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EVALUATION OF RESIDUAL STRESS IN SELECTIVE LASER MELTING OF 316L STEEL

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ABSTRACT

Selective Laser Melting (SLM) has great potential in additive manufacturing methods because it allows producing full density complex parts with desired inner structure and surface morphology. Mechanical properties of SLM objects depend strongly on the material properties as well as strength of the connections between tracks and layers since all objects made by SLM are superposition of the single tracks and single layers. High temperature gradient as a result of the locally concentrated energy input can lead to residual stresses, crack formation and part deformations both during laser processing and after cutting objects from the substrate. X-ray diffraction method was used for investigation of residual stress in SLM samples from 316L steel fabricated by one-zone strategy with 50% overlap of the tracks. Samples had rectangular shape and different thickness: 50 μm (one layer), 0.2 mm (5 layers) and 1 mm (25 layers). All as-made samples attached to the substrate had the tensile stress. Normal residual stress along the scan direction was 1.2-1.7 times higher than perpendicular direction. In some areas residual stress was about and exceeded the yield strength of 316L wrought material.

INTRODUCTION

Selective laser melting (SLM) is a kind of additive manufacturing technology. SLM objects are produced from powder material track by track and layer by layer. Object-building technique could be various: from one-directional overlapped tracks to stochastic exposure strategy in line with the "island principle", Concept Laser GmbH (2012), but the essence of SLM method is step-by-step local melting of powder material by laser.

The behaviour of individual SLM tracks and their geometric characteristics depend on the process parameters, and physical-chemical and granulomorphometrical properties of the powder. Each powder shows peculiar behaviour in the process of track formation, Yadroitsev *et al.* (2012). Mechanical properties of SLM part depend strongly on the material properties as well as strength of the connections between unit elements which are single tracks and layers. Due to the nature of manufacturing, SLM parts have anisotropy of mechanical and structural properties. High temperature gradient as a result of the locally concentrated energy input leads to high stresses. Stresses generated during manufacturing process can not only cause deformation parts, changing the geometric dimensions, but also formation of cracks. A residual stresses can significantly affect the performance of the parts; distortion can occur when removing it from the substrate on which the part is produced, Knowles *et al.* (2012).

Merselis *et al.* (2006) found that before removal SLM parts from 316L powder had tensile stress of 12 ± 7 MPa at the upper zone of the part. Roughness of the top surface caused this low value of the stress. After cutting about 120 μm it was found that for random sector exposure the stresses were equally large in X and Y direction (about 146-165 MPa); the base plate removal yielded a

large reduction of the stress levels (69-65 MPa). Stresses perpendicular to the scanning direction were significantly larger than the stresses along the scanning direction for the samples produced by one-directional strategy and cut from the substrate (302 *versus* 209 MPa for 10 mm sample). Residual stresses augmented with height of samples: it was about 20-30 MPa for 2.5 mm sample and 200-300 MPa for 10 mm sample.

Furumoto *et al.* (2010) investigated the residual stresses induced during layered manufacturing processes with a strain gauge. A strain gauge was attached on the bottom face at the centre of the base plate. The metal powder was a mixture of 70% Cr-Mo steel powder, 20% Cu alloy powder and 10% Ni powder in weight. The results showed that the deformation of the base plate from carbon steel increased with the number of consolidated layers and then became almost constant when the layer number was over 400 layers. There were tensile stresses within the SLM samples and these values were extremely large at the top surface and at the boundary between the substrate and the consolidated structure (about 800 MPa). Van Belle *et al.* (2012) proposed a numerical model to simulate the genesis of residual stresses in SLM parts. Calculated residual stress also was higher in the top layer and in the area of the interface between the substrate.

Residual stress at the first layer of the structure was decreased when the base plate was heated before consolidating the deposited powder, Furumoto *et al.* (2010). When each of the consolidated layers was repeatedly heated by the laser beam irradiation, the residual stresses also decreased. Kruth *et al.* (2012) using bridge curvature method estimated that post-heat treatment reduced the thermal stresses more than optimizing parameters for island scanning strategy.

Factors caused residual stresses are the deformation gradients in various areas of the SLM object by the thermal gradients and volumetric changes arising during phase transformations. In case of multi-material objects or different material of the powder and the substrate difference in coefficient of thermal expansion also is the source of stresses, On-line residual stress resources (2012). Thus studying of residual stress during SLM is actual and vital issue.

MATERIALS AND METHODS

Stainless steel (SS) grade 316L powder from Sandvik Osprey Ltd. was selected for this study as wide-used austenitic single-phase metallic alloy. The nominal chemical composition of the employed powder was as follows (weight %): Fe – balance, Ni – 10-14%, Cr – 16-18%, Mo – 2-3%, Si – 0.75% max, Mn – 2% max, C – 0.03% max, P – 0.045% max, S – 0.03% max. The 10th, 50th and 90th percentiles of equivalent diameter (weight by volume) of 316L powder were $d_{10}=3.0$ μm , $d_{50}=7.1$ μm and $d_{90}=27.5$ μm , respectively. The substrate from SS grade 304L and the powder material were similar in chemical composition, but powder contained 2-3% of molybdenum.

3×3 cm one-layer, 5 and 25-layers samples with 50 μm - layer thickness were produced from 316L steel powder by one-zone strategy with 50% overlap at the substrate with 100 mm diameter and 11.7 mm - height. SLM experiments were carried out using single-mode continuous-wave Ytterbium fiber laser operating at 1075 nm wavelength (IPG Photonics Corp.). The laser beam had a TEM₀₀ Gaussian profile, 70 μm was spot size diameter. Laser power was 50 W, scanning speed was 0.10 m/s. Nitrogen was used as a protective gas.

The residual stress measurements were done with X-ray diffractometer Proto XRD. Lattice deformations of the Fe- γ {311} were determined using MnK α (2.10314 Å) radiation source with a

power of 12 kV and 4 mA. The irradiated area was about 1 mm in diameter. Data were measured using the $\text{Sin}2\psi$ method in iso-inclination mode at 5ψ different iso-inclination angles: 25° , 13.6° , 0° , -13.6° , -25° . The residual stresses were calculated considering plan stress conditions using X-ray elastic constants of $\frac{1}{2}S_2=7.14\times10^{-6}\text{ MPa}^{-1}$ and $S_1=-1.20\times10^{-6}\text{ MPa}^{-1}$. The electrolytic removal technique was used to determine in-depth residual stress distribution by XRD.

2. RESULTS AND DISCUSSION

During grinding of the substrate, the contact zone between wheel and work piece can be considered as a band heat source moving in the cutting direction. The residual stresses induced purely due to this thermal effect will be highly tensile in the direction of motion of the heat source and less in the perpendicular direction, Reddy *et al.* (1999). Residual stress after grinding of the substrate is a result of compressive stress owing mechanical effects and tensile stress owing thermal effects.

Compressive stress was found in the substrate from 304L after grinding. Absolute value of residual stress in the direction perpendicular to the grinding was higher than stress in the parallel direction (Figure 1). Roughness of the top surface was conditioning factor that the peak compressive stress was found under the top surface layer. The total height of roughness profile of stainless steel 304L substrate was (R_t) $12 \pm 2.9\text{ }\mu\text{m}$, maximum height of roughness profile (R_z) $8 \pm 0.6\text{ }\mu\text{m}$ (Figure 2). Abusive grinding produces tensile residual stress since the thermal effect becomes dominant; gentle grinding generates compressive residual stress due to the mechanical effect. In the absence of high temperature gradients, the mechanical strain in the workpiece is dominant, giving compressive residual stress, Helieby and Rowe (1980).

Figure 1. The profile of the residual stresses curves of the substrate after grinding.

SLM samples were produced with 50% overlap on the single-zone strategy, the scanning direction did not change during the manufacturing process. The aim of the study was to investigate the residual stress for the objects manufactured in one-scanning direction. This strategy is not optimized for full-density objects, but it may be useful for understanding the values and gradients of residual stresses during SLM. All produced samples were adhered well to the substrate and low levels of porosity were observed (Figure 3). Taking into account the typical values of modulus elasticity for SS 316L as 193 GPa, $17.5\times10^{-6}\text{ K}^{-1}$ coefficient of thermal expansion, and the solidus

temperature $T_m = 1400^\circ\text{C}$, calculated residual tensile stresses at $T_0 = 25^\circ\text{C}$ are 4.64 GPa. This value is considerably exceeds the yield strength of approximately 290 MPa. Residual stress experimentally estimated in the direction perpendicular to the scanning wastensile with values of 280 ± 35 MPa for one-layer object, 275 ± 60 MPa for 5 layers, and 236 ± 59 MPa for 25 layers. Average values for residual stress along the scanning direction overdraw stress in perpendicular direction 1.2-1.7 times (Figure 4).

Figure 2.3-D image of the substrate surface from SS grade 304L (a); profile of the substrate (b).

Figure 3. Microstructure of the 25-layer sample cross-sections: perpendicular view (a); lateral view (b); top view (c); fine microstructure (d).

Fig. 4. The profile of the residual stresses curves for central region of 3×3 cm SLM samples: one-layer sample (a); 5-layers sample (b); 25-layers sample.

To install the anisotropy of residual stresses in one-directional laser scanning the following experiment was performed. By laser beam a square 30×30 mm was re-melted in the center of a 1 mm thin steel plate with size 60×60 mm. The laser power was 50 W, the scanning speed was 0.12 m/s, the laser beam is shifted by $60 \mu\text{m}$, as in the SLM experiment. The plate is bent in XZ plane, scanning direction was X-axis, which means that the residual stress along the scan direction was higher than in the perpendicular direction.

The anisotropy in the residual stresses can be explained by the strong texture of the SLM material (Figure 3). The ratio of the Young modulus in the parallel direction to that in the perpendicular direction can attain the values between 1.2 and 2 in SLM samples, as was shown Yadroitsev (2009). This anisotropy is neglected when residual stress was calculated, but the general tendency of increasing the residual stress with increasing the elastic modulus is confirmed. The measured parallel residual stress of 400-500 MPa are even above the value of the yield strength for wrought material and approaches to the ultimate tensile strength of about 480-560 MPa. A very fine sub-

micron grain structure is formed after SLM (Figure 3d) and exhibits elevated mechanical properties.

CONCLUSION

For the one-zone strategy with 50% overlapping SLM samples had tensile stresses. The residual stress in the direction along to the scanning direction was higher than in the perpendicular direction for all the specimens regardless of the height of the sample. The maximum stress reached in the place of joint sample with the substrate. For the 25-layer sample the residual stresses in the parallel and perpendicular to the scanning direction were very variable and were of 404 ± 91 and 236 ± 59 MPa, respectively.

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