Effects of High Temperature on Torsional Fatigue Performance of Additively Manufactured Inconel 718 of Vertical Build Orientation

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The additive manufacturing process has allowed for advancement in the rapid development of aircraft gas turbine engine components, due to its rapid prototyping capabilities with the added benefits of geometric design flexibility, and reduced production cost. These turbine engine components often experience a multiaxial stress state at high temperature, in which an understanding of the axial and torsional response exhibited by these additively manufactured materials is of import. The present study is novel in that it assesses the torsional fatigue performance of additively manufactured machined and heat-treated Inconel 718, a metal superalloy commonly used in gas turbine engines, of vertical (Z) build orientation, at an elevated temperature of 650°C. Preliminary findings exhibit a reduction in shear moduli and plastic shear strain absorbing capacity at 650°C compared to room temperature. Also evident was cyclic softening from the first to the stabilized cycle and an approximate torsional fatigue life on the order of 10^3 cycles when cycling at an angle of twist range of $\Delta\varphi = \pm 15°$.

I. Introduction

Additive manufacturing (AM) of metal components has achieved growing prevalence in the aerospace and energy propulsion industries due to its advantages over traditional subtractive manufacturing methods, including geometric flexibility, rapid prototyping capabilities, and reduced production cost [1,2]. Inconel 718 (IN718) is a nickel-based superalloy commonly used in the fabrication of the turbine blades of aircraft engines, where it is subject to a multiaxial stress state at elevated temperatures [21]. As such, an understanding of the performance of these additively manufactured materials under axial and torsional loading is critical for safe in-service operation. The torsional fatigue behavior of AM IN718 at room temperature has been investigated [1-4, 15], but the impact of high temperature service environment requires an investigation of the coupled effect that elevated temperature has on the resulting torsional fatigue properties.

Studies in literature that have reported the torsional fatigue response of AM IN718 at room temperature have explored the effects of build orientation [1-4], surface roughness [2,15], and heat treatment [1,4] on its performance. The experimental methods employed include completely reversed ($R_\phi = -1$) torsional fatigue tests performed with angle of twist-control for a range of $\Delta\phi = 30°$ [1,2], angle of twist control varying in intervals of five degrees between $\phi = \pm 10°$ and $\phi = \pm 32°$ [4], and shear strain control for ranges of $\Delta\gamma_{max} = 1.732\%$ and $\Delta\gamma_{max} = 2.944\%$ [3]. The application of heat treatment was concluded to improve torsional fatigue performance by increasing the shear stress range compared to the as-built state [1,4]. Build orientation was found to have a more pronounced effect on the fatigue properties of AM IN718 at room temperature, with the horizontal (X) build orientation exhibiting a longer torsional fatigue life compared to the vertical (Z) and diagonal (XZ) build orientations [2,4]. Another study examining the torsional fatigue behavior of AM Ti-6Al-4V showed that the torsional fatigue

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life of vertically built (Z) AM Ti-6Al-4V is shorter than diagonally built (XZ) AM Ti-6Al-4V due to the alignment of the maximum shear plane with the its directional defects and weak build planes, though both underwent ductile failure similar to a previous study reported on vertically (Z) and diagonally (XZ) built AM IN718 [7]. Surface roughness was further found to vary with build orientation, with horizontally built (X/Y) samples possessing a higher surface roughness compared to vertically built (Z) and diagonally built (XZ) samples, resulting in differences in fracture behavior response reported [2]. Another study has examined the torsional fatigue life of coupons with defects and coupons with an as-built surface finish [15]. Initiation and propagation of fatigue cracks at the surface of the horizontally built (X) specimens rather than at internal defects as in the vertically built (Z) and diagonally built (XZ) was speculated to be the result of the greater surface roughness [2]. Surface and sub-surface defects have been found to cause higher stress concentrations compared to internal defects, making surface roughness the dominating parameter in the uniaxial, multiaxial, and torsional fatigue failure of as-built AM metal specimens [2,4-12]. For machined specimens, internal defects such as lack of fusion (LOF) regions, pores, and unmelted particles resulting from the additive manufacturing process are often the primary cause of fatigue failure [5,11-14]. The hot isostatic pressing (HIPing) post-manufacturing process was found to minimize internal defects and improve torsional fatigue life for AM Ti-6Al-4V and AM 17-4 PH, though it was found to have an insignificant effect on fatigue behavior in instances where optimized AM processing parameters have minimized internal defects to within a critical size limit such that they do not govern fatigue performance [7,9,16-17]. Evidence of recrystallization associated with the heat-treatment process has been reported, including an increase in the formation of grain boundaries and enlargement of crystal size observed that varies greatly from the microstructure in the as-printed state [19]. Additionally, HIPing and other post-processing treatments, such as heat treatments, have shown little impact on the fatigue performance of non-machined specimens due to the dominance of surface defects in promoting torsional fatigue failure, nevertheless one study found that annealed as-built AM Ti-6Al-4V samples exhibited higher shear moduli and longer fatigue lives than as-built samples under the same loading conditions [7,9,12,16-17].

Minimal research has been performed on the torsional fatigue response of AM IN718 at elevated temperatures, with one study assessing the torsional fatigue behavior of AM IN718 at 450°C that focused on comparing it to its forged counterpart [18]. This study found that there is an approximate 10% reduction in the shear modulus of AM IN718 at 450°C compared to room temperature, as well as a decrease in the torsional fatigue life [18]. While a large volume of gas porosity induced by the AM process was observed, intrinsic defects did not appear to induce crack initiation as torsional fatigue cracks primarily initiated at carbides and/or metallic inclusions [18]. Given that gas turbine engine components experience extreme temperatures, it is necessary to evaluate the torsional fatigue performance of AM IN718 at 650°C, to begin to provide some insight on the multiaxial fatigue response.

The present study is novel in that it assesses the torsional fatigue behavior of machined and heat-treated vertically built (Z) AM IN718 at 650°C for comparison against its torsional fatigue behavior at room temperature from results reported in previous studies [1,2]. Research findings include torsional fatigue life, torsional fatigue constants (i.e., shear moduli etc.), hysteresis deformation response, and fracture response observed for tests conducted at 650°C and an angle of twist range of $\Delta\phi = \pm 15°$.

II. Experimental Design

The torsional fatigue performance of AM Inconel 718 under the effect of high temperature was assessed by performing angle of twist-control torsional fatigue experiments on vertically built (Z) AM IN718 samples at 650°C. Samples were additively manufactured using the EOS M290 Direct Metal Laser Sintering (DMLS) system with the following optimized AM processing parameters: a layer thickness of 40 μm, argon gas chamber environment, 285 W laser power, 0.11 mm hatch spacing, and a scan speed of 960 mm/s [2]. Each vertically built (Z) sample was manufactured as the cylindrical rod shown in Fig. 1a, with a gage diameter of 0.625 in and a total length of 4.33 in. The additively manufactured samples were then subject to the following heat-treatment process: “Solution annealing at 1950°F (~1065 °C) for 1 hour, air/argon cooling, ageing at 1400°F (760°C) for 10 hours, furnace cool to 1200°F (~650°C) for 2 hours, hold at 1200°F (~650°C) for 8 hours, air/argon cooling,” [1,22], followed by the electrical discharge machining (EDM) process which was used to remove the samples from the build platform.

The as-built cylindrical rod stocks were then machined into the specimen geometric design depicted in Fig. 1b, with a gage diameter of approximately 0.208 in and total gage length 1.967 in. The direction of the build layers in the vertically built samples, along with the loading direction, are displayed in the high temperature torsional fatigue setup, shown Fig. 2. The surfaces of specimens tested in this study have been machined to reduce the effects of surface roughness to better assess the impact of internal AM defects on the torsional fatigue performance. An MTS test frame, model MTS 214.31 rated for 20,000 lbf·in of torque, was used to conduct the high temperature torsional fatigue experiments by an external vendor. All torsional fatigue experiments were performed under completely reversed angle of twist-control ($R_{\phi} = -1$), cycling at an angle of twist range of $\Delta\phi = \pm 15°$, at an angle of twist rate of $\dot{\phi} = 1.654$ deg/s. One side of the sample was held fixed while the opposite side was subject to rotation through the angle of twist range. Induction heating coils were used to maintain the 650°C testing temperature, which was monitored using six K-type thermocouples, two placed in the radial sections and four placed in the gage section. The samples were held at 650°C for approximately one hour to stabilize prior to performing torsional fatigue experiments. The results obtained from these torsional fatigue experiments were compared to findings reported for as-built IN718 at room temperature [2]. Images of the fracture surface were procured with the DinoLite Edge Series microscope using a multi-point calibration that facilitated imaging at various magnifications. Detailed imaging of the fracture surface and presence of additive manufacturing-induced defects was performed using the Hitachi SU3500 Scanning Electron Microscope (SEM) using secondary electron mode.

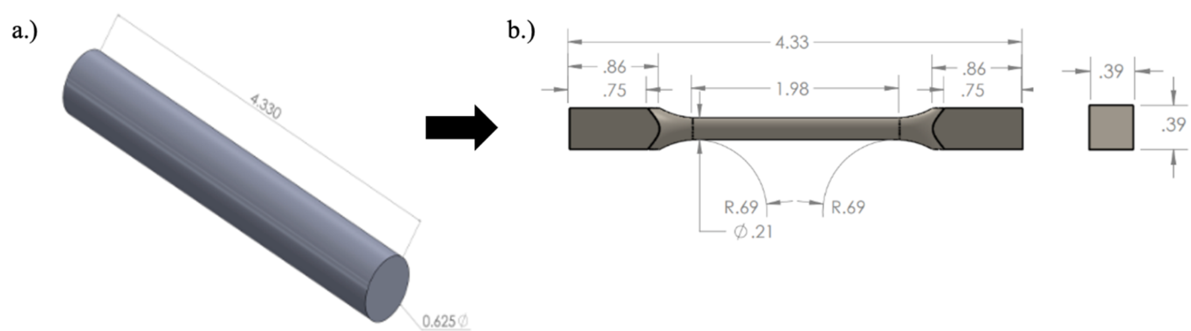

Fig. 1 Specimen geometry of the vertically built samples (Z), in inches, a.) as-printed, and b.) after machining.

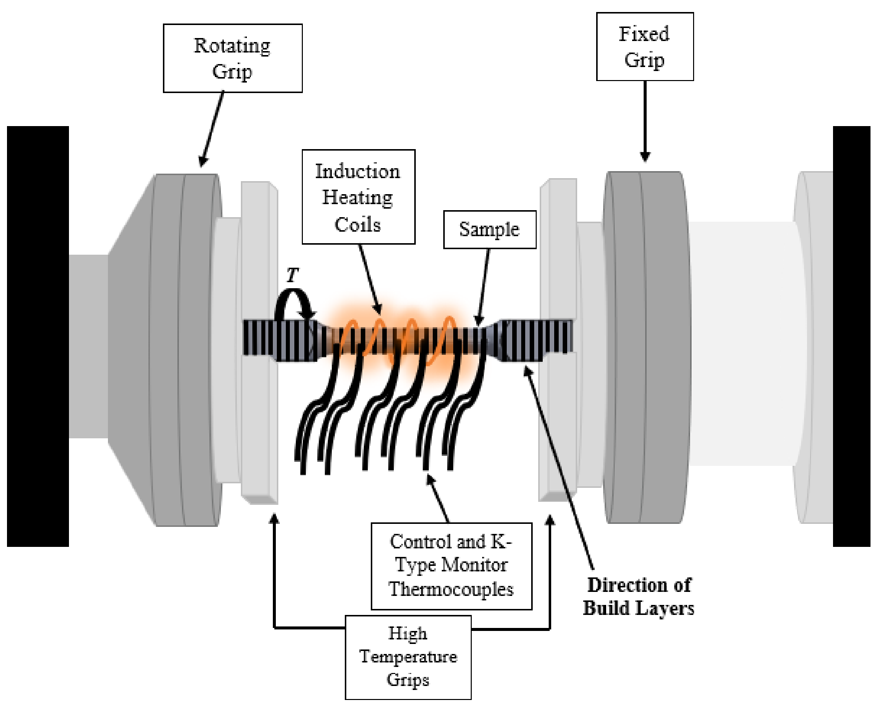

Fig. 2 Experimental setup for torsional fatigue test performed at 650°C.

III. Results & Discussion

Data was outputted in terms of torque, T, versus angle of twist, ϕ, that was then converted to shear stress, τ, and shear strain, γ, using Eq. (1) and Eq. (2), respectively.

$$\tau = \frac{Td}{2J} \tag{1}$$

$$\gamma = \frac{\phi d}{2L} \tag{2}$$

Equation (1) and Eq. (2) utilize the gage diameter, d, gage length, L, and polar moment of inertia, J, for a solid shaft, computed using Eq. (3).

$$J = \frac{\pi d^4}{32} \tag{3}$$

The first and stabilized hysteresis cycles for vertically built DMLS IN718 tested at 650°C are presented in Fig. 3a, along with the hysteresis deformation response from the first cycle to the last cycle in Fig. 3b. The last cycle shown in Fig. 3b corresponds to the last cycle prior to a significant drop in shear stress. Additionally, the shear stress versus life plot for these samples are presented in Fig. 4. Torsional fatigue testing at an angle of twist range of $\Delta\phi = \pm 15°$ and 650°C yielded an approximate fatigue life of 10^3 cycles. A comparison of the hysteresis deformation response reveals a decrease in the shear stress range evident of cyclic softening occurring at 650°C, further validated by the shear stress versus life plot. Additionally, minimal stabilization is observed for Sample 3(Z), with more pronounced stabilization observed for Sample 4(Z) from the first cycle to midlife hysteresis. The cyclic softening suggests an increase in dislocation motion accompanying an increase in temperature [23].

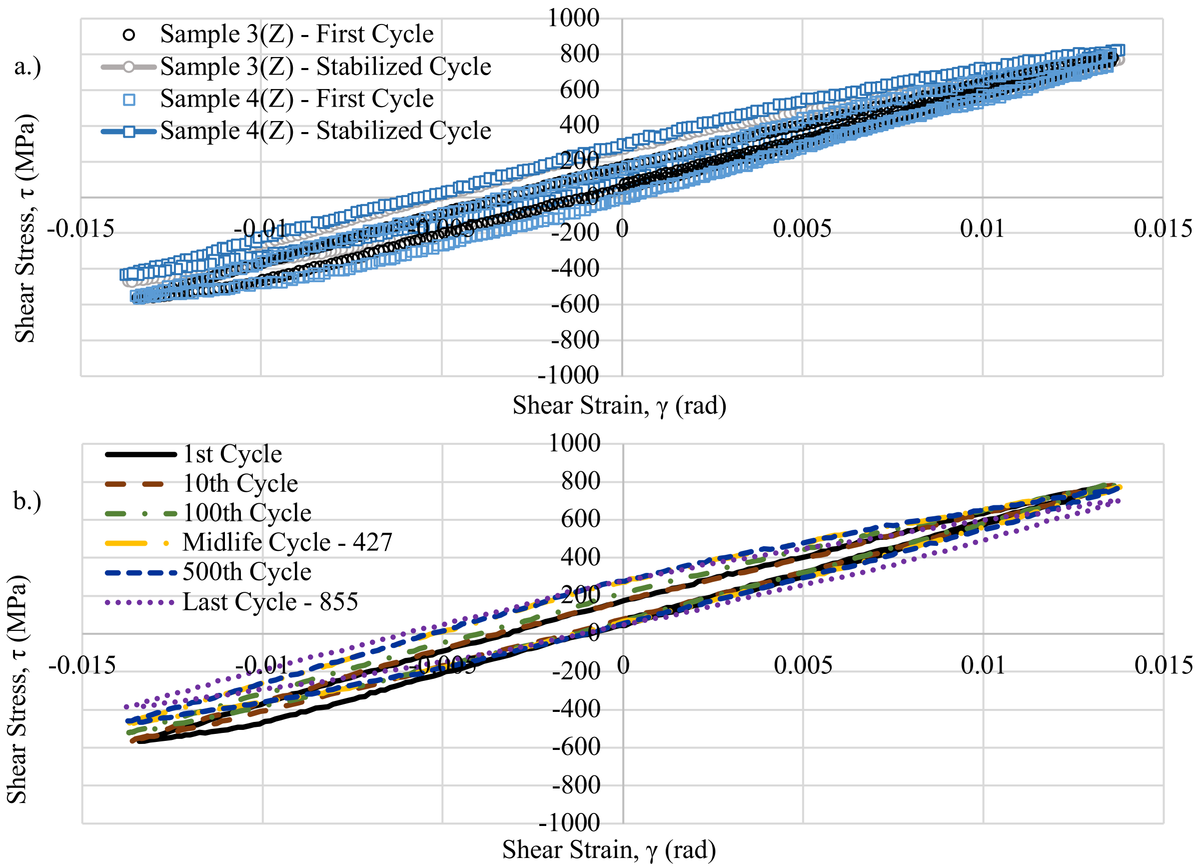

Fig. 3 a.) Comparison of the first cycle and last cycle hysteresis of DMLS IN718 for Sample 3(Z) and 4(Z) and b.) hysteresis deformation of DMLS IN718 Sample 3(Z) tested at 650°C.

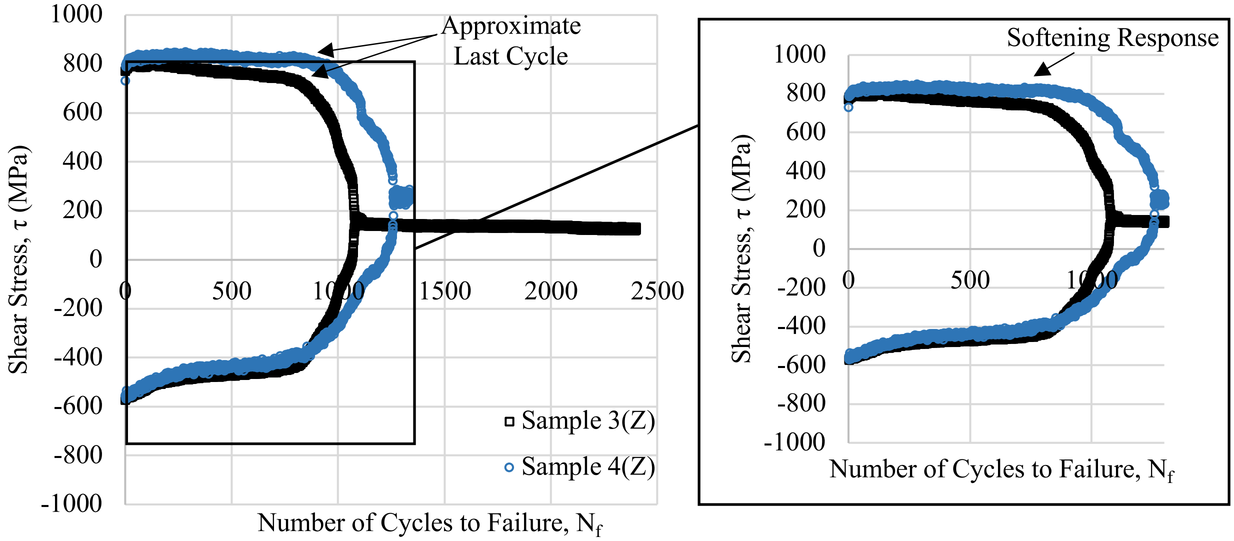

Fig. 4 Shear stress versus life plot showing softening response exhibited by DMLS IN718 Sample 3(Z) and Sample 4(Z) at 650°C.

The torsional fatigue response of vertically built, machined and heat-treated DMLS IN718 at 650°C was compared to the response of both as-built and heat-treated vertically built specimens at room temperature, reported in literature [1,2]. WebPlot Digitizer [20] was used to digitize the data presented in [1,2] assessing the torsional fatigue response of vertically built DMLS IN718 at room temperature reported in literature to serve as a comparison to the torsional fatigue results obtained at 650°C in the present study. A comparison of the first cycle hysteresis at room temperature and 650°C is presented in Fig. 5a while a comparison of the stabilized cycle hysteresis is presented in Fig. 5b, and the associated torsional fatigue properties are presented in Table 1 for additional comparison. It is evident from Fig. 5a, Fig. 5b, and Table 1 that DMLS IN718 possesses a much larger plastic shear strain range at room temperature compared to 650°C, suggesting a reduction in the material's ability to absorb plastic shear strain deformation at a higher temperature. Further, shear stress range reported in literature for heat-treated DMLS IN718 at room temperature is larger than that of machined and heat-treated DMLS IN718 at 650°C [1]. There is also a significant reduction in shear modulus, with the average shear modulus for the first cycle at 650°C being approximately 56.6 GPa and the shear moduli for the first cycle at room temperature for as built and heat-treated being reported as 70.84 GPa and 66.10 GPa, respectively [1,2].

Table 1. Approximate torsional fatigue properties from the first cycle hysteresis for DMLS IN718 at 650°C compared to room temperature reported in [1,2].

Sample	Test Temp	Approximate Number of Cycles to Failure	Cycle	Shear Stress Range, $\Delta\tau$ (MPa)	Mean Shear Stress, τ_m (MPa)	Plastic Shear Strain Range, $\Delta\gamma_p$(rad)	Elastic Shear Strain Range, $\Delta\gamma_e$ (rad)	Total Shear Strain Range, $\Delta\gamma$ (rad)	Shear Modulus, G (GPa)
As-Built (Z) [2]	Room Temp	-	First	1212.7	-14.8	0.0138	0.017	0.0309	70.84
			Stabilized	1371.7	-19.5	0.0113	0.0197	0.0310	69.55
As-Built + HT (Z) [1]	Room Temp	-	First	1694.8	-43.146	0.00558	0.02564	0.0312	66.10
			Stabilized	1669.4	-28.84	0.00575	0.0256	0.0314	65.20
3(Z) – Machined + HT	650°C	1112	First	1346.2	107.3	0.00235	0.0245	0.0269	54.97
			Stabilized	1244.8	151.5	0.00413	0.0232	0.0273	53.65
4(Z) – Machined + HT	650°C	1257	First	1357.6	114.9	0.00356	0.0233	0.0269	58.25
			Stabilized	1256.2	196.1	0.00399	0.0235	0.0275	53.53

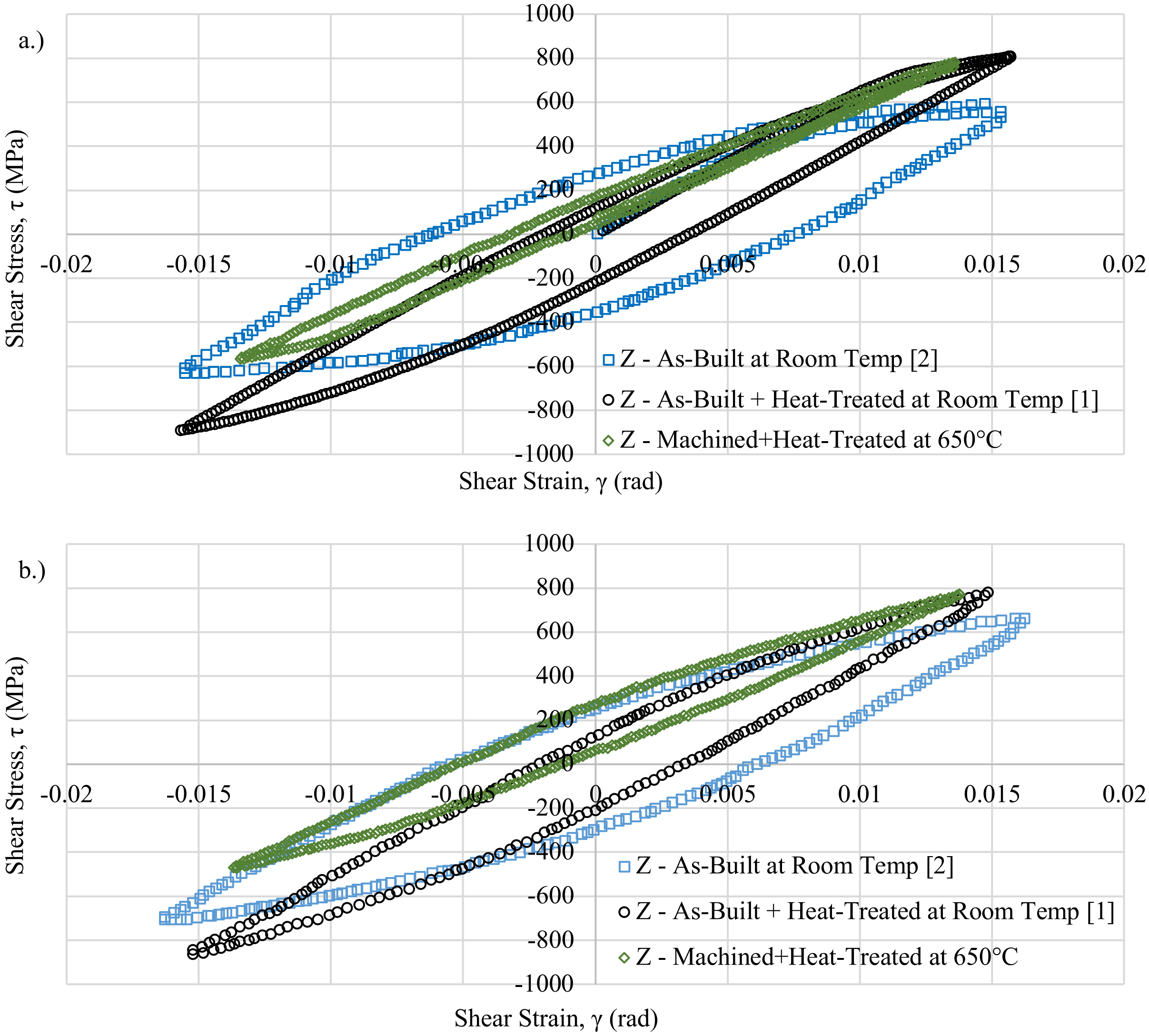

Fig. 5 a.) First cycle hysteresis and b.) stabilized cycle hysteresis for Sample 3(Z) tested at 650°C compared to room temperature data reported in literature [1,2].

Analysis of the fracture behavior response was performed, comparing torsional fracture surfaces tested at $\Delta\phi = \pm 15°$ between room temperature and 650°C. At 650°C, DMLS IN718 that had been vertically built, machined, and heat-treated exhibited a predominantly star-spline brittle fracture response as shown in the micrographic images presented in Fig. 6, while as-built, vertically built DMLS IN718 exhibited a ductile fracture response at room temperature as reported in literature [2]. Fatigue cracks propagated along the same direction in which the torsional loading acts, but perpendicular to the vertically built layers. In order to further assess the torsional fatigue fracture response of DMLS IN718, a Hitachi SU3500 SEM was used to procure images of the internal AM defects driving torsional fatigue failure of the samples tested at 650°C, as presented in Fig. 7.

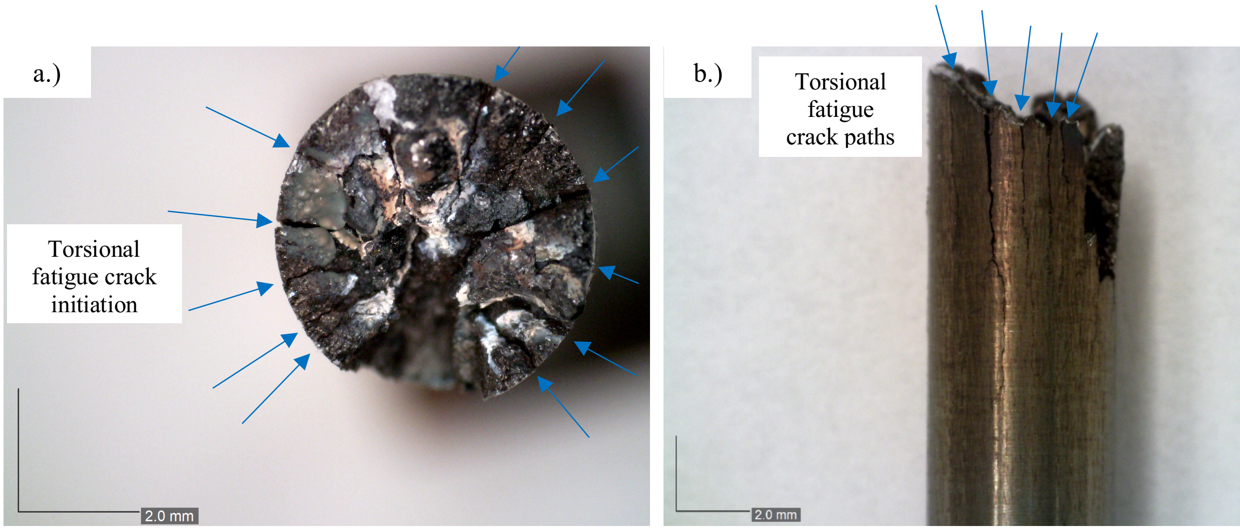

Fig. 6 Micrographic images of the machined and heat-treated DMLS IN718: a.) torsional fatigue fracture face and b.) side of fractured samples

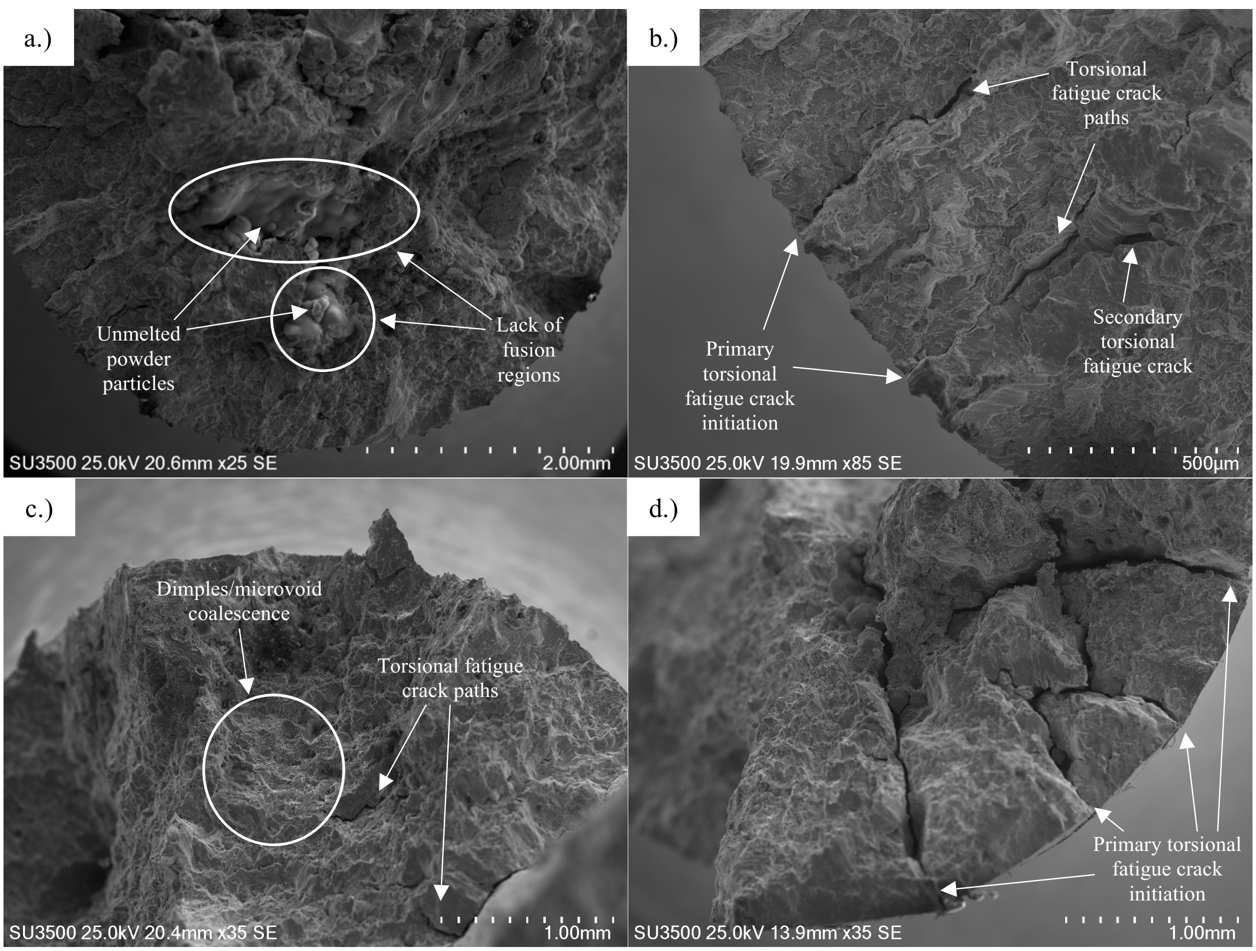

Fig. 7 SEM images showing torsional fatigue fracture response of vertically built machined and heat-treated DMLS IN718 at 650°C.

Torsional fatigue crack initiation in vertically built samples at 650°C appears to occur at sub-surface defects, with crack propagation near regions of additive manufacturing-induced microstructural defects, namely lack of fusion regions. Additionally, a dimpled fracture region/microvoid coalescence characteristic of a ductile fracture mode was observed, suggesting that the samples underwent a combination of brittle and ductile failure. Future work will be performed to further confirm these findings.

IV. Conclusion

As the additive manufacturing process has grown in prevalence within the aerospace and energy propulsion industries, specifically in the design and manufacturing of gas turbine engine components, it has become increasingly important to assess the mechanical performance of these additively manufactured components. Aircraft gas turbine engine blades manufactured from Inconel 718 are often subjected to a multiaxial stress state environment at high temperatures, in which an assessment on the torsional fatigue performance of this material at elevated temperatures can begin to provide insight into its multiaxial fatigue response. The results obtained in this study are the first to demonstrate the torsional fatigue response of vertically built, machined, and heat-treated DMLS IN718 subject to an elevated temperature of 650°C and angle of twist cycling at $\Delta\phi = \pm15°$, including its torsional fatigue properties, shear stress vs. life, and hysteresis deformation response. These results are compared to the torsional fatigue performance of vertically built DMLS IN718 at room temperature, assessed in a previous study [2]. Torsional fatigue testing of DMLS IN718 at the stated conditions yielded a life of approximately 10^3 cycles. The torsional fatigue properties at 650°C were inferior to those recorded at room temperature, with a shear moduli at 650°C of about 56 GPa compared to the shear modulus at room temperature previously reported as approximately 70 GPa [2]. Additionally, DMLS IN718 exhibited a much larger plastic shear strain range at room temperature compared to 650°C, indicating a reduction in energy absorption by the material at an elevated temperature. Further, it is evident from the shear stress versus life data that cyclic softening took place in the DMLS IN718 samples tested at 650°C. A key difference in the torsional fatigue behavior of vertically built DMLS IN718 at 650°C and at room temperature is the fracture behavior. At room temperature, vertically built DMLS IN718 exhibited ductile fracture [2], whereas a predominantly brittle fracture response is observed at 650°C. Images of the fracture surface captured with the SEM showed fatigue crack initiation taking place primarily at sub-surface defects, as well as near additive manufacturing-induced unmelted powder particles and lack of fusion regions along which torsional fatigue cracks propagated. The presence of dimpled fractured regions, coupled with a star-spline brittle fracture response observed in optical micrographic images, suggest a combination of brittle and ductile fracture responses. Future work will be performed to further confirm these preliminary findings.

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