IN718 Additive Manufacturing Properties and Influences

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ABSTRACT

The results of tensile, fracture, and fatigue testing of IN718 coupons produced using the selective laser melting (SLM) additive manufacturing technique are presented. The data have been "sanitized" to remove the numerical values, although certain references to material standards are provided. This document provides some knowledge of the effect of variation of controlled build parameters used in the SLM process, a snapshot of the capabilities of SLM in industry at present, and shares some of the lessons learned along the way. For the build parameter characterization, the parameters were varied over a range that was centered about the machine manufacturer's recommended value, and in each case they were varied individually, although some co-variance of those parameters would be expected. Tensile, fracture, and high-cycle fatigue properties equivalent to wrought IN718 are achievable with SLM-produced IN718. Build and post-build processes need to be determined and then controlled to established limits to accomplish this. It is recommended that a multi-variable evaluation, e.g., design-of-experiment (DOE), of the build parameters be performed to better evaluate the co-variance of the parameters.

INTRODUCTION

A large aggregate of tensile, fatigue, and fracture test data has been produced from coupons generated from the additive manufacturing (AM) process called selective laser melting (SLM). The preponderance of testing done to-date used IN718, nickel-base super alloy, and this is the material discussed in this document. SLM is a laser powder-bed fusion process using a laser to melt and consolidate powder. This produces three-dimensional objects as a sequential buildup of layers, and this process shows promise in the aerospace industry, since it can produce near net shapes and has the potential for producing very complex configurations that are difficult with conventional manufacturing techniques.

<u>Build and Heat Treatment</u>

A Concept M2 powder bed fusion selective laser melt machine was used for builds performed by NASA Marshall Space Flight Center (MSFC). The results reported herein were for tests of IN718 nickel-base superalloy. Specimens were produced as a dedicated build or as representative "witness samples" of build lots where prototype components were produced. No effort was used herein to segregate results from different powders in the analysis, although some information was available.

All specimens were stress relieved for 1.5 hours at 1950°F in a vacuum and then quenched in argon. After stress relief, parts were excised from the build platen. Hot-isostatic pressing (HIP) was performed next. The HIP process subjects parts to high pressure and temperature. In this case, an argon atmosphere was maintained at a pressure of 15 ksi and a temperature of 2125°F for four hours, and then the furnace was slow cooled. Two heat treat conditions were used that differed from this point in the post-build processing. Some specimens received heat treat "A". For these, after stress relief and HIP, parts were homogenized for one hour at 2150°F in a vacuum and then quenched to below 1100°F in argon in less than 10 minutes. These were then solution treated at 1750°F for one hour in a vacuum, argon quenched, and then aged in two steps at 1325°F for eight hours followed by 1150°F for ten hours. This is the heat treatment specified by AMS 5663 [1]. Other specimens received heat treat “D”. In this case, after stress relief and HIP, specimens were solution treated at 1950°F for 1 hour, argon quenched, and then aged in two steps at 1400°F for 10 hours followed by 1200°F for 10 hours. This is the heat treatment specified by AMS 5664 [2]. No homogenization step was performed on the heat treat D specimens.

Build Orientation

The build orientation is defined using the naming convention for additive manufacturing adopted at MSFC, as shown in figure 1 below. The letter “Z” identifies the build direction, i.e., the direction in which subsequent layers are stacked, while “XY” identifies the build plane. The material is considered to be transverse-isotropic, i.e., properties do not vary by direction in the build plane, hence the “XY” notation was adopted for any direction lying in the build plane.

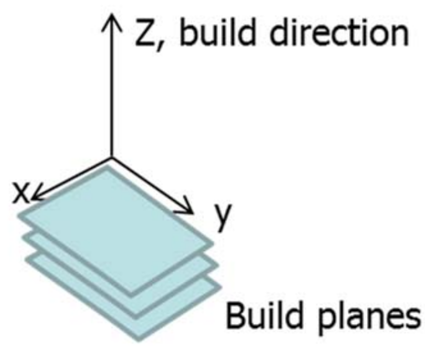


Figure 1: NASA-MSFC naming convention for build directions.

Tensile Tests

Tensile test coupons were smooth rounds with a diameter of 0.25-inches and a length in the reduced section of 1.25-inches. This accommodated a 1.00-inch gauge-length, which is used in evaluating the elongation. Both Z- and XY-orientations were tested, and all specimens were machine-turned to the tested configuration. Tensile tests were conducted and analyzed per ASTM E8 [3].

High-Cycle Fatigue (HCF) Tests

The high-cycle fatigue specimen configuration was similar to the tensile, with the center tapered very slightly. Specimens were tested with various surface conditions, including “as-built”, low-stress ground, bead-blasted, and a proprietary process called micro-mechanical processing (MMP). HCF testing was performed per ASTM E466 [4], and only the Z-orientation was considered. All HCF testing was conducted at a stress ratio (minimum stress/maximum stress), R = 0.1.

Fracture Tests

Compact tension specimens were fracture tested per ASTM E1820 [5]. The tested orientations are identified as “Z” and “XY” in this article. These have correspondence with the build directions, discussed above, and the orientations are defined pictorially in figure 2. The Z-orientation corresponds to Z-X or Z-Y, using the correct ASTM nomenclature, where the first digit(s) identify the loading direction, and the second digit(s) identify the direction of crack extension. The Z-orientation would lead to delamination of adjacent build planes. The XY-orientation corresponds to X-Y or Y-X in the ASTM convention. The XY-orientation would lead to tearing of the build planes.

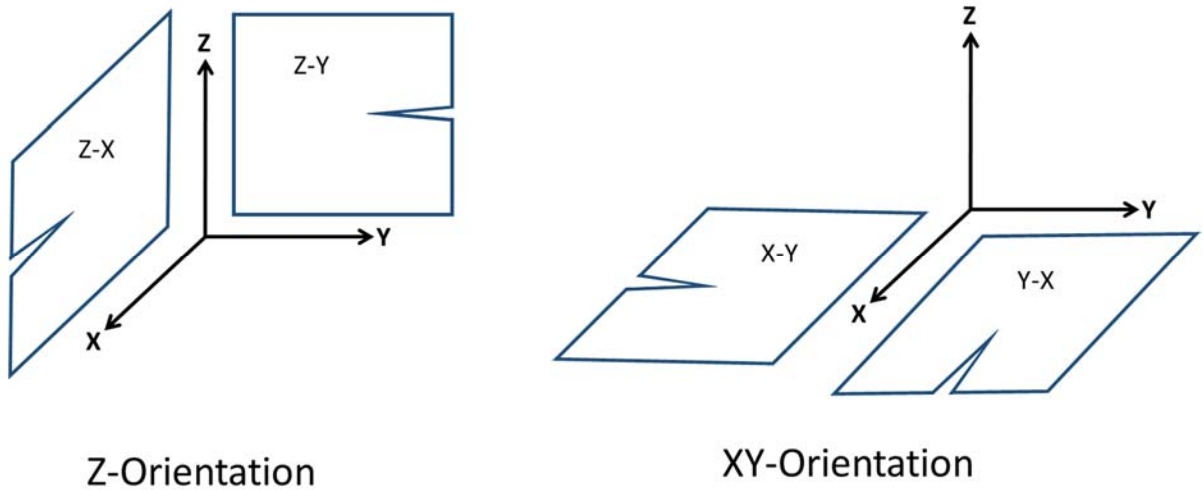


Figure 2: The polygons are two dimensional representations of compact tension (CT) specimens. ASTM specifies the first digit as the loading direction and the second digit as the growth direction, and this is shown superimposed on the individual CT figures, and the label that was adopted for the orientations is shown below the figures.

BUILD PARAMETERS EFFECT MECHANICAL PROPERTIES

Several runs were conducted at MSFC where the majority of build-control parameters were set at the machine manufacturer's recommended value, and then one parameter was varied above and below the recommended value to evaluate the sensitivity of the parameter and find the best settings. Parameters characterized in this fashion included the build layer thickness, core laser power, laser scan hatch width, and laser scan speed. Build layer thickness is the depth of the powder layer that is consolidated as each layer is produced, and hatch width is the distance between laser passes within a layer, defining the overlap of adjacent passes within the layer.

Varying of a single parameter is simplistic, and it is incapable of simultaneously optimizing multiple parameters that are known to be covariant, i.e., variables that are known to have a similar effect on the results. Whereas the recommended values were the stationary values used, these results should be useful and are expected to be close to the best settings.

<u>Core Laser Power</u>

Figures 3 and 4 show the effect of varying core laser power on the tensile strengths and the fit-back elongation of the gauge length of two different build layer thicknesses, respectively. The elongation presented is the "4D" result that arises from fit-back of the broken tensile specimen: this uses the extension of the gauge length, which is initially four times the diameter. Two build layer thicknesses were evaluated: 0.030-mm and 0.045-mm., and all build parameters were per recommendation while the laser power was varied in a range that surrounded the recommended value. Notice that for the 0.045-mm layer thickness, the ultimate tensile strength increases as input power increases. This seems to level off and variance decreases as power increased. Notice also that the gauge elongation for the

0.045-mm layer thickness increases as input power increases. As laser power increases the 0.045-mm layer thickness seems to be converging towards the same value as the 0.030-mm layer thickness.

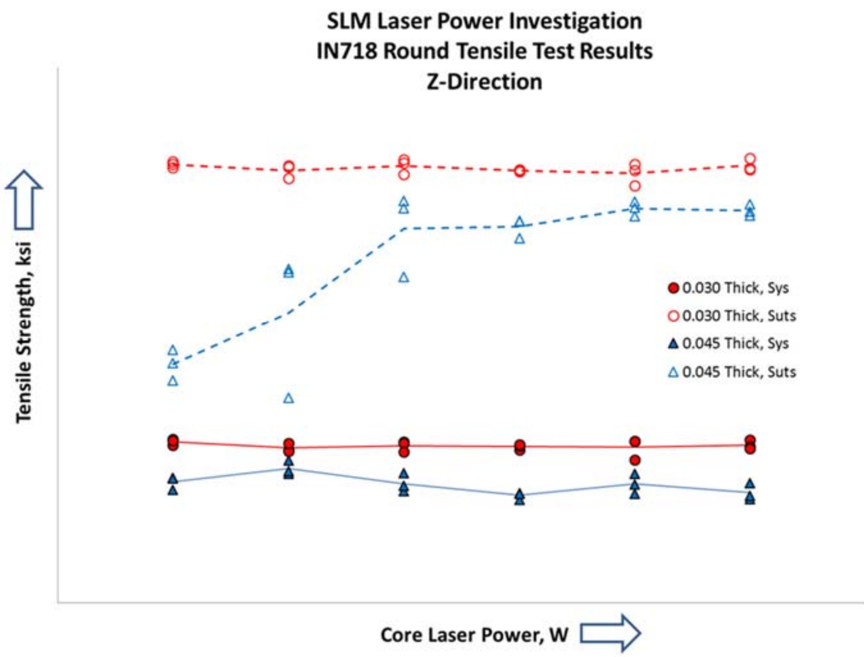


Figure 3: Effect of core laser power on ultimate tensile strength (Suts) and yield strength (Sys). NOTE: two build layer thicknesses are plotted.

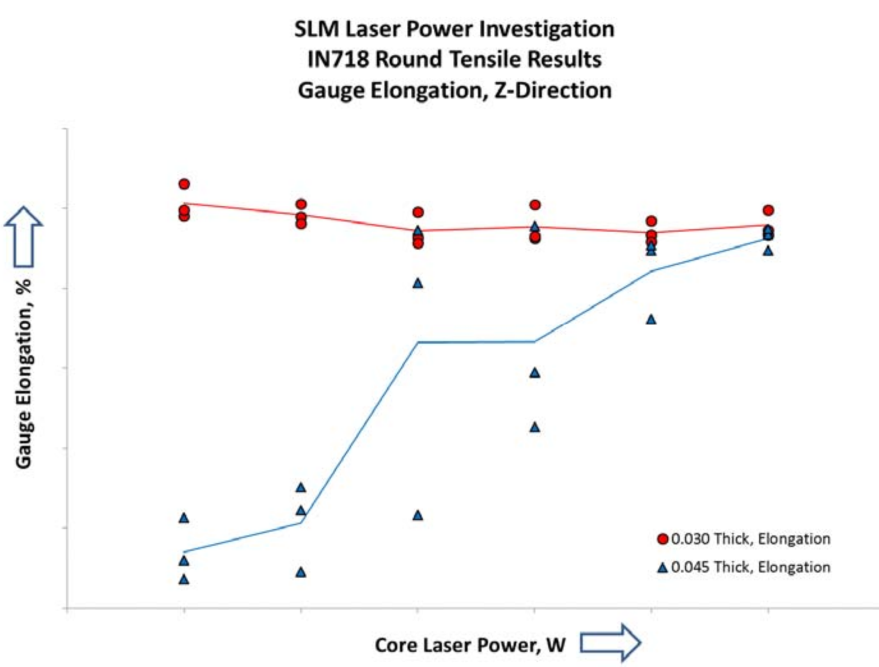


Figure 4: Effect of core laser power on fit-back gauge length elongation. NOTE: two build layer thicknesses are plotted.

<u>Laser Scan Hatch Width</u>

Figures 5 and 6 are graphs of tensile strengths and gauge elongation versus laser scan hatch width. Hatch width is the distance between consecutive passes, and it defines the overlap between laser passes within a given build layer. Two combinations of layer thicknesses/core laser power were evaluated: 0.030-mm/180 watts and 0.045-mm/200 watts. Build parameters were set per recommendations, except for hatch-width, which was varied around the recommended value. Notice that for 0.045-mm build layer thickness the ultimate tensile strength increases as hatch width increases. This seems to level off and variance decreases to a level considered acceptable when the power level is slightly above the recommended value, but it does not reach the same strength as the 0.030-mm build layer thickness results. Yield strength may increase for the 0.045-mm build thickness to a stable value at a hatch width slightly below the recommended value, and again, the yield strength is slightly below the 0.030mm build layer thickness results.

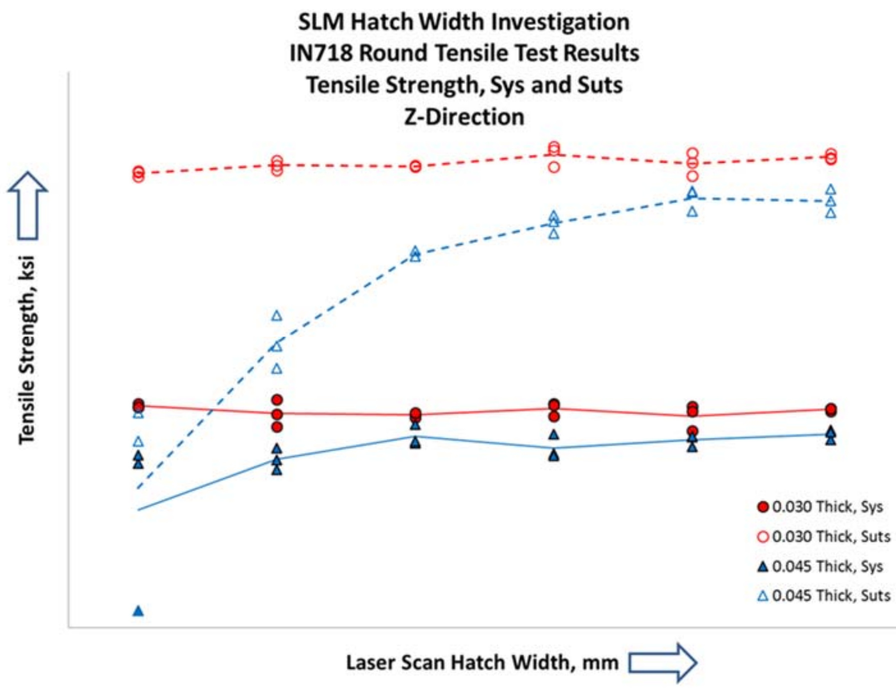


Figure 5: The Effect of laser scan hatch width on ultimate tensile and yield strengths. NOTE: two build layer thicknesses are plotted.

Notice in figure 6 that for the 0.045-mm layer thickness the gauge elongation increases as hatch width increases. Gauge elongation appears to increase slightly for the 0.030-mm layer thickness up to the recommended value, and has insignificant variance for increasing hatch widths beginning slightly below the recommended value.

<u>Core Laser Scan Speed</u>

Core laser scan speed was varied around the recommended value while the other build variables were maintained as recommended. For this run, only the 0.030-mm build layer thickness was considered. Ultimate tensile strength and yield strength were essentially constant over the entire range of laser scan speeds tested, as can be seen in figure 7. This is probably true of the gauge elongation as seen in figure 8 as well: since the variability was so large, the inserted average curve means little.

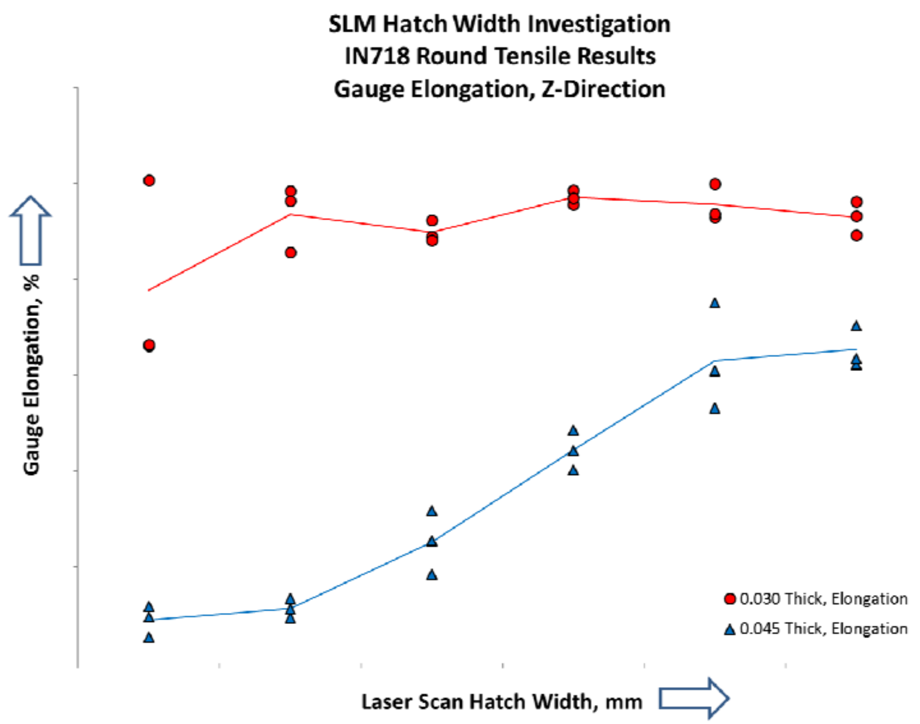


Figure 6: The Effect of laser scan hatch width on gauge elongation. NOTE: two build layer thicknesses are plotted.

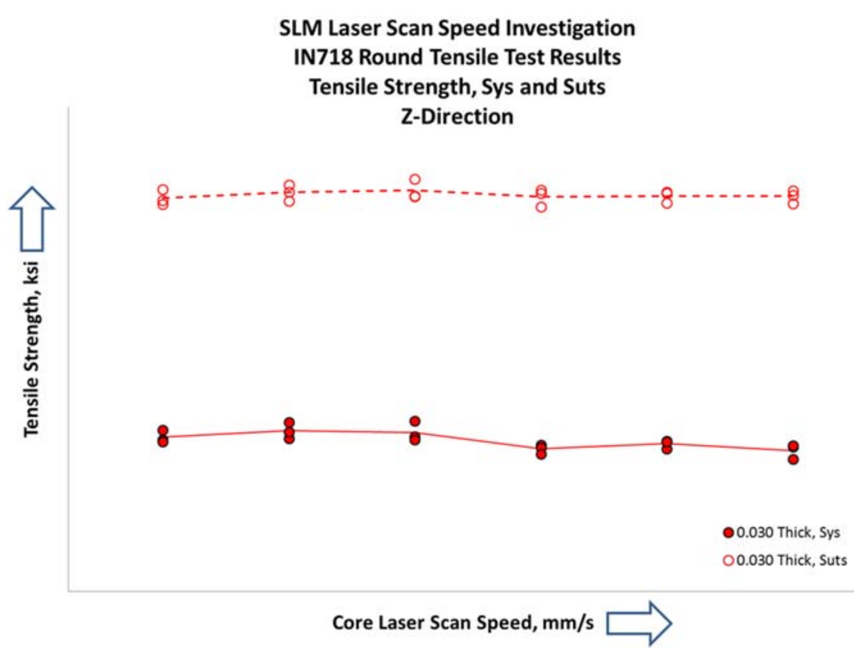


Figure 7: Tensile strengths, Suts and Sys as a function of the core laser scan speed for two different build thicknesses.

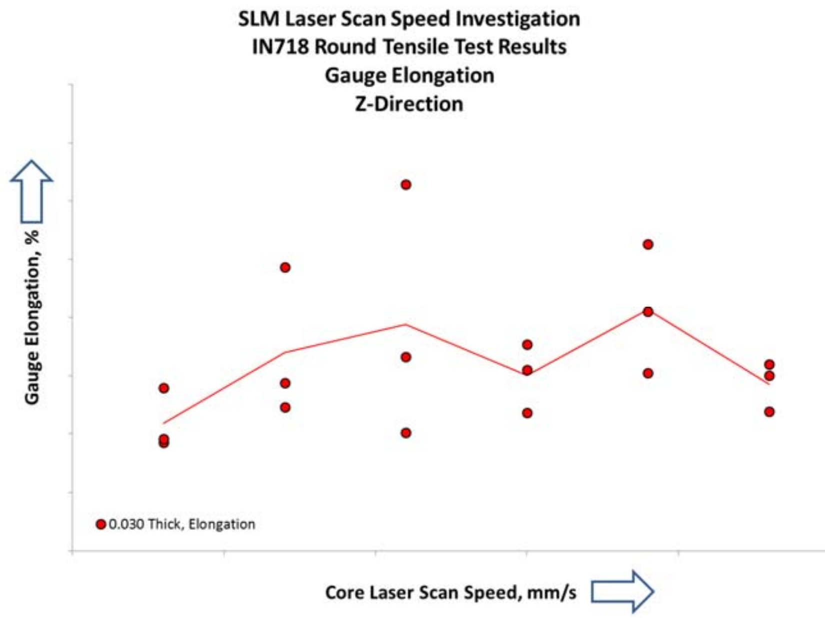


Figure 8: Gauge elongation as a function of the core laser scan speed for two different build thicknesses.

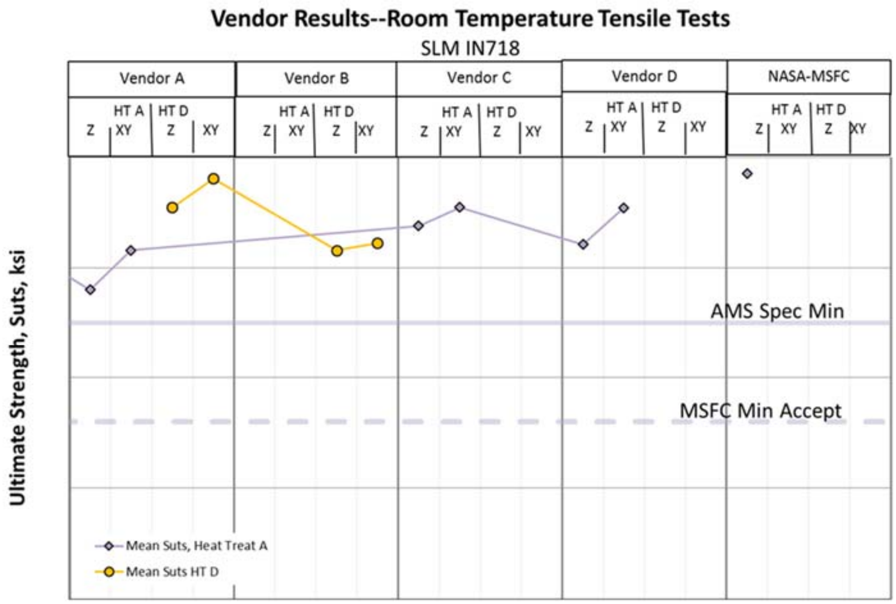
SURVEY OF CAPABILITIES ACROSS VENDORS

A large set of data was accumulated from numerous vendors, and the results are provided next. Most of these came from the inclusion of witness samples in the builds of prototype components. For the sake of the following discussion, vendors have been identified by a letter, and the results shown should be considered typical of the SLM process.

Tensile Results

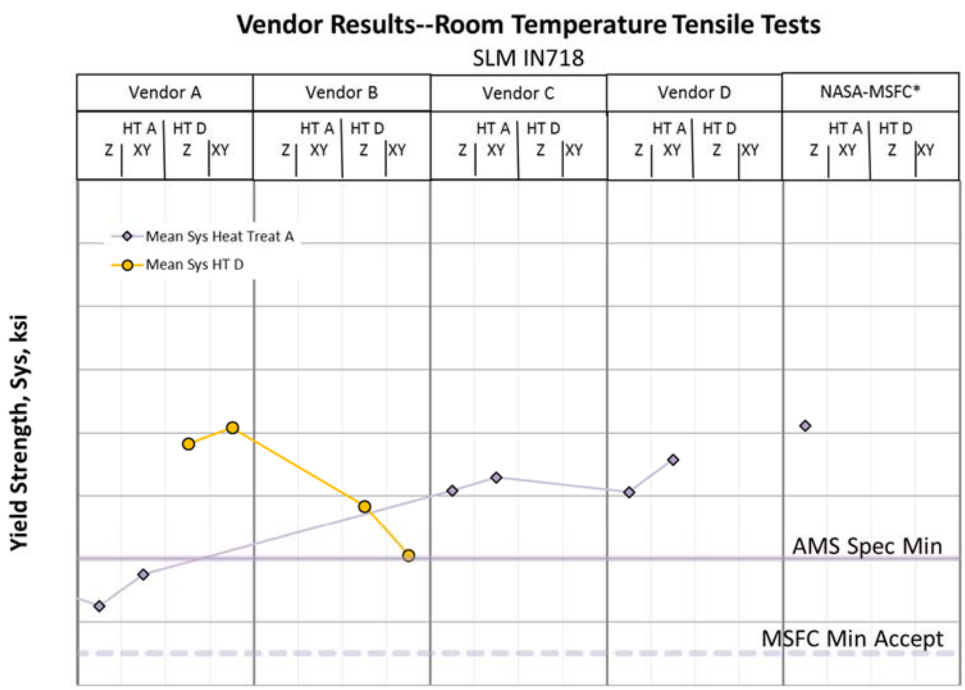
Figures 9 and 10 show ultimate tensile strength (Suts) and yield strength (Sys) for the vendors. Each point shown is an averaging of like data. Notice that Z- and XY-orientations results were similar for Suts, and that the XY-orientation produced slightly higher Suts. All Suts data are above the AMS 5663/5664 minimum (AMS Spec Min). Little data is available for heat treatment D, but for vendor A, the results for heat treatment D are higher than those of heat treatment A. The vendor-to-vendor variability is significant.

The Sys results are consistent with those provided for Suts: Sys for Z- and XY-orientations were approximately the same, and the XY-orientation Sys was slightly better. Yield strength results for all but one vendor meet or exceed the AMS 5663/5664 reference value, and that one was above the adopted MSFC minimum (MSFC Min Accept).



*NASA-MSFC tensile tests are 0.030" build thickness,
coming from the laser power, scan speed, and hatch width trials.

Figure 9: Ultimate Tensile Strengths observed for each vendor. NOTES: Each of these points is generated as an average of all of the like data available, and both Z- and XY-oriented testing is shown.



*NASA-MSFC tensile tests are 0.030" build thickness,
coming from the laser power, scan speed, and hatch width trials.

Figure 10: Yield Strengths observed for each vendor. NOTES: Each of these points is generated as an average of all of the like data available, and both Z- and XY-oriented testing is shown.

Figure 11 has been included to show the elongation results for the various vendors. It should be noted that the AMS specification minimum for planar ductility varies with direction, i.e., longitudinal or long-transverse directions differ, and the upper of these was adopted for comparison as the more difficult to achieve. In all cases, the ductility results are well above the AMS specification minima.

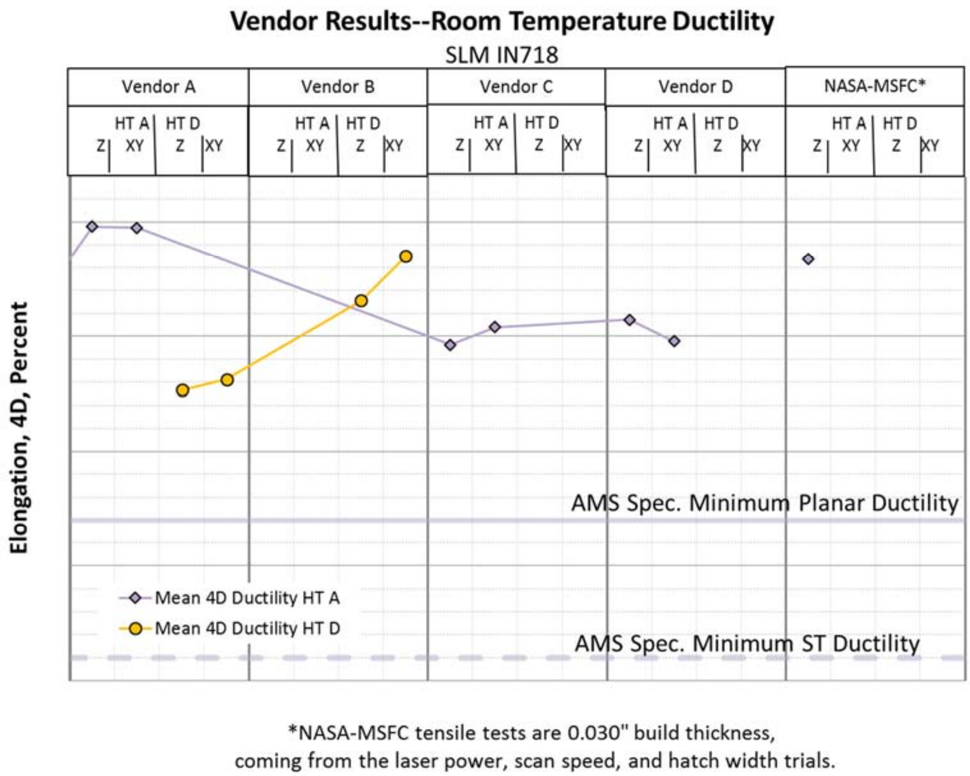


Figure 11: Elongation for each vendor. NOTES: Each of these points is generated as an average of all of the like data available, and both Z- and XY-oriented testing is shown.

Fracture Results

Figure 12 shows the fracture test results. Fracture testing did not provide valid KIc (plane strain fracture toughness) results. The results might still be useful, since they are characteristic of fracture behavior for the thickness tested. The surface crack toughness, KIe, is provided as a reference. Z- and XY-orientations provided similar results for fracture toughness, and all results were above KIc as provided in the NASGRO® materials database. This is as expected, and the fact that the results are below KIe is also expected. No further inference should be made.

High-Cycle Fatigue (HCF) Results

Figure 13 shows the HCF results for each vendor. All of these were tested in the as-built surface condition, and all received heat treatment A. For these results, vendors A and C results appear to be in-family, while vendor D was lower than A and C. All of these HCF were below the MMPDS-08 reference curves. These MMPDS-08 curves are provided as a reference, and it should be noted that they represent examples of the same alloy, but the processing was not the same as the SLM-IN718.

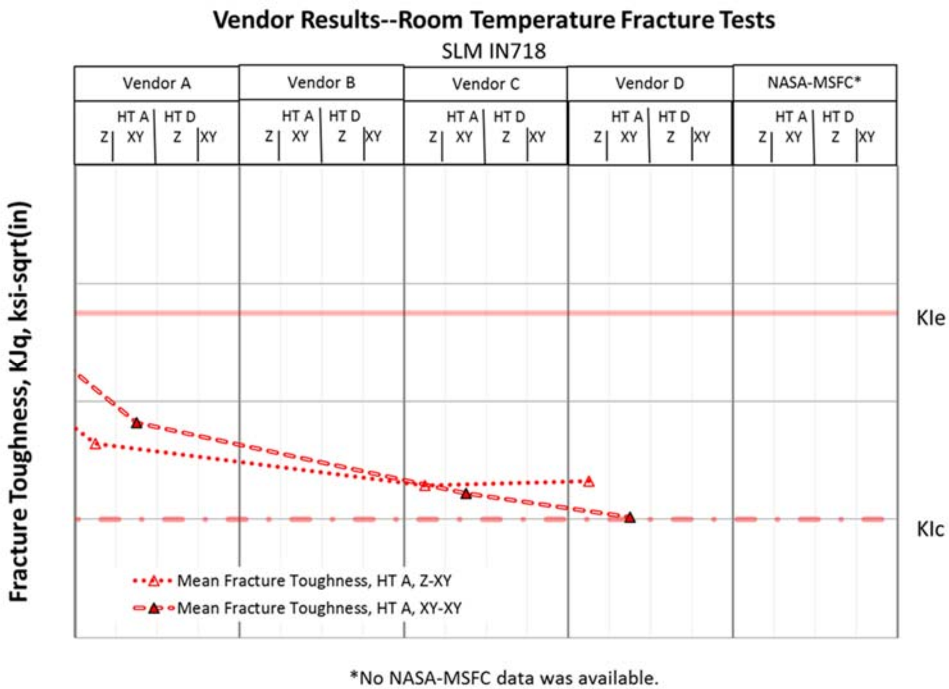


Figure 12: *Toughness for each vendor. NOTE: Each of these points is generated as an average of all of the like data available. For fracture results shown, Z- indicates the Z-XY orientation per ASTM E1820, while XY indicates the XY-XY orientation.*

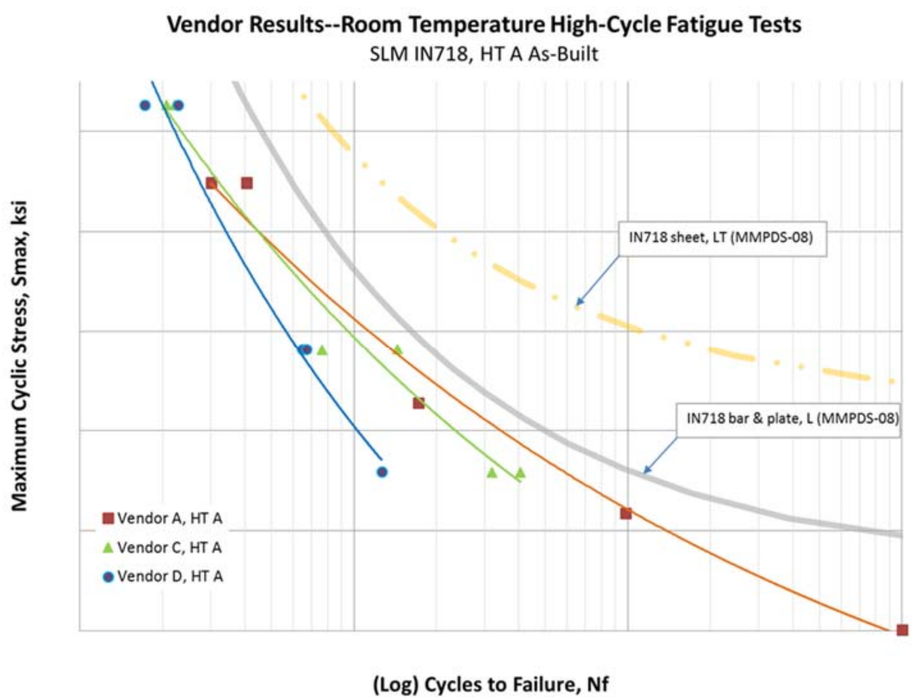


Figure 13: *High-cycle fatigue test results for each vendor. Surface finish was "as-built". NOTES: Power law fit lines have been inserted to help with visualizing the trends, and MMPDS-08 fits have been inserted to provide a basis of comparison.*

Figure 14 shows the HCF results for coupons that have received surface processing. HCF curves from MMPDS-08 are provided as a reference, and it should be noted that they represent examples of the same alloy, but the processing was not the same as the SLM-IN718. For the HCF results in figure 14, vendor C, heat treatment A, low-stress ground specimens performed as well as the published MMPDS-08 high cycle fatigue results for sheet. Vendor D, heat treatment A, low-stress ground specimens and vendor B, heat treatment D, bead-blasted specimens performed better than the published results for IN718 bar and plate, but below the published results for IN718 sheet. Vendor A, heat treatment D specimens with micro-machining performed below all of the published information.

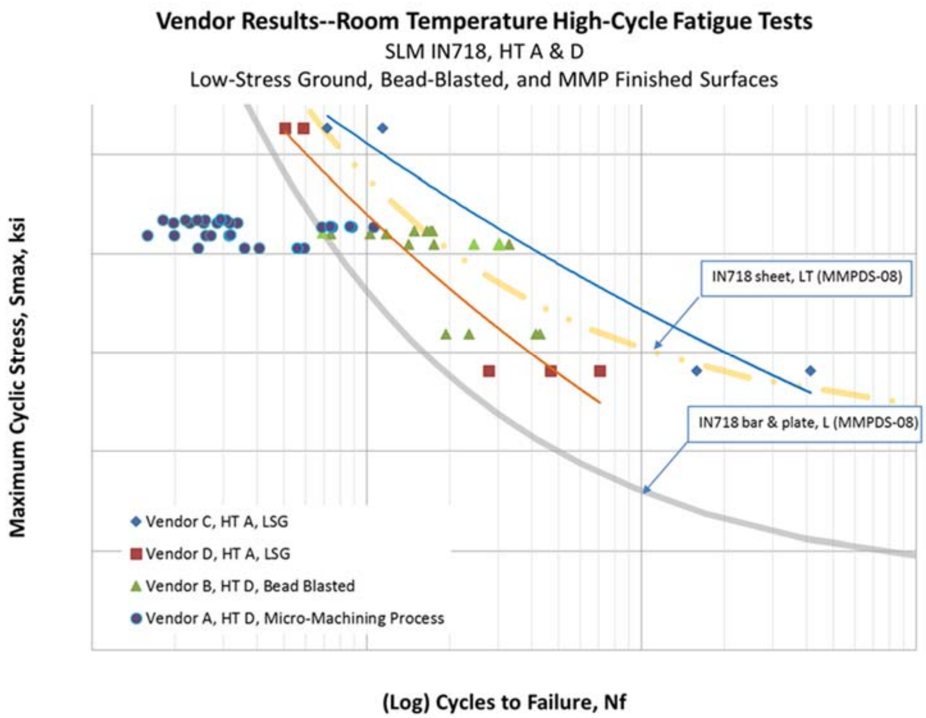


Figure 14: *High-cycle fatigue test results for each vendor. Surface finishes were modified using low-stress grinding, bead-blasting, and micro-machining processes. NOTES: Power law fit lines have been inserted to help with visualizing the trends, and MMPDS-08 fits have been inserted to provide a basis of comparison.*

Figure 15 shows elevated temperature (1000°F) fatigue test results for two vendors where surfaces have been low-stress ground. These have been plotted against the MMPDS-08 reference curve for that temperature. All high-cycle fatigue results were below the published results at 1000°F.

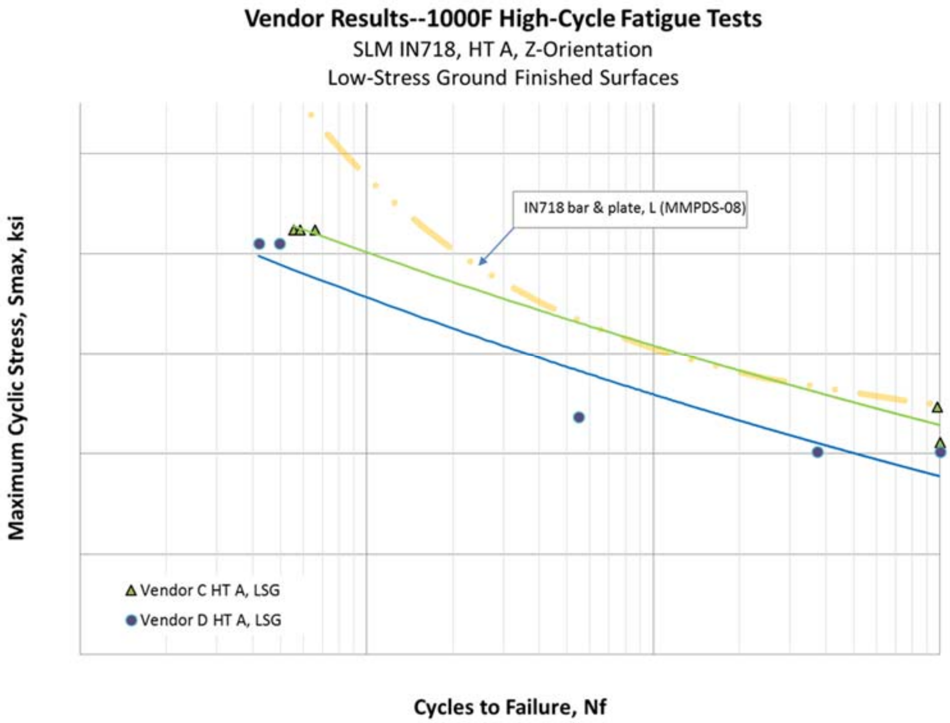


Figure 15: Elevated temperature fatigue tests. NOTE: Power law fit lines have been inserted to help with visualizing the trends.

DISCUSSION

<u>Build Parameters</u>

The evidence presented shows that the building parameters can be important to the production of a component. The value of the results presented is weakened because all build parameters were not considered simultaneously in the test matrix: each variable was evaluated separately, and several should be expected to be covariant, i.e., they can be expected to have similar effects on the resulting material properties. A multivariable test program that considers the potential for covariance, such as a "design-of-experiment" (DOE) evaluation method, is suggested.

It seems that the machine manufacturer's recommendations produce a good build, although the build layer thickness of 0.045-mm is suspect after reviewing these results, and the 0.045-mm build layer thickness was abandoned at some point in the data production. Optimization of the process seems appropriate, and this is expected to produce tensile, fracture, and high-cycle fatigue properties similar to those found with wrought IN718 materials. Consideration of the build parameters might also lead to an increase of the build rate and result in an economic benefit.

The cost of developing a design database similar to that produced for IN718 wrought materials is an important consideration, and knowledge of the SLM processing controls is not yet mature. This leads to a suggestion that materials, processes, and components should be matured simultaneously. Statistically significant information for design purposes is not available for the component design, and the context for materials properties evaluations needs to be set in the context of the environments the component will see and in the context of the build capabilities. Following this approach, an alternative flight certification scheme might be developed.

Industry Capability

Tensile, fracture, and fatigue specimens were evaluated for four outside vendors plus the NASA-MSFC additive manufacturing facility. Unfortunately, the build parameters for the various vendors were not available, and so a maturing of build parameters does not result from the survey of vendor capability. However, these data can be considered as representative of the current industry practice, which might be useful. SLM-manufactured IN718 can perform similarly to wrought IN718, as witnessed by comparing to the various standards cited. In addition, it stresses that well-controlled processes are essential.

Contamination

As the MSFC IN718 dataset was evaluated, it became apparent that much of the database was "tainted", that materials had been changed out to facilitate development priorities, and traces of the earlier powder charges could be seen in sample microstructure. When this was identified, cleaning procedures to avoid cross-contamination of the powders were adopted. Test results provided herein excluded the contaminated specimens. It is essential that SLM machinery be dedicated to a specific material or that adequate cleaning procedures be used when build powders are changed.

Database Configuration

A very large number of variables needed to be tracked in this investigation: build parameters and powder pedigree, post-build heat treatments, machining and other surface modifications. An excel spreadsheet had been used, and evaluation of pertinent information in that format was a cumbersome process. A relational database structure is being implemented that allows the input and extraction of information in a convenient fashion. The chosen structure should allow a wide variety of users to input their respective information, and it would allow quick re-analysis as new information is made available.

CONCLUSIONS

1. Additive manufactured IN718 tensile, fracture, and high-cycle fatigue properties can match specified wrought material properties.

2. Materials properties varied from vendor-to-vendor. The four vendors evaluated in this investigation provided specimens that met the specified wrought material tensile and fracture properties, but none performed as well as the high-cycle fatigue references in the as-built surface condition, and only one performed as well as the high-cycle fatigue properties of wrought IN718 sheet after surface treatments. For the lower reference, i.e., HCF of IN718 plate and bar, three vendors met the performance specified after surface treatments.

3. Recommended build parameters for the most part produced properties that are in-family with wrought material properties, but for any given machine, the build parameters should be evaluated to insure that builds are produced with optimal properties and economic efficiencies.

4. Evaluations of SLM-manufactured materials properties should be multi-variable investigations that can capture the co-variance of the build parameters.

RECOMMENDATIONS

1. Use multi-variable testing methods (design of experiment) to better understand and optimize the build parameters.

2. Evaluate the response of tensile properties to varied heat treatments.

3. Investigate additional alloys.

4. Develop a well-defined approach to flight certification.

5. Establish closed-loop control capabilities that utilize feedback to better control the SLM process and ensure uniform results.

ACKNOWLEDGEMENTS

A very large group contributed to this publication, and their contributions are appreciated. The contributing groups include the Materials Lab, the Propulsion Lab, the Office of Strategic Analysis and Communication, and the Advanced Development Office at MSFC. This belies the true size of the group, though, who include the Nonmetallic Materials Engineering Branch wherein the Additive Manufacturing Facility resides, the Mechanical Materials Test Facility, the Metallic Materials Engineering Branch, and the Liquid Engines Office. Thanks for the opportunity.

REFERENCES

[1] AMS 5663M, *Nickel Alloy, Corrosion and Heat-Resistant, Bars, Forgings, and Rings*, ASM

[2] AMS 5664E, *Nickel Alloy, Corrosion and Heat Resistant, Bars, Forgings, and Rings,* ASM

[3] ASTM E8-11, *Standard Test Methods for Tension Testing of Metallic Materials*, ASTM, 2011.

[4] ASTM E466-07, *Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials*, ASTM, 2007.

[5] ASTM E1820-11, *Standard Test Method for Measurement of Fracture Toughness*, ASTM, 2011.

[6] MMPDS-08, Metallic Materials Properties Development and Standardization, April 2013, Battelle Memorial Institute.