the SR1 samples, with a lower level of porosity. After observing the HIP, T6, and HIP+T6 samples, it can be seen that they are very similar; they show high levels of precipitates and small amount of porosity.

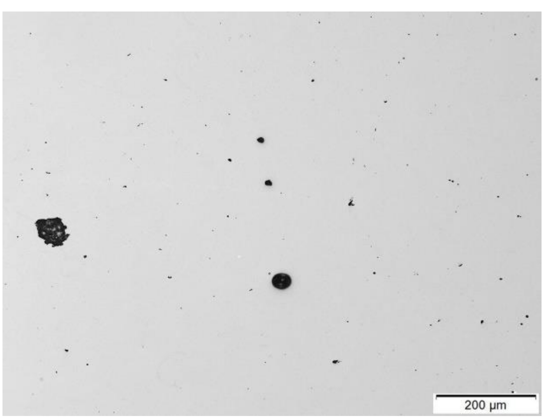

Figure 8: As-Built X-Plane

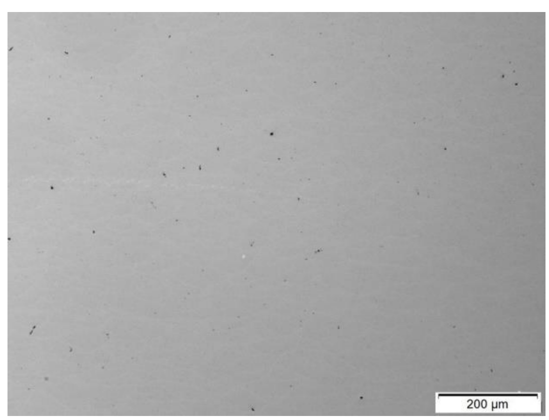

Figure9: SR1 X-Plane

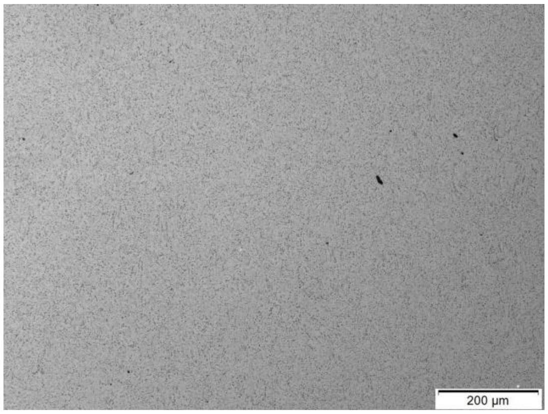

Figure 10: HIP X-Plane

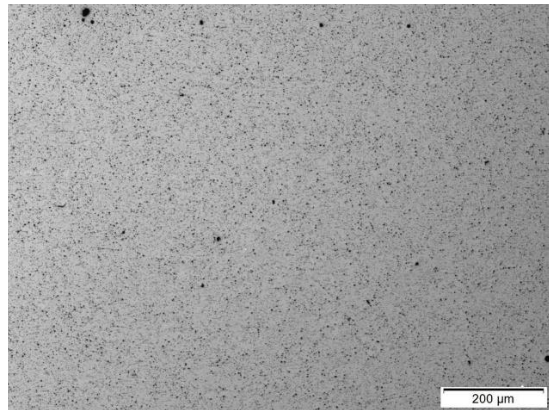

Figure 11: T6 X-Plane

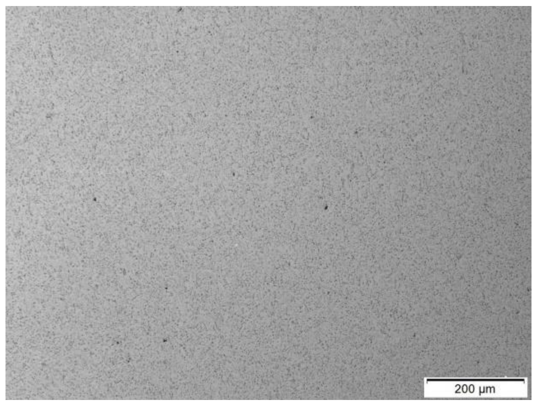

Figure 12: HIP + T6 X-Plane

Mechanical Properties

After the tensile tests performed, all data was analyzed to obtain the average Yield Stress, Ultimate Tensile Strength (UTS), Young's Modulus, and Elongation at Fracture for all samples. As it can be seen in the table below, the samples that showed the best results on Yield Stress and UTS and Young's Modulus were the as-built; horizontal and vertical orientations showed similar results. Nevertheless, as-built samples showed small percentage on Elongation at Fracture compared to the others, showing that they are brittle. On the other hand, even though HIPed samples showed the lowest numbers on strength, they showed high percentage on Elongation, meaning they turned ductile.

Heat Treatment	Orientation	Yield Stress (MPa)	UTS (MPa)	Young's Modulus (GPa)	Elongation at Fracture (%)
As Built	Horizontal	261.3	409.3	74.05	7.4
	Vertical	293.3	406.5	74.9	8.3
SR1	Horizontal	156.3	252.3	70.8	16.5
	Vertical	155.2	241.0	67.8	19.4
HIP	Horizontal	85.5	134.5	68.7	31.8
	Vertical	88.3	136.0	99.7	24.4

T6	Horizontal	264.8	314.2	65.9	11.5
	Vertical	260.3	311.2	66.2	12.9
HIP+T6	Horizontal	180.0	239.3	65.4	20.2
	Vertical	188.2	245.4	62.4	18.1

Table 2: Mechanical Properties Across Heat Treatments 0hr

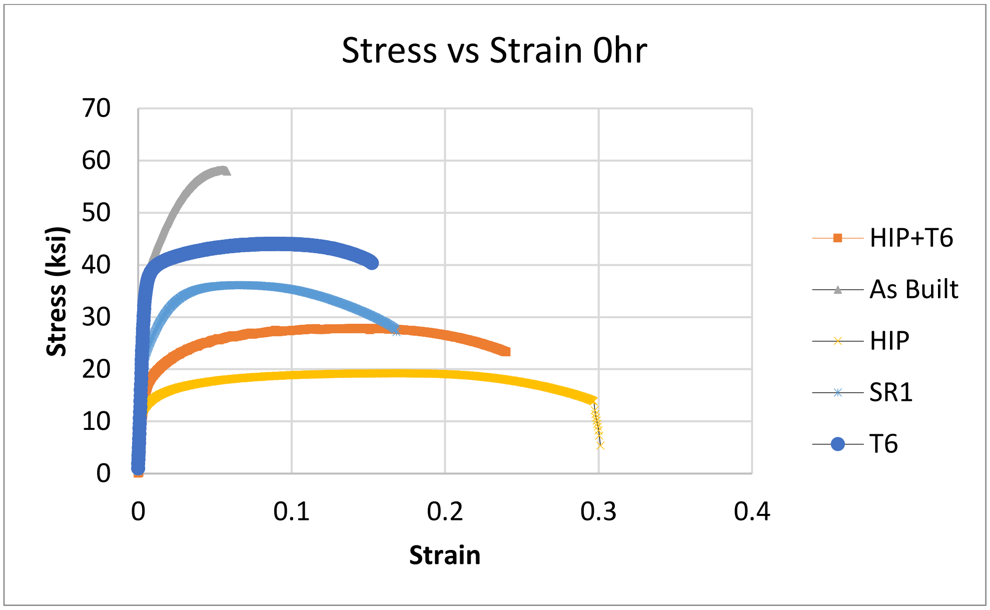

Figure 13: Stress vs Strain Graph 0hr

Furthermore, Figures 14-17 show the result of the mechanical properties of the aged samples after testing. As it can be seen, all mechanical properties change when thermal aging is applied. Most samples show enhanced performance on UTS and Yield Stress at 285 °F, specially at 100hr, and increased elongation as the temperature and aging time increase.

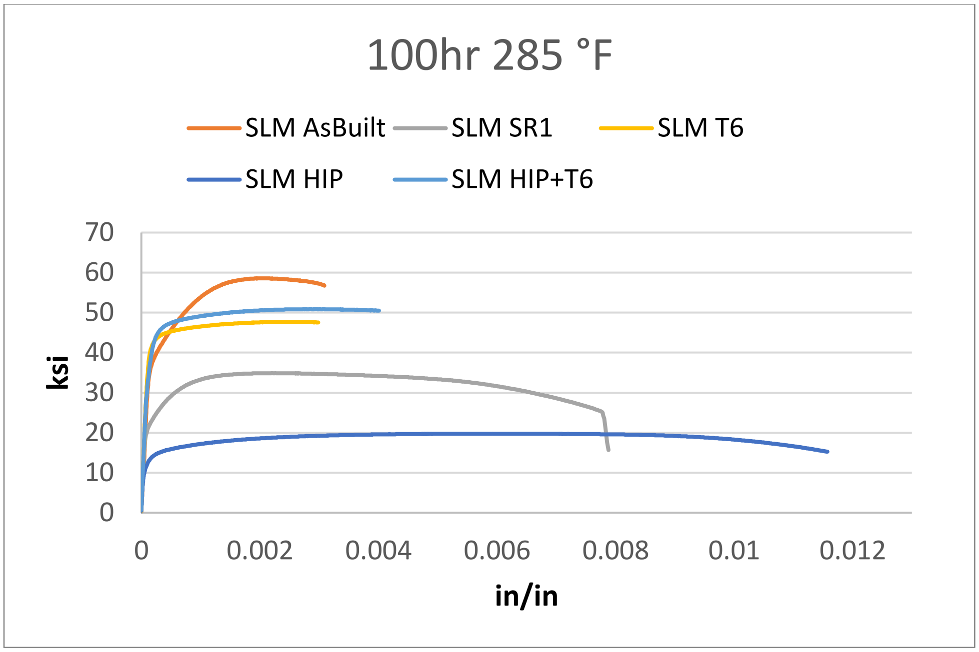

Figure 14: Stress vs Strain Graph 285 °F 100hr

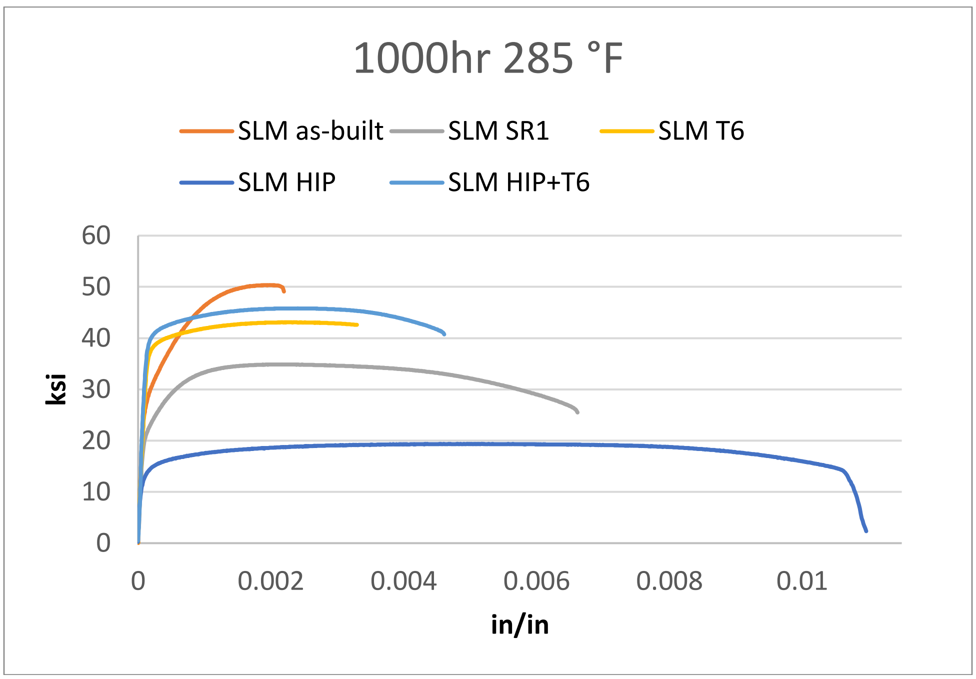

Figure 15: Stress vs Strain Graph 285 °°F 1000hr

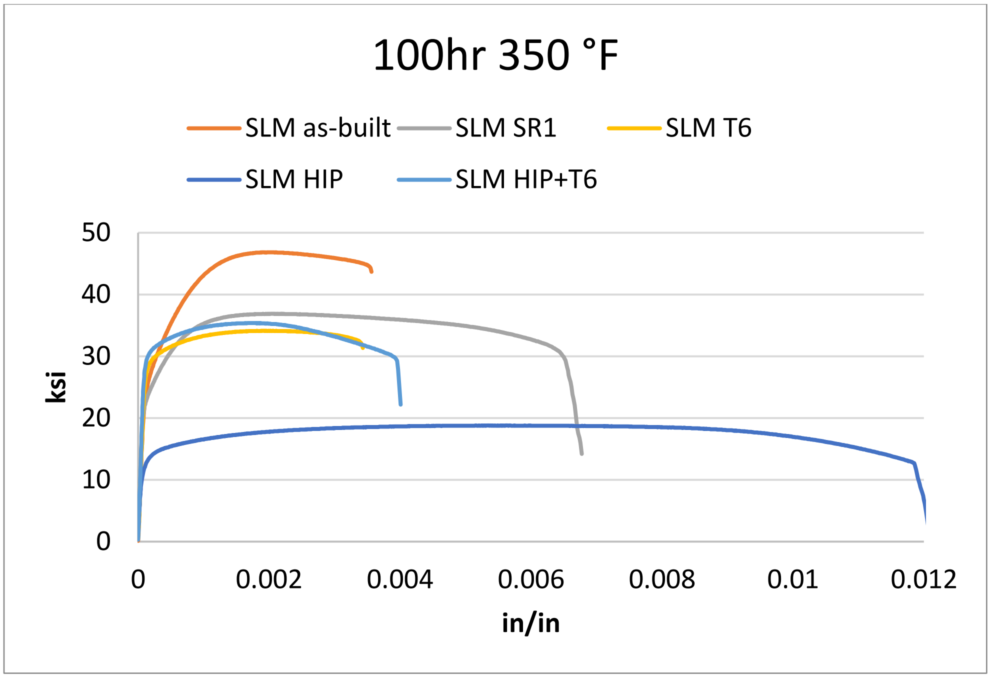

Figure 16: Stress vs Strain Graph 385 °F 100hr

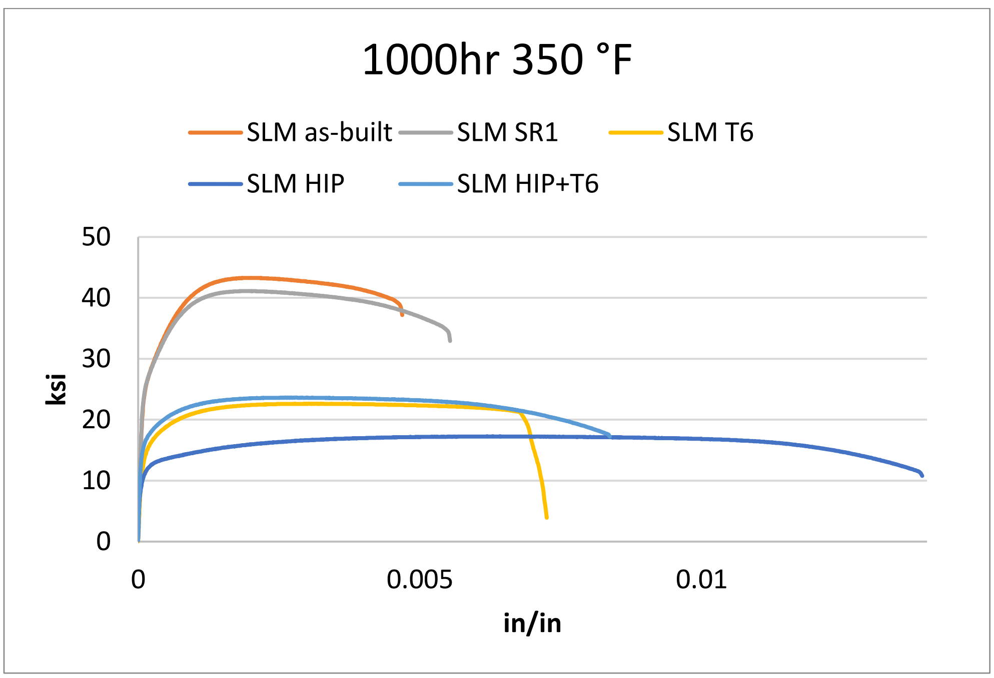

Figure 17: Stress vs Strain Graph 385 °F 1000hr

Conclusion

All samples were built using as SLM machine, LPBF technology, and multiple heat treatments were applied to them. This was done to further the research done on Aluminum F357 as it has no proper standards to heat treat this material. After applying the heat treatments, multiple samples were subjected to thermal aging. Next, they were mechanically tested, and a microstructure analysis was performed. As it can be seen in the results section, this material showed high values in UTS and Yield Strength in its As-Built form, but showed higher levels of ductility as it was heat treated. This material also changes dramatically as it becomes aged, showing higher levels of ductility as it is aged with more temperature during longer times. Depending on the application, this study has demonstrated how the material's properties can be changed/manipulated by heat treating it to obtain whatever characteristics are needed.

Future Work

This study is an ongoing research; several sections of this project are still being worked on such as hardness testing and etching the samples. With these sections of the project being completed, the specimens will be further analyzed. After finishing these portions of the study, a better understanding of the microstructure and performance of this material under the different heat treatment conditions will be obtained.

Acknowledgements

The research described here was performed at The University of Texas at El Paso (UTEP) within the W.M. Keck Center for 3D Innovation (Keck Center). The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official opinion or policy of any other agency.

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