Determination of the Initial Anisotropy of Inconel 718 manufactured by Additive Manufacturing

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Abstract: This article deals with the determination of the initial plasticity area for the Inconel 718 nickel alloy produced by selective laser melting technology. A non-destructive method based on linearity deviation is used, which allows multiaxial loading with any combination of stress components. The printed material is tested in its as-built state and virgin powder is used. The results of a total of 4 mechanical tests show that the material produced in this way does not correspond to the plasticity criterion according to von Misses, and the yield strength in pure tension and the effective stress obtained in pure torsion do not have the same stress values, but the shear component of the stress is significantly dominant.

Keywords: Yield surface tracing; Inherent anisotropy; Inconel 718; Additive manufacturing; Selective laser melting

1 Introduction

Inconel 718 is a nickel-based steel alloy that has suitable mechanical properties, even at higher temperatures. Therefore, this alloy is mainly used in the aerospace industry. The disadvantage of this alloy is its poor machinability. Especially in the aerospace industry, there are components with complex shapes that need to be machined in a complicated way [1]. Additive manufacturing solves this problem to some extent. Using 3D printing technology such as Selective Laser Melting (SLM), it can produce elements with complex shapes. However, this technology has a disadvantage in build. The orientation of the building in 3D printing has an effect on the mechanical properties of the material.

This paper is focused on the investigation of a nickel-based alloy, specifically Inconel 718, which is made using additive technology, specifically SLM technology. This paper deals with the experimental determination of the initial yield surface under combined loading using a non-destructive method.

2 Materials and methods

The method of tracing the yield surfaces with a centre point is used. This method is suitable for combined loading with any ratio of axial and torsional stress components [2]. Tubular samples were used for the experiments, so it was possible to simultaneously control the components of the axial and torsional stress. The samples were produced using the SLM method with vertical orientation of the building, using virgin powder, and were tested in the as-printed state. The geometry of the sample is based on the standard for low-cycle fatigue [3], and the specific geometry used in these experiments is shown in Fig. 1. However, due to the manufacturing method, the real dimensions of the sample are slightly different. The real dimensions of the sample were 11.3 mm on the inner diameter and 13.9 mm on the outer diameter of the test part (length 28 mm in Fig. 1).

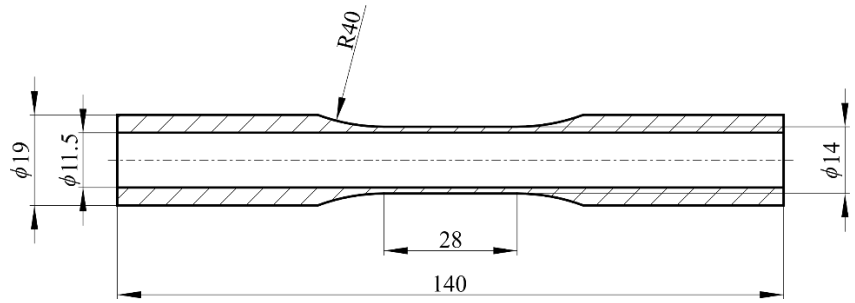

Fig. 1 Sample geometry for elastic region tracing.

All experiments performed were stress controlled. The ratio of axial and torsional stress rates was varied using a specific angle ψ_i. Thus, this angle defines a specific probing path. Using this angle, we can determine the effective stress rate, which depends on the increase of the stress components. These components of stress can be written in the following form

$$\dot{\sigma} = \dot{\sigma}_{eqv} \cdot cos\psi_i \, , \dot{\tau} = \dot{\sigma}_{eqv} \frac{cos\psi_i}{\sqrt{3}}, \tag{1}$$

where $\dot{\sigma}_{eqv}$ is the required equivalent stress rate. The same equivalent stress rate $\dot{\sigma}_{eqv}$ =1 MPa/s is used for all probing paths. On the contrary, relief was performed with a constant equivalent stress rate of 10 MPa per second to shorten the time of the entire test. The sequence and rate ratio of each probing path can be seen in Fig. 2.

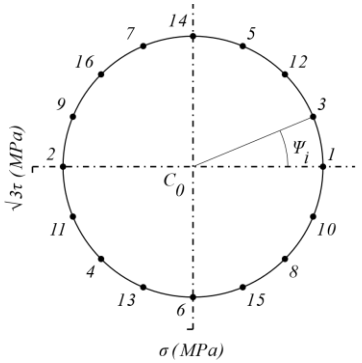

Fig. 2 Probing paths scheme for the experiment.

The LabControl hydraulic biaxial machine with maximum load values of 100 kN/1000 Nm was used for the tests. The criterion of the effective increment of the plastic strain, according to eq. (2), is used to terminate the given probing path and evaluate the point that corresponds to the specific yield point. This equation is evaluated online during measurement. As soon as this condition meets the prescribed value of 50 μS, the probe is terminated and the next in the sequence continues.

$$\Delta\varepsilon_{eff} = \sqrt{\Delta\varepsilon_{pl}^2 + \frac{1}{3}\Delta\gamma_{pl}^2}, \tag{2}$$

To determine the plastic components of strain in eq. (2), an additive rule is used in the following form

$$\Delta\varepsilon_{pl} = \varepsilon - \varepsilon_{el} - \varepsilon_R, \quad \Delta\gamma_{pl} = \gamma - \gamma_{el} - \gamma_R. \tag{3}$$

The total axial strain value ε is read by the extensometer during the test, as the total strain in shear γ. Epsilon 3550 extensometer with a gauge length of 25 mm was used for the tests. This type of extensometer allows us to measure both axial and torsional deformation simultaneously. The elastic components of strain ε_{el} and γ_{el} in relation (3) are determined as the ratio of the current stress value to the modulus of elasticity (for tensile component σ/E and for shear then τ/G). The moduli of elasticity (E and G) are determined as the slope of a straight line from the predetermined $\Delta\sigma$ region defined by eq. (4). For the following experiments, this value was set at 100 MPa. The modulus of tensile and shear elasticity determined from this region is then invariable for the evaluation of the given probe. Eq. (4) is repeated for each probing path. The result is 14 values of the modulus of elasticity of tensile and shear (for pure tension and pure torsion, the opposite component is neglected).

$$\Delta\sigma = \sqrt{\sigma^2 + 3\tau^2}, \tag{4}$$

The residual components of the strain in (3) ε_R and γ_R are then evaluated as a constant from the equation of a straight line that describes the modulus of elasticity. This value characterises, for example, the landing of the sample in the testing machine and is also evaluated for each probing path separately.

Conclusions

The total tracing of the yield surface, consisting of 16 partial probes, was repeated 4 times in total. All measurements were performed on the same sample and all specific yield stress values are listed in Table 1.

Table 1. Specific yield stress values for all tests and probing paths.

	Test 1		Test 2		Test 3		Test 4	
n. of path	σ (MPa)	$\sqrt{3}\tau$ (MPa)	σ (MPa)	$\sqrt{3}\tau$ (MPa)	σ (MPa)	$\sqrt{3}\tau$ (MPa)	σ (MPa)	$\sqrt{3}\tau$ (MPa)
1	225	0	198	0	206	0	207	0
2	268	111	256	118	291	120	281	116
3	158	378	167	403	157	378	165	394
4	-190	459	-205	493	-210	504	-208	501
5	-265	109	-265	109	-276	114	-276	115
6	-279	-116.4	-270	-112	-271	-114	-263	-111
7	-194	-471	-195	-473	-187	-450	-206	-499
8	171	-413	174	-421	182	-441	179	-429
9	-300	0	-311	0	-308	0	-277	0
10	-240	-241	-252	-252	-249	-250	-254	-254
11	0	-566	0	-574	0	-589	0	-623
12	234	-234	238	-239	232	-233	239	-241
13	263	-110	274	-114	275	-114	266	-111
14	235	235	240	240	240	240	241	243
15	0	591	0	594	0	625	0	633
16	-254	254	-259	257	-263	263	-256	258

Similar values as those given in this chapter were also obtained by control measurements on another sample of the same geometry. Fig. 3 shows the moduli of elasticity for individual load speed ratios using a box graph.

The first column, marked 0, indicates either pure tension or pure torsion. From the individual load speed ratios, it can be seen that the highest deviations for the tensile component give the probing path, when the shear component of the stress prevails over the tensile one. This is a probing path 5, 7, 13 and 15 from Fig. 2. The average value of the Young modulus is 137.7 GPa, which is lower compared to conventionally produced material [4]. However, lower values of the modulus of elasticity in Inconel 718 manufactured unconventionally were pointed out by [5]. On the contrary, the highest dispersion for the modulus of elasticity in shear is seen in all experiments by combinations where the tensile component dominates with respect to the shear component, in Fig. 2 it is probes 3, 9, 11 and 10. The other three ratios are very close to the average value of 92.8 GPa. This may to some extent be because the sample produced in this way shows significantly higher values of stress in torsion than in tension.

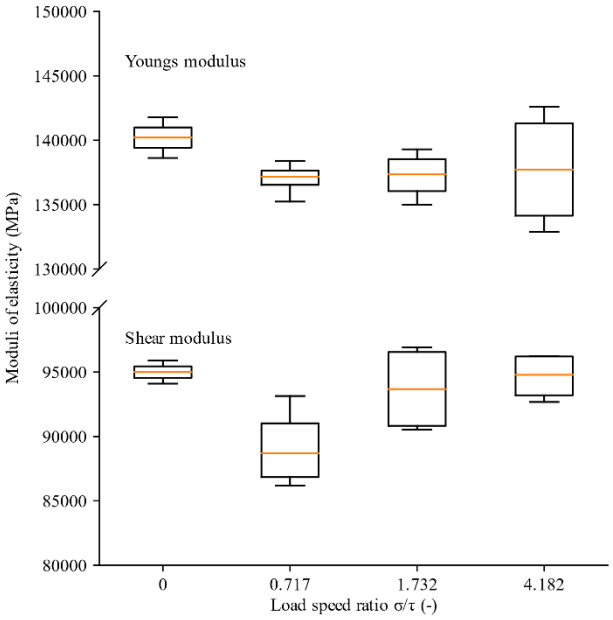

Fig. 3 Moduli of elasticity for Inconel 718 produced by additive manufacturing.

Fig. 4 shows the initial yield surface of the nickel-based alloy Inconel 718, produced by additive technology, specifically by SLM in the stress space $\sigma - \sqrt{3}\tau$. It can be seen from the results that the shear stress component is significantly dominant. The shear stress has an average value for all measurements of 610 MPa and in the opposite direction of 588 MPa. The average value for normal stress is 209 MPa, respectively, 298 MPa in pressure. Therefore, the data obtained cannot be fitted using the von Misses condition, as is the case with conventionally manufactured samples [6]. For a simple description, we can fit the points to the function of an ellipse with a main semiaxis size of 599 MPa and a minor semiaxis. size of 253.5 MPa, as can also be seen in Fig. 4.

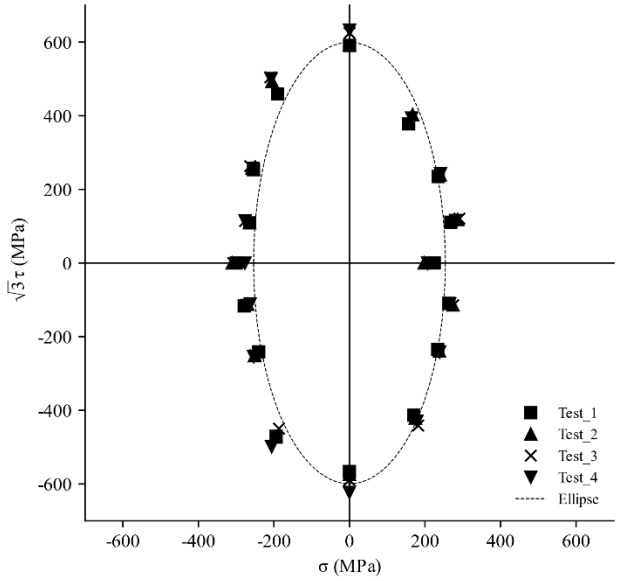

Fig. 4 Initial yield locus for Inconel 718 produced by additive manufacturing.

Acknowledgements

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References

[1] Rahman, M., Seah, W.K.H. and Teo, T.T. The machinability of inconel 718. *J Mater Process Tech*, **63**(1-3), pp. 199-204 (1997).

[2] Štefan, J., Parma, S., Marek, R., Plešek, J., Ciocanel, C. and Feigenbaum, H. "Overview of an Experimental Program for Development of Yield Surfaces Tracing Method," *Applied Sciences*, **11**(16), 7606 (2021).

[3] STM E2207 - 15 Standard Practice for Strain-Controlled Axial-Torsional Fatigue Testing with Thin-Walled Tubular Specimens. West Conshoshocken, USA: ASTM International, 2015.

[4] Tayon, W.A., Shenoy, R.N., Redding, M.R., Keith Bird, R. and Hafley, R.A. "Correlation Between Microstructure and Mechanical Properties in an Inconel 718 Deposit Produced via Electron Beam Freeform Fabrication," *J Manuf Sci E-T ASME*, **136**(6), 061005 (2014).

[5] Kelley, P. F., Saigal, A., Vlahakis, J.K. and Carter, A. „Tensile and Fatigue Behavior of Direct Metal Laser Sintered (DMLS) Inconel 718" in *Proceedings of the ASME 2015 International Mechanical Engineering Congress and Exposition, Volume 2A: Advanced Manufacturing*, Houston, Texas, USA, 2015.

[6] Gil C.M., Lissenden C.J. and Lerch B.A., "Determination of Yield in Inconel 718 for Axial-Torsional Loading at Temperatures up to 649 C," *NTRS – NASA/TM*, 208658, pp. 1-33 (1998).