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INVESTIGATION OF RESIDUAL STRESS EVOLUTION DUE TO CYCLIC LOADING BY YIELD SURFACE TRACKING

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1. Introduction

Additive manufacturing (AM) technologies, particularly Selective Laser Melting (SLM), enable the production of complex metallic parts directly from powder. SLM, a powder bed fusion process, builds components layer-by-layer using a focused laser source. However, the inherent thermal complexity of the process, characterized by rapid heating and cooling cycles, leads to the formation of significant residual stresses (RS). The magnitude and distribution of these stresses are highly sensitive to process parameters such as laser power, scanning speed, and scanning strategy [1]. Within the context of AM, the most critical of these are macroscopic residual stresses, which can severely impact the structural integrity and fatigue life of as-built components.

This work investigates the reduction of these stresses by applying the yield surface tracking technique, an approach traditionally used for studying plastic anisotropy, implemented on an axial-torsional testing machine [2].

2. Material and methodology

The investigated material is Inconel 718, a precipitation-strengthened nickel-based superalloy containing elements such as Nb, Ti, and Al. When produced by SLM, its as-built microstructure is typically heterogeneous, characterized by columnar grains, fine dendritic structures, and the presence of interdendritic Laves phases [3]. This complex microstructure is a primary contributor to the high residual stresses observed in as-built components.

For this study, tubular thin-walled specimens were produced by the SLM process. The specimens were built in a vertical orientation using virgin powder and were tested in their as-built condition, without any post-process heat treatment.

The specimen geometry is based on the standard for low-cycle fatigue testing. Due to the nature of the AM process, the final dimensions deviated slightly from the nominal design. The actual measured dimensions of the gauge section were an inner diameter of 11.3 mm, an outer diameter of 13.9 mm, and a length of 28 mm.

2.1 Yield surface tracking

The evolution of residual stresses was investigated using a yield surface tracking method with a defined center point. The tubular geometry of the specimens allowed for the precise application and control of combined axial-torsional stress states, which is a prerequisite for this technique.

All experiments were conducted under stress control. The combined axial-torsional stress paths were defined by a specific angle, ψ_i, which governs the ratio of the stress rates. The sequence of the 16 applied loading paths is shown in Fig. 1.

The component stress rates, axial ($\dot{\sigma}$) and torsional ($\dot{\tau}$), were defined as:

$$\dot{\sigma} = \dot{\sigma}_{eqv} \cdot cos\psi_i \, , \dot{\tau} = \dot{\sigma}_{eqv} \frac{sin\psi_i}{\sqrt{3}}, \qquad (1)$$

where the equivalent stress rate ($\dot{\sigma}_{eqv}$) was set to a constant 1 MPa/s for each probing path. The unloading phases were performed at a faster rate of 10 MPa/s to reduce the total experiment time.

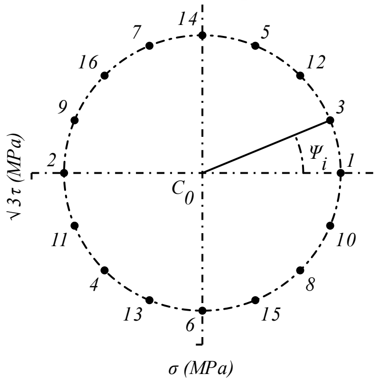

Fig. 1. Scheme of the loading paths applied during one yield surface tracking stage.

2.2 *X-ray Diffraction Analysis*

The evolution of the stress state was monitored using X-ray diffraction. Macroscopic residual stresses in both the axial and tangential (hoop) directions were determined using the conventional *sin²ψ* method. The measurements were performed at discrete points around the specimen's circumference at 30° intervals. To ensure a direct comparison, the irradiated spots were kept identical for all measurement steps: in the initial as-built state and after each of the three subsequent yield surface tracking stages. The size of the primary X-ray beam was defined by 4×0.5 mm² crossed slits.

In addition to the macroscopic stresses, the collected diffraction patterns were analyzed to extract key microstructural information. The stresses correspond to the γ-phase, which is the dominant component of the alloy. This included phase analysis to quantify the weight fraction of the constituent crystallographic phases. For the primary *γ*-phase, the analysis showed the evolution of crystallite size (D), microstrain (e), and the corresponding dislocation density (ρ). These parameters provide insight into the microstructural changes accompanying the mechanical relaxation of the residual stresses.

3. Results

The experimental results, graphically summarized in Fig. 2, confirm the effectiveness of the yield surface tracking method for residual stress reduction. The as-built specimen initially contained a high tensile stress state, with axial (σ_A) and tangential (σ_T) components of 673 MPa and 210 MPa, respectively. This corresponds to a von Mises equivalent stress (σ_{eqv}) of approximately 600 MPa.

The most significant stress relaxation occurred during the first of the three tracking stages, which alone reduced the equivalent stress by 67%. The subsequent two stages provided further, more gradual reductions. After the completion of all three stages, the final equivalent residual stress was lowered to 141 MPa. This constitutes a total reduction of over 76% from the initial as-built state, with the final axial and tangential components reaching stable values of 158 MPa and 49 MPa.

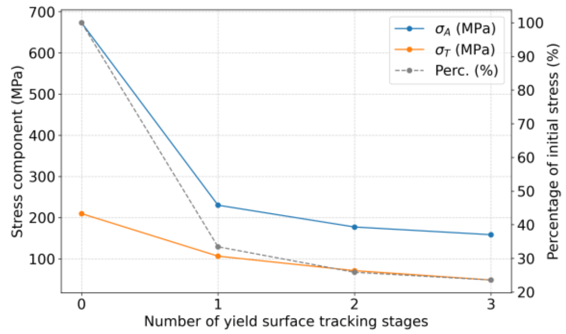

Fig. 2. Reduction of residual stress components as a function of the number of yield surface tracking stages. The secondary axis indicates the percentage of the initial equivalent stress.

4. Conclusions

The key contribution of this work is the novel application of the yield surface tracking technique, typically used for anisotropy studies, as an effective method for mechanical stress relaxation in as-built SLM Inconel 718. The method achieved a substantial reduction of more than 76% of the initial high residual stresses. The research also includes the development of a corresponding numerical simulation and the characterization of the material's cyclic response with a combined Chaboche-Voce model. This integrated experimental-numerical approach paves the way for a comprehensive simulation of the entire manufacturing and stress relaxation process.

Acknowledgments

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