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Residual stress via the contour method in compact tension specimens produced via selective laser melting

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The complex thermal history of parts produced via selective laser melting (SLM) leads to a complex residual stress state. While it is generally accepted that these residual stresses are unfavorable, their exact influence on the mechanical behavior of parts produced by SLM is unknown. Two-dimensional stress mapping using the contour method shows that residual stresses have a major influence on the anisotropic behavior of Ti6Al4V produced via SLM. Furthermore, maximum stress values are close to the yield stress.

Keywords: Additive manufacturing; Selective laser melting; Residual stress; Contour method; Fractography

In selective laser melting (SLM), a high-power laser locally melts successive layers of powder to produce complex shaped three-dimensional metal parts. The highly localized heat input leads to extremely large thermal gradients, which can surpass $10^7\ \mathrm{K\ s^{-1}}$ and $10^7\ \mathrm{K\ m^{-1}}$ [1]. In turn, these gradients produce a complex residual stress state inside the part. Stresses are introduced mainly by the shrinkage of the solidifying top layer, which is restricted by the previously consolidated layers. This induces tensile stresses in the top layer which are close or equal to the material yield stress [2], while the underlying previously consolidated material is compressed. Over time, as more and more layers are added on top of a specific point, this turns the original tensile stresses into compressive stresses.

The shrinkage of the top layer cannot be assumed to be planar isotropic, as this would neglect the track-by-track nature of the laser scanning. The stresses are on average two times larger in the direction of a scan track [3]. Shortening the individual tracks by adjusting the scan strategy to a so-called "island scanning" strategy can greatly reduce residual stresses [2,4–7]. By rotating the scan pattern between layers, the directional anisotropy of one layer is compensated for by the next layer, creating a more homogeneous stress distribution.

Several studies have been performed on residual stresses in additively manufactured parts. Most of these studies focused on thin walls produced via the LENS® process [8–12], as this geometry allows a quasi-2-D approach and simplifies the analysis. It has been shown both through experiments and modelling that the vertical tensile stresses near the outer edges of the walls may exceed the material yield stress, causing cracks. Ding et al. [12] used an uncoupled thermomechanical model of a thin wall to predict residual stresses. The results, which were also quantitatively verified using neutron diffraction, showed that the longitudinal stresses were large compared to the transverse and normal stresses. Furthermore, the longitudinal stresses, tensile at the top surface, decreased more or less linearly moving downwards along the normal (vertical) direction. Moat et al. [13] used neutron diffraction and the contour method to map the stress field inside a thin wall. Results from both methods coincided well and showed that the overall stress state in the part, while still attached to the base plate, can be described as being compressive in the center and tensile along the side and top surfaces. Rangaswamy et al. [14] also used neutron diffraction

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and the contour method on 3-D solid structures produced via LENS® rather than a thin wall. The residual stresses were found to be small in the horizontal plane, but large in the vertical direction. The stress maps showed that mainly vertical stresses were present, which were compressive in the center and in tension along the outer surfaces. Krol et al. [15] modelled the effect of different support structures on the final residual stresses and validated the model with neutron diffraction measurements, showing that an optimal choice of support structure and preheating can lower the residual stresses. Contrary to the results of the authors above, Barbas et al. [16] measured compressive stresses on all outer surfaces but the top of a small 5 mm^3 CP2 Ti cube. Lipinski et al. [17] later used these results to explain the fatigue behavior of scaffolds produced by SLM.

Apart from the detailed investigations mentioned above, residual stress analysis of SLM has mainly been limited to qualitative or semiquantitative analyses by measuring deformation rather than stresses, e.g. via the use of cantilever or bridge-shaped specimens [6,7,18]. Furthermore, residual stress modeling efforts for SLM face difficulties due to the small scale at which the phenomena are taking place, which drastically increases computational time. In general, of the major metal additive manufacturing techniques, SLM suffers most from residual stresses. Preheating during electron beam melting and the large heat input during LENS® lower the thermal gradients in those processes, thereby limiting residual stress buildup. While authors such as Leuders et al. [19] have used residual stresses as an explanation for the mechanical behavior of Ti6Al4V processed via SLM, studies that combine both the mechanical properties and residual stresses are lacking.

Samples were produced on a SLM machine by Layerwise NV, Belgium [20] using Grade 5 Ti6Al4V powder with a powder particle size ranging between 5 and 50 μm. ASTM Standard E399 nomenclature was used in labeling the specimens described below. The XZ- and ZX-oriented samples were produced individually. The XY-oriented samples were produced in a stack, after which individual samples were sliced using electro-discharge machining (EDM). The XY sample used in this paper came from the center of the stack, i.e. not from the bottom or the top. Sample orientations are shown in Figure 1. Compact tension specimen dimensions are according to ASTM Standard E399. The notch was introduced using wire EDM.

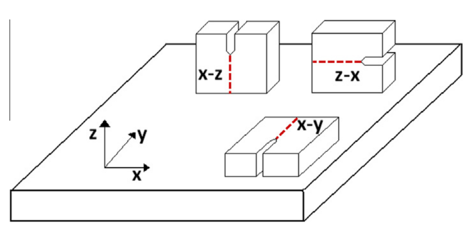

Figure 1. Sample orientations of the XZ, ZX and XY compact tension specimens. The dashed red lines indicate the direction in which the crack would normally propagate, but also indicate the plane along which the samples were cut for the contour method. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For each orientation, one sample was used for residual stress measurements. Three samples per orientation were used for fracture toughness and another three for fatigue crack growth rate (FCGR) testing. Another three FCGR samples per orientation were subjected to a stress relief heat treatment consisting of 4 h at 650 °C and furnace cooling.

FCGR tests were performed on an Instron Combined Schenck using a fixed amplitude ΔP and a frequency of 5 Hz. The length of the crack was monitored using a camera system.

A detailed review of the contour method and its application can be found elsewhere [21,22]. In short, samples were cut using wire EDM with a brass wire 100 μm in diameter. To minimize cutting errors, the parts were clamped on both sides of the cut using a specifically designed holder, similar to the one shown in Ref. [21]. Duration of the cutting was about 15 min, resulting in a cut plane of 20 mm × 12.5 mm. The deformation of both cut planes was measured four times using a COORD3 coordinate measurement machine with a 3 mm diameter stylus. The accuracy and precision of the machine are 5 and 1 μm, respectively. Each surface was measured using a 0.4 mm point spacing, resulting in a 49 × 31 grid of 1519 data points. After averaging the four data sets for one surface, the raw data was cleaned and the data for the two opposing surfaces of one cut was averaged to remove all antisymmetrical errors induced during wire EDM cutting. To avoid unrealistic local stress peaks due to random errors in the surface data, the data is then fitted with a quadratic spline approximation using a node spacing of 3.3 mm. One half of a compact tension sample is modeled in the commercially available ABAQUS finite-element package. The spline is then evaluated at the ABAQUS node coordinates of the cut plane, and the measured deformation is applied to the model. The ABAQUS model node spacing at the cut plane equals 0.3 mm, and the model consists of 51110 C3D8R-type elements. The normal stresses obtained are assumed equal to the stresses that would be needed to return the cut to a flat surface, i.e. the residual stresses that were released during cutting. Plasticity effects and the bulge error were not accounted for, but were minimized by secure clamping close to the cut and the use of a thin wire.

In Figure 2a, both halves of the fracture surfaces of a representative XY-oriented sample after fracture toughness testing are shown. The bottom part of the shown surface consists of the notch that was made using EDM, and is not an actual part of the fracture surface. Above, a pre-crack is grown to ~7 mm in length using cyclic fatigue cracking, as dictated by ASTM standard E399. Afterwards, the sample is loaded statically with increasing force until fracture occurs. The pre-crack front is indicated by the red dashed line in the left fracture surface for clarity. The front is relatively straight. Additionally, Figure 2a also shows the residual stress map of the stresses perpendicular to the fracture surface. Peculiarly, the stresses are tensile in the center, balanced by compression at the top and bottom edge. The maximum stress values are well below the yield stress, which equals 1100 MPa or higher for Grade 5 Ti6Al4V produced via SLM [23]. Furthermore, the stress distribution