

## A Methodology to Evaluate the Influence of Part Geometry on Residual Stresses in Selective Laser Melting

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### Abstract

The subject of residual stresses induced by the Selective Laser Melting (SLM) process has been one of the main focus areas in literature over the past decade. It has been reported that residual stresses can be responsible for shape and dimensional distortions, cracking and compromised mechanical properties (reduced yield and fatigue strength). These shortfalls limit the applicability of SLM components in industry, particularly for the aerospace industry where part lifetime and hence fatigue life is of utmost concern. High temperature gradients have been reported to be responsible for the residual stress build up. A key aspect that has not been considered in literature is part geometry and orientation and its influence on residual stress levels. Thus, this study proposes a methodology for investigating this influence for different geometric features. In this work, samples were built from tool steel powders. The Hole Drilling Method (HDM) and X-Ray Diffraction (XRD) techniques are proposed for measuring residual stresses. Preliminary results show that the geometry of a part influences residual stress magnitudes and distributions, with sharper ends exhibiting higher stresses than less sharp specimen ends.

### Keywords

Selective Laser Melting, Residual stresses, Part geometry, Residual stress measurement

### 1 INTRODUCTION

One of the inherent phenomena of additive manufacturing, particularly Selective Laser Melting (SLM), is the build-up of residual stresses [1]. In order to achieve parts with high densities, high temperatures are required for the full melting of the powders - usually twice the melting temperature of the material [2]. The localised heating and melting of powders, coupled with the short interaction of the high energy laser beam with the powder bed, generates rapid heating and cooling cycles [3], [4]. This induces thermal gradients and consequently residual stresses in the part under consolidation [2], [5], [6], [7], [8]. Besides high thermal gradients, a host of other factors also contributes to the magnitude and distribution of residual stresses. These factors include thermal properties of the material, layer thickness, part thickness, scanning strategy and so on. In this work, we propose a methodology for evaluating the combined influence of building orientations and geometrical features such as fillets, chamfers and sharp edges on occurrence of residual stresses.

### 2 UNDERSTANDING RESIDUAL STRESSES

The phenomenon of residual stresses can be a significant problem in SLM and other processes based on similar technologies [9] such as Electron Beam Melting, Laser Engineered Net Shaping

(LENS) [10] and Microwelding. SLM can be regarded as a series of micro-welds and therefore the same residual stresses encountered in micro-welding are also present in SLM [11]. According to Vrancken et al. [12], the SLM process results in the highest residual stresses among the metal additive manufacturing methods. These stresses have been reported to cause part distortion [8], pores, cracks and delaminations [2], [13], [14], [15], and even plastic deformation during consolidation [16]. Mercelis and Kruth [17] have described two mechanisms that are responsible for the formation of residual stresses in SLM. The first mechanism is attributed to the heating of the material when irradiated by the laser. Upon exposure, the material expands. This expansion is partially hindered by the underlying cooler solidified substrate, resulting in a compressive stress condition. These compressive stresses may be sufficiently high to induce plastic deformations [13]. The second mechanism occurs upon cooling of the material after exposure. The material shrinks upon removal of the laser beam. However the shrinkage is hindered by the plastic deformation that was developed during heating. Furthermore, the underlying solidified layer hinders the contraction of the top layer. These mechanisms result in a tensile residual stress in the upper surface [3], [13], [17]. Residual stresses are more pronounced in dense parts compared to porous parts as porosity tends to relax residual stresses

[3], [13] such that the stress normal to a pore is zero [3].

### **2.1 Influence of Part Geometry on Residual Stresses**

Part geometry, particularly length and the second moment of area influence the occurrence and magnitudes of residual stresses in final parts [18], [19]. Previous experiments have shown that residual stresses tend to decrease through the part thickness [18]. This is attributed to underlying layers being exposed to a greater number of laser beam passes. A higher number of laser beam passes acts as a form of post treatment (or laser surface remelting) which has the effect of reducing residual stresses [18].

### **2.2 Influence of building orientations**

Building orientations have a reported impact on the mechanical strength of finished parts. From their work on SLM of stainless steel 316 L, Meier and Haberland [20] conclude that specimens built vertically show lower tensile strength and reduced ductility when compared to those built horizontally. Vrancken et al. [12] carried out a study on building orientations and stack building influence on mechanical properties, including residual stresses. They conclude that specimens built vertically have high fatigue crack growth rate. The influence of building orientations on toughness properties was investigated by Kruth et al. [21] and it was found that the building direction has negligible influence on toughness of samples although a significant influence of part geometry on toughness properties was recorded. Manfredi et al. [22] used four "orientations" to evaluate the properties (density, tensile strength etc.) achievable for Direct Metal Laser Sintering (DMLS) of AlSiMg. More orientations should be considered to include all the three building planes (XY, XZ and YZ); this is the objective of this work's experimental plan. According to Meier and Haberland [20], the building orientation affects the tensile strength of parts, with horizontally built parts exhibiting higher strength compared to vertically built ones and even those manufactured using conventional means. These findings are also in line with conclusions by Vrancken et al. [12].

### **2.3 Influence of scanning vector length**

Employing short scan vectors has been reported to reduce residual stress [3]. This is so because when the scanning area is small and short scan vectors are used, the laser beam scans successive lines in a very short space of time such that the temperature of the already scanned area will still be high when the laser beam scans along another path. This way, temperature gradients are reduced between neighbouring scan lines, resulting in reduced thermal stresses. On the other hand, long scan vectors promote cooling of the already scanned area because the laser beam should travel a long distance along the scanning area. In this case, the high temperature differences between scanned area

and the new scan line results in greater thermal stresses [23]. The direction of scanning also determines the direction of thermal stresses. Jhabvala et al. [16] observed that residual stress-related bending was in the y-direction, orthogonal to the scanning direction chosen.

## **3 MATERIALS AND METHODS**

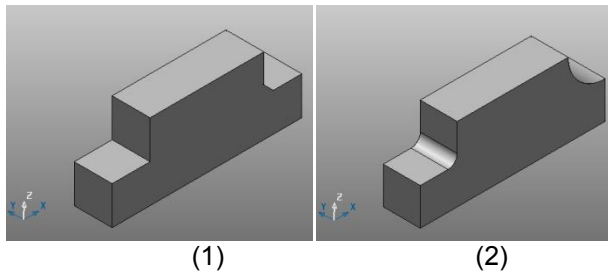
### **3.1 SLM with m2 lasercusing system**

The specimens were fabricated using the M2 Laser Cusing machine installed at Stellenbosch University's Rapid Product Development Laboratory. The machine has a building envelope of 250 x 250 x 280 mm and is equipped with a 200 W continuous wave Yb:YAG solid state fibre laser. Laser focus diameter can be varied from 70 – 200  $\mu\text{m}$ , and the powder layer thickness permissible is 20 – 50  $\mu\text{m}$ . This machine uses the island exposure strategy, patented by Concept Laser GmbH, in which the scanning area is divided into 5 mm X 5 mm squares which are scanned randomly [3], [13], [24].

#### *3.1.1 The geometries*

Previous geometries that were considered in SLM were mainly to do with evaluating the achievable dimensional accuracy, minimum feature size, minimum wall thickness and manufacturability of overhangs [2], [25], [26]. In this work, components of the same length, width and height were built according to geometries given in Figure 1. The chosen geometries and associated features are in line with previous studies to evaluate influence of building orientations and features on strength properties of finished parts [12], [20], [22]. These geometries make it possible to investigate how the presence or absence of certain geometric features (such as chamfers, sharp edges and fillets) influences the magnitudes of residual stresses in SLM. The success of measurement of residual stresses is dependent on the size and shape of the component to be measured. In this study, the selected geometries make it possible to conveniently measure residual stresses using the Hole Drilling Method (HDM) and X-Ray Diffraction (XRD) technique. Geometry 1 is a block with sharp edges and a chamfer (Figure 1(1)). It is expected that the action of the laser beam cannot be the same for the two ends (sharp corner versus chamfered one) due to the difference in the scan lengths associated with each of these ends. This is the motivation for choice of geometrical features and applies to geometry 2 as well. Geometry 2 is a modification of geometry 1. This modification includes fillets in place of sharp and chamfered edges as shown in Figure 1(2). As with geometry 1, the presence of these features results in anticipated differences in heat transfer regimes for the different radius of fillet. Overall, geometry 1 and geometry 2 are expected to exhibit some difference in the residual stress magnitudes and distributions due to

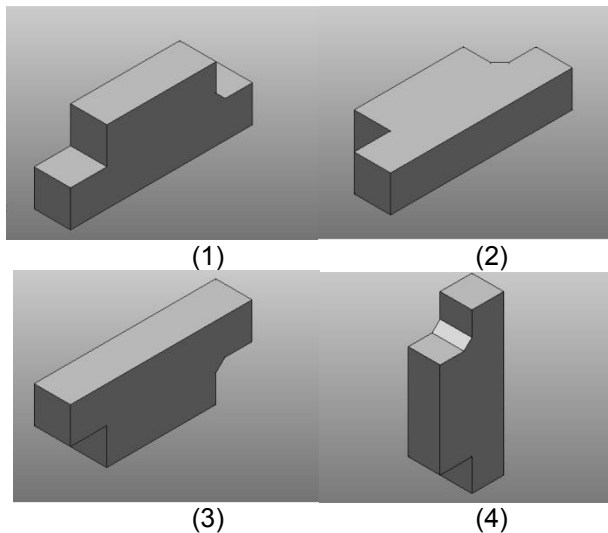
the differences in scan lengths and heat transfer dynamics around the features.



**Figure 1 -** CAD model for Geometry 1 and 2

### 3.1.2 Building orientations

Four building orientations or planes were chosen for the proposed specimen as given in Figure 2 and 3. The planes shown in Figure 2 and 3 are XY (specimen 1 & 5 i.e. +Z direction), XZ (specimen 2 & 6), XY (specimen 3 & 7 i.e. -Z direction) and ZY (specimen 4 & 8). As evident from these geometries

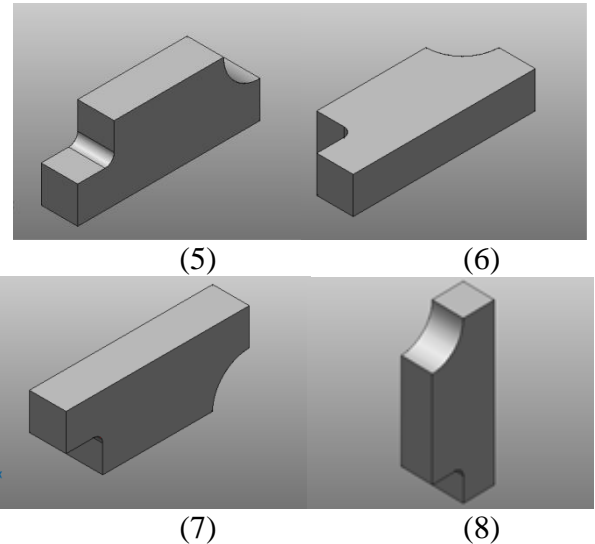


**Figure 2 -** Building orientations for Geometry 1 with sample number/label

and orientations, specimens 3, 4, 7 and 8 will need supports in order to be built robustly. All the specimens were built from tool steel powder. The specimens were built on one base plate and, therefore, the same process parameters were employed for all the samples in their respective orientations. Wire Electron Discharge Machining (Wire EDM) was used to cut off the specimens from the baseplate and to remove supports.

### 3.2 Measurement of Residual Stresses

Two measurement methods – Hole Drilling strain gauge Method (HDM) and X-Ray Diffraction (XRD) technique - are proposed in order to check consistency of the results. HDM involves the drilling of a small hole in the material to be tested and using strain gauges to measure changes in strain state.



**Figure 3 -** Building orientations for Geometry 2 with sample number/label

When a hole is drilled in a material, the locked-up stress is relieved and a corresponding change in the strain state is recorded using strain gauges. The change in strain is then related to the stress state through a series of equations through the theory of Kirsch [15], [18]. XRD is the most widely used [19] non-destructive residual stresses measurement technique. Since material deformations cause changes in the spacing of the lattice planes from their stress-free value to a new value that corresponds to the magnitude of the applied stress [27], these changes can be used to evaluate internal strains and stresses in a material. This method is limited to shallow depths [28] or near surface regions [29]. Test surfaces should be thoroughly cleaned to remove grease, coatings and roughness, which may act as barriers to the X-ray beam, leading to many errors [19], [28]. In this work, the D8 Discover Diffractometer was employed for residual stress measurement.

For both methods, the measurements will be taken from the faces of the specimens as shown in Figure 4. Since the objective is to study the influence of the geometric features on the residual stress distributions, three reference points are chosen for the two specimens as shown in Figure 4 (represented by the small circles). The mid-point (2<sup>nd</sup> point) will be used as the control point whereas the other two points near the geometric features to be studied will be the measurement points. The measurement points are located close to the features whose influence on residual stresses is to be evaluated at Cartesian coordinates (12, 10) and (38, 10), with the control point being situated at (25, 10).

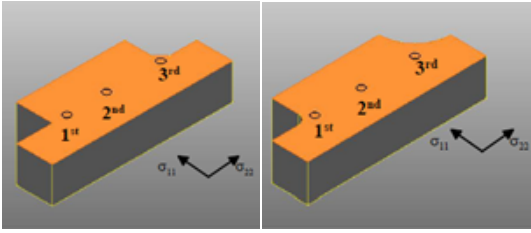


Figure 4 - The measurement positions

#### 4 XRD MEASUREMENT RESULTS

Figures 5 and 6 show the results of the residual stress tensor components ( $\sigma_{11}$ ,  $\sigma_{22}$  and  $\sigma_{12}$ ) as functions of position along the length of the samples. The results show tensile normal stresses,  $\sigma_{11}$  and  $\sigma_{22}$  for specimen 2; relaxing laterally from ~200 to 124 MPa and ~540 to 453 MPa respectively. A similar trend is observed for  $\sigma_{22}$  on specimen 1, relaxing from 378 and 247 MPa. On the other hand, a change in stress from 130 MPa tensile to 10 MPa compressive is observed for the normal component  $\sigma_{11}$  of specimen 1. For both specimens, the residual stress magnitudes do not change significantly from point 2 to point 3. The shear stress components do not show significant variation. As

expected, the sharper corner of specimen 1 (1<sup>st</sup> point) exhibits comparatively very high residual stress when measured against the control point (34 % higher for point 1 than point 2 for the  $\sigma_{22}$  component). On the contrary, reducing the sharpness of this corner on specimen 2 results in a much lower percentage residual stress difference (approximately 11 %) between point 1 and point 2 for the  $\sigma_{22}$  component. The same trend is observed for the  $\sigma_{11}$  component whereby an approximate 120 % reduction of residual stress is realised for specimen 1 against a much lower 50 % reduction for specimen 2. Furthermore, for the  $\sigma_{11}$  component, the stresses at the sharper end (point 1) are 108 % higher than at the less sharp end (point 3) for specimen 1. A similar trend is observed for specimen 2, with point 1 exhibiting approximately 38 % higher stresses than point 3 (less sharp end). For the  $\sigma_{22}$  component, the same trend is observed that the sharp ends exhibit higher stress values (at approximately 34 % for specimen 1 and 16 % for specimen 2). Generally, the measured residual stresses are higher for specimen 2 than specimen 1, probably due to the different sample positions on the building platform.

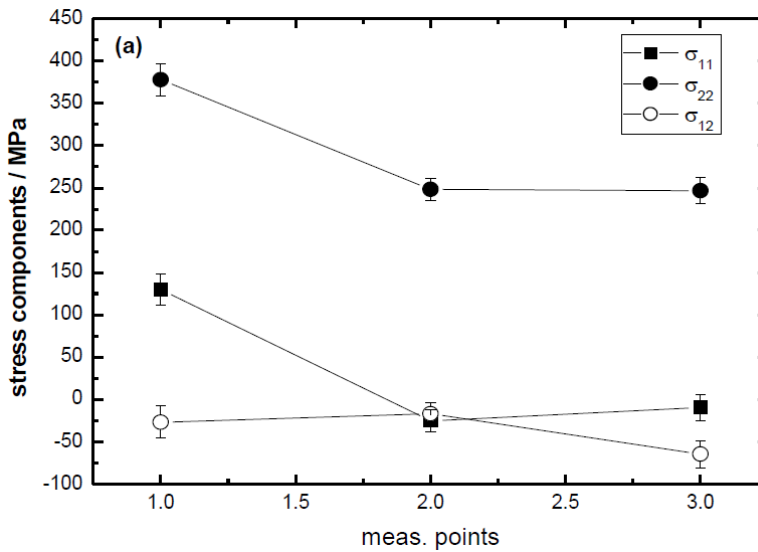


Figure 5 - Stress components for specimen 1

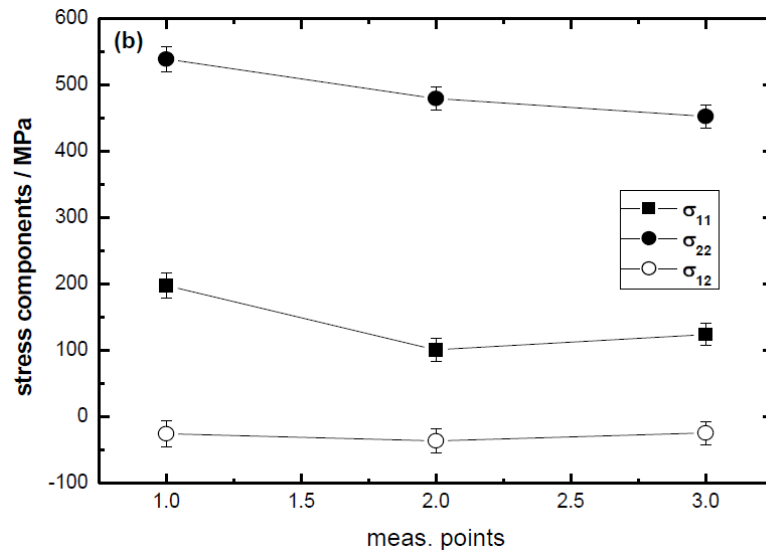


Figure 6 - Stress components for specimen 2

## 5 CONCLUSIONS AND FUTURE WORK

Preliminary experimental results point to the following important conclusions:

- High residual stresses which are largely tensile in nature were recorded for both specimens. The observed trend is that these residual stresses relax from position 1 to 3 for both specimens.
- The sharper edges of the specimens exhibit higher stresses and these stresses are relaxed as the sharpness is reduced.
- For both specimens, the  $\sigma_{22}$  stress component is greater than the  $\sigma_{11}$  component. This trend can be attributed to the greater distances between scanning sectors along the length of the specimen (corresponding to  $\sigma_{22}$ ) than across its width. This is in agreement with literature that residual stresses are higher for larger scanning sectors.
- The shear components of stress are small and do not vary significantly along the specimen length, especially when compared to the normal stress components.
- The control points exhibit different residual stress values, although these values follow a similar pattern. This is probably due to the different sample positions on the baseplate, whose influence on residual stresses should also be evaluated.

The observed differences in stress magnitudes for the two specimens sets a good basis for future investigations to involve studying the influence of sample position on residual stress distributions, further building on the work done in literature. The samples built in the XY (-Z direction) and YZ directions (i.e. samples 3, 4, 7 and 8) will have residual stresses relieved before actual measurement owing to wire EDM. This should have a direct effect on the magnitude and distribution of

the residual stresses around the measurement locations. It is also evident that the total scanning area for sample 4 and 8 is much smaller (maximum 200 mm<sup>2</sup>) compared to all the other samples (maximum 1000 mm<sup>2</sup>), thanks to the chosen orientations. This means that the time to scan neighbouring islands is shortened, resulting in reduced temperature gradients between islands. However, the Least Heat Influence (LHI) [23] which is expected to reduce thermal stresses becomes inapplicable. Against this background, it will be interesting to evaluate the influence of the scanning area on residual stresses.

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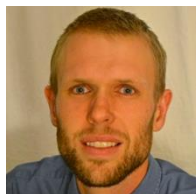
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