

Residual Stresses in Selective Laser Melted Samples of a Nickel Based Superalloy

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Abstract. Additive Manufacturing (AM) through the Selective Laser Melting (SLM) route offers ample scope for producing geometrically complex parts compared to the conventional subtractive manufacturing strategies. Nevertheless, the residual stresses which develop during the fabrication can limit application of the SLM components by reducing the load bearing capacity and by inducing unwanted distortion, depending on the boundary conditions specified during manufacturing. The present study aims at characterizing the residual stress states in the SLM parts using different diffraction methods. The material used is the nickel based superalloy Inconel 718. Microstructure as well as the surface and bulk residual stresses were characterized. For the residual stress analysis, X-ray, synchrotron and neutron diffraction methods were used. The measurements were performed at BAM, at the EDDI beamline of -BESSY II synchrotron- and the E3 line -BER II neutron reactor- of the Helmholtz-Zentrum für Materialien und Energie (HZB) Berlin. The results reveal significant differences in the residual stress states for the different characterization techniques employed, which indicates the dependence of the residual state on the penetration depth in the sample. For the surface residual stresses, longitudinal and transverse stress components from X-ray and synchrotron agree well and the obtained values were around the yield strength of the material. Furthermore, synchrotron mapping disclosed gradients along the width and length of the sample for the longitudinal and transverse stress components. On the other hand, lower residual stresses were found in the bulk of the material measured using neutron diffraction. The longitudinal component was tensile and decreased towards the boundary of the sample. In contrast, the normal component was nearly constant and compressive in nature. The transversal component was almost negligible. The results indicate that a stress re-distribution takes place during the deposition of the consecutive layers. Further investigations are planned to study the phenomenon in detail.

Introduction

Additive manufacturing (AM) offers the opportunity to produce geometrically complex parts compared to the traditional production technologies. An important AM technology for metals is selective laser melting (SLM), where a part is produced by melting a powder bed in layers [1]. However, residual stresses that arise during the process may limit the application of SLM parts by inducing unwanted distortion depending on the boundary conditions. Strategies for stress optimization must be developed to minimise distortion and with focus on other sensitive properties relying on residual stress. The material used in this study is the nickel based super Alloy 718 which has several applications in aerospace and chemical industry due its superior

corrosion and heat resistance [2]. The SLM process is generally known to form a high amount of residual stresses due to the high temperature gradient present during laser melting. In principle the mechanisms of stress formation are similar to the fusion welding process. In the absence of solid state phase transformations tensile residual stresses are formed due to the hindered shrinkage of the already solidified material. The amount of stresses can be equal to the yield stress. After cooling to ambient temperature, a residual stress gradient between surface and core regions of the part is present. Its magnitude depends amongst others on the geometry and the stiffness of the whole part as well [3-8]. Adopting the scanning strategy during SLM can alter the level and distribution of the residual stresses [9-12]. Typically, the scanning is performed cyclic in sectors along the parts. This alters the heat flow and therefore the local temperature distribution. As a consequence, the stress formation is locally affected. However, the thermal-mechanical behaviour is complex and therefore to be evaluated by experimental investigation as a basis for modelling [5, 12-14]. This enables deliberate adjustment of process parameters to control the residual stresses and associated distortion during fabrication. In order to evaluate localised residual stress distributions in SLM parts different regions have to be investigated. Beside the surface and the bulk, the sub-surface area is of particular interest. Diffraction methods enable for non-destructive measurement of spatial resolved stress distributions. X-ray and neutron diffraction are appropriate to cover surface and bulk. On the other hand, the intermediate area (sub-surface) is accessible by the application of high energy synchrotron diffraction [15]. This study aims at the characterization of residual stresses in SLM parts by using different diffraction measurement techniques.

Experimental

Alloy 718 was processed and provided by SIEMENS AG, Power and Gas, Berlin, Germany. The specimens were produced on an EOS M290 machine using the standard EOS parameter set for Alloy 718. The processing parameters, like track width, scan speed and power input, are confidential but were kept constant during fabrication. The deposition of each layer during the SLM process was identical with the hatching and scanning along the length and the width of the specimens, respectively. The residual stresses were determined using three complimentary techniques. The surface and the sub-surface was characterised by laboratory X-ray as well as high energy synchrotron diffraction (instrument EDDI at Bessy HZB, Berlin) using the $\sin^2\psi$ -method [16]. Due to high energy, up to 150 keV, penetration depths of up to 100 μm are achievable at EDDI depending on the lattice plane evaluated [17]. The sample bulk was measured by neutron diffraction (instrument E3 at HZB Berlin) [18]. Table 1 gives important parameters for each measurement setup. The $\{311\}$ diffraction line of nickel was used for stress evaluation in case of X-ray diffraction and for neutron diffraction. Synchrotron measurements were conducted in energy dispersive (EDXRD) mode using a white beam [17]. Therefore, up to four diffraction lines (see Table 1) could be utilised. Their mean value (weighted by their multiplicity) was taken for the stress evaluation.

The SLM specimens were cuboids with a length of 100 mm and a width of 20 mm. The longitudinal edges were shaped round. Each measurement was conducted in a quarter of the sample along two lines as indicated in Fig. 1. Symmetry of the residuals stresses with respect to the centre of the sample was assumed. One measuring line was placed along the centre of the sample, while the other one was in parallel along the edge. For X-ray and synchrotron diffraction the measurement was conducted in the surface according to the penetration depth of the radiation up to 60 μm . In case of neutron diffraction, the measuring lines were placed at a distance of 2 mm below the sample top surface. The microstructural characterisation included optical microscopy and Electron Back-Scattered Diffraction (EBSD). For this purpose, a small volume representing the transverse cross section of the sample was prepared by electrical discharge machining (EDM), see Fig. 1. Additionally, powder taken from this area served as stress free reference for neutron diffraction.

Table 1. Measuring and evaluation parameters for residual stress analyses

	X-ray diffraction	Synchrotron diffraction	Neutron diffraction
Radiation	Mn K α	White beam E = 50 keV-150 keV	$\lambda = 1.476 \text{ \AA}$
Diffraction line	Ni{311}	Ni{111}, Ni{200}, Ni{220}, Ni{311}	Ni{311}
2 θ angle	156°	10°	85.3°
Gauge volume	\varnothing 2 mm collimator	1 \times 1 mm ² (primary beam)	4 \times 4 \times 2 mm ³
Stress components	long, trans	long, trans	long, trans, norm
Exposure time	5 s	300 s	900 s
DEC	$s_1(hkl)$ and $\frac{1}{2}s_2(hkl)$ calculated from the single crystal constants using the Eshelby/Kröner-model		

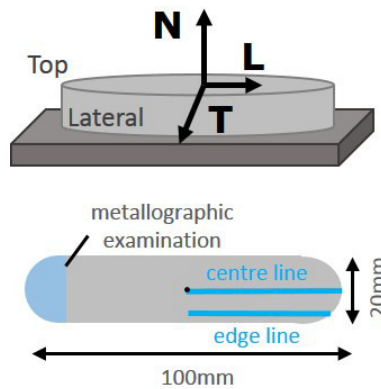


Figure 1. Schematic of the sample with measuring lines located in the centre and along the edge as well as the area considered for metallographic examination

Results

Microstructure. The parts produced by SLM process showed typical features characteristic to multi-pass welds but on a micro scale. As can be seen from Fig. 2 the bulk of the sample consisted of small overlapping runs. The heat flow was opposite to the building direction which leads to a columnar growth of the grains. Strong rotated cube texture specific of the heat dissipation along the specimen thickness was observed along the building direction, which is partly attributed to the shorter hatch length utilized for the SLM.

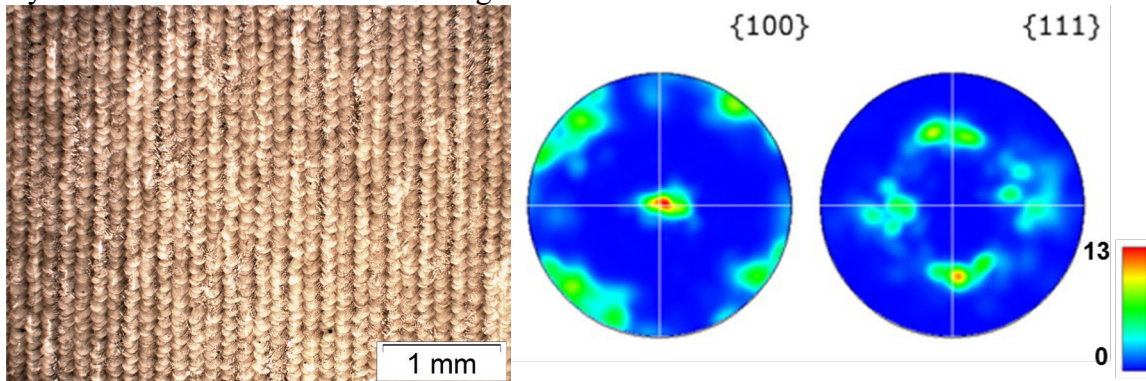


Figure 2. Cross section of the bulk by light optical microscopy (left), {100} and {111} pole figures obtained by EBSD showing rotated cube texture (right)

Residual stresses. The residual stresses obtained by X-ray diffraction are shown in Fig. 3 (left). In longitudinal as well as transverse direction the stresses were in tension. No gradient was present along the sample centreline. While the stresses in longitudinal direction showed values between 600 MPa and 850 MPa the stresses in transverse direction were significantly higher. Values around 1000 MPa indicate stresses comparable to the yield point of the wrought alloy. No differences were observed for the sample centre and the edge line. The stress distribution is uniform along the top surface.

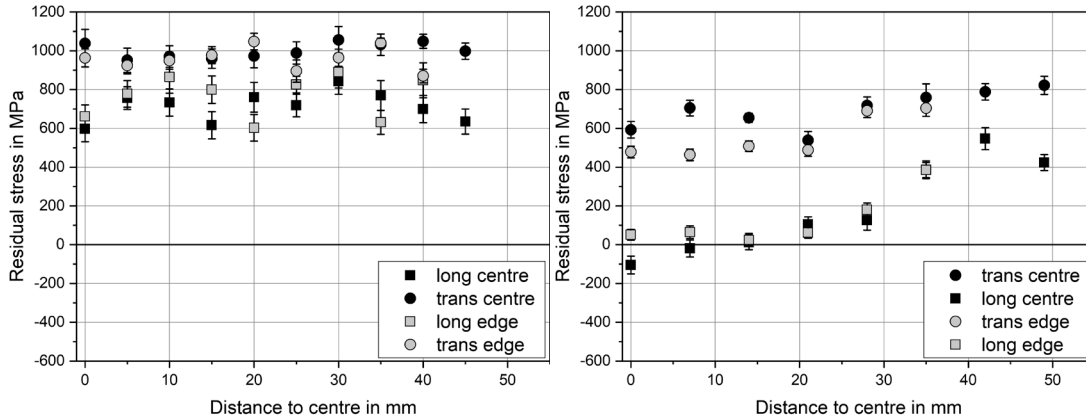


Figure 3. Longitudinal and transverse residual stresses in the top-surface obtained by X-ray diffraction at the sample centre and edge line (left) and in the sub-surface obtained by synchrotron diffraction at the sample centre and edge line (right)

With increasing penetration depth, the residual stresses changed their magnitude and also distribution as shown in Fig. 3 (right). In longitudinal direction the residual stress level was slightly shifted in parallel to values between 400 MPa and 800 MPa. Only a slight gradient was present along the measuring line indicating lower stresses in the sample centre. This gradient was more pronounced in transverse direction where the stresses in the centre were significantly lowered even to compressive values of -100 MPa. Far from the centre of the sample the stresses remained in tension showing approximately 400 MPa. As already indicated by X-ray diffraction the measured centre line and edge line of the sample are comparable showing the same stress gradients.

Different stress characteristics are to be found in the bulk of the sample 2 mm below the top surface (see Fig. 4). Lower tensile longitudinal stresses were present along the sample length which turned into compression (-250 MPa) in the border region. Transverse stresses were balanced around zero at the measured centre line.

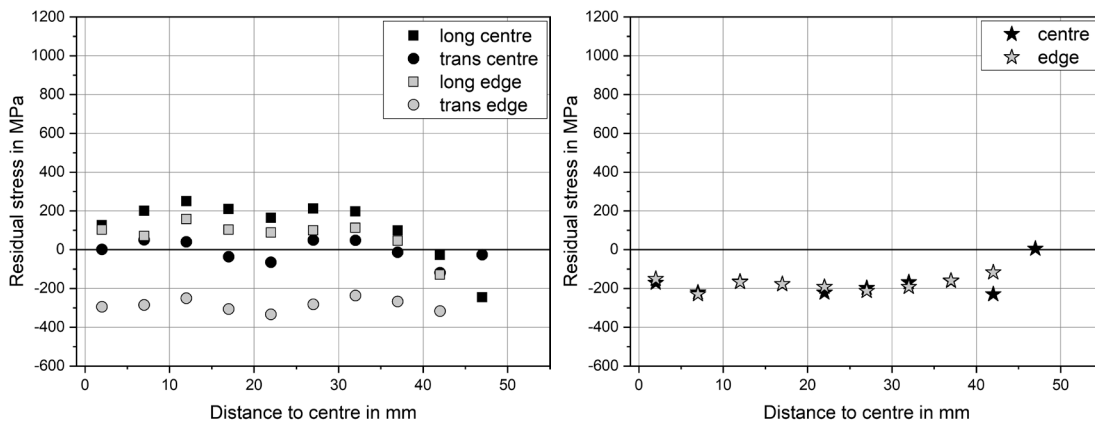


Figure 4. Longitudinal and transverse residual stresses (left) and normal residual stresses (right) in the bulk obtained by neutron diffraction at the sample centre and edge line

Considering the measured edge line, the transverse stresses were shifted in parallel into compression up to -300 MPa. On the other hand, longitudinal stresses remained in tension at a similar level compared to the centre line.

The normal stress components in the sample bulk are shown in Fig. 4 (right). The distribution and also the level of the stresses is similar in the centre and the edge line. The stresses are constant around -200 MPa.

Taking into account all the stresses determined by the different measuring techniques applied it becomes clear that a significant stress redistribution took place during deposition of the single layers during the SLM process. The highest tensile stresses were always formed in the very last deposited layer. Immediately after reheating by deposition of the following layers the stresses were lowered especially transversely in the sample centre region. With ongoing deposition of layers and increasing distance to the top surface the stresses were then shifted to lower tensile or even compressive values due to the balance of forces.

Summary

Three different diffraction measuring techniques featuring different penetration depths were capable to determine localised residual stress profiles in samples of nickel-based superalloy 718 manufactured by SLM. Using X-ray diffraction, longitudinal and transverse stress components in the top surface showed high tensile values up to the yield limit. In the intermediate zone below the surface, synchrotron diffraction disclosed a pronounced stress gradient along the length of the sample for both stress components. Particularly, the transverse residual stress relaxed very quickly towards the centre of the sample. Residual stresses analysed by neutron diffraction in the bulk showed considerably lowered stresses proving the stress re-distribution during deposition of the SLM layers. Even compressive stresses were found in transverse and predominantly normal direction in the sample.

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