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Effect of powder bed preheating on distortion and mechanical properties in high speed selective laser melting

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Abstract Selective Laser Melting (SLM) is known to cause residual stresses due to the inherent large thermal gradients from high heating and cooling rates during manufacturing. The residual stresses tend to induce distortion, delamination of parts from the base plate as well as cracking because they reduce the threshold flaw size required for crack initiation. These challenges form a barrier to the use of this additive manufacturing method for structural applications for the aerospace industry where high part integrity is a critical requirement. The aim of the study was to evaluate the degree of distortion and crack growth resistance during increasing monotonic loading and cyclic loading of As-built Ti6Al4V parts produced on the Aeroswift high speed SLM process preheated at 200˚C. The monotonic loading results are comparable to those of commercial SLM systems but are lower when compared conventional manufacturing methods. The crack growth resistance of the As-built specimen is lower than that of heat treated specimen. Distortion at this preheating temperature is evident at from 12cm away from the base of the cantilever and spreads to height of 3.2mm.

1. Introduction

Additive Manufacturing according to ASTM is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies [1]. Classification of the processes is based on feed material, energy source and on how the feed is introduced into the machine. Selective Laser Melting (SLM) is a powder bed fusion type of process where a thin layer of metallic powder is deposited on a bed and a laser selectively melts the powder according to a 3D model. Selective Laser Melting has become a promising processing method for the manufacture of parts in the aerospace, automotive, biomedical and other industries. Its advantage is in its ability to produce complex and customised parts [2-5]. The SLM process involves fast heating and cooling of material by a laser creating high local thermal gradients. This results in highly nonequilibrium microstructures (e.g. Martensite), along with substantial residual stresses [6]. The residual stresses are associated with pronounced deformations especially for thin-walled features [7]. Distortion or even cracking of the part can sometimes happen during the process when the stresses reach critical levels [3]. Moreover, residual stresses strongly influence crack initiation and growth [8,9]. All this will affect the part's functionality and integrity. Post processing methods have been employed to reduce residual stresses and increase elongation to failure. This though, implies additional time or step and importantly, the post build heat treatments do not address part distortions during the build, and any distortions will still need to be dealt with [10]. A solution that can be implemented during manufacture is needed to address this.

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Work has been done on preheating with promising results. Residual stresses have been effectively reduced and mechanical properties improved by preheating in different materials by a number of authors, Vracken et al.[11] and Ali et al.[12] on Titanium alloys, Buchbinder et al.[13] on Aluminium alloys and Mertens et al. on steel[14] .

This study will evaluate the degree of distortion and crack growth resistance during increasing monotonic loading and cyclic loading of Ti6Al4V parts produced on the Aeroswift high speed SLM process preheated at 200 degrees Celsius

2.Methods

2.1 *Materials and Process*

The material composition of powder determined by Electron Dispersive Spectroscopy (EDS) was 87.18wt% titanium, 8.45 wt% aluminium and 4.36 wt% vanadium. The specimen were manufactured on the Aeroswift high speed Selective Laser Melting machine at the CSIR National Laser Center. The laser power used was 2kW under an argon filled atmosphere and a preheating temperature of 200˚C. The build samples are shown in fig. 1. The Archimedes method was used to measure the density of the specimen and it yielded >99% for all the specimen.

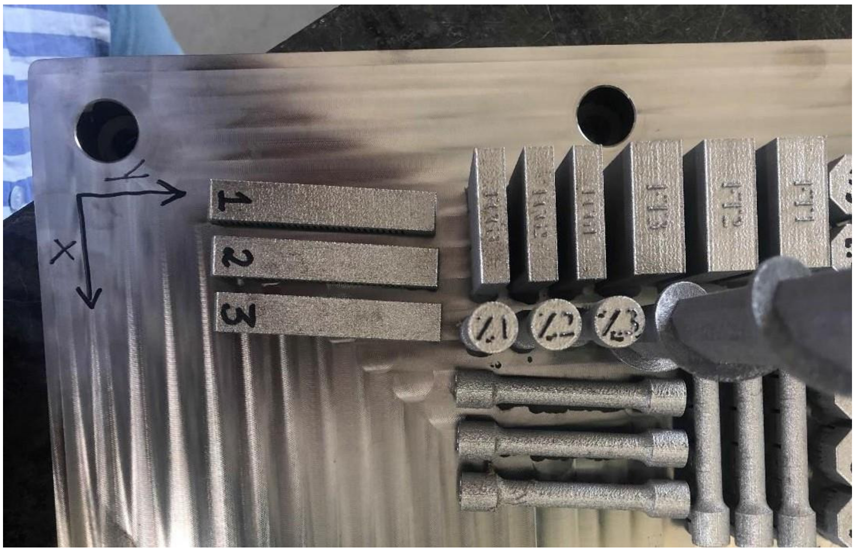

Figure 1. Ti6Al4Vspecimen built for the study on a base plate.

2.2 *Mechanical Testing*

Standard samples (ASTME8) were machined and tensile tests were conducted using an Instron universal testing machine with a crosshead velocity of 1 mm/min. A set of three tensile specimens were tested. Blocks manufactured for fracture toughness and fatigue crack growth rate specimen and were machined to size according to ASTM standards E399-17 and E647-15 respectively. Their direction was based on previous work done by Cain et al. [8]. This study is based on the worst performing direction which was the ZX from the Cain et al. study. This direction is designated by the ASTM E399 standard: axis direction perpendicular to the notch plane followed by the axis direction in which the crack is expected to propagate. The ESH 45kN servo-hydraulic machine is used for Fatigue Crack Growth and Fracture Toughness testing

2.3 *Distortion Measurements*

Three cantilevers were manufactured to measure distortion, hteir geometry and dimensions is shown in figure 2 below.. While they were still attached to the base plate, their height was measured relative to the base plate. They were then wirecut up to the base of the cantilever and the height was measured again. . The MetraScan 750 Optical Elite System 3D scanner was used to do the measurement. The spread of the cantilever Δl is calculated by equation 1.

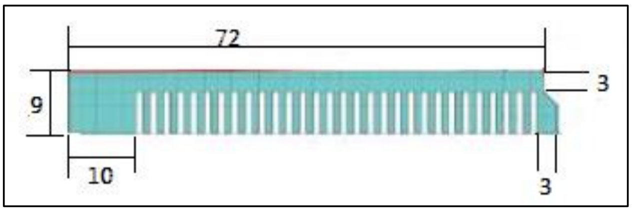

Figure 2. Cantilever geometry and dimensions

$$\Delta l = l_h - l_0 \qquad \text{(eq. 1)}$$

Where l_h is the height of the cantilever after cutting off the base plate and l_0 is the height before cutting

3.Results

3.1 *Tensile Testing*

The tensile mechanical properties of Aeroswift As-built specimen, commercial SLM systems As-built specimen and ASTM cast and wrought standard results are shown in table 1. The Aeroswift results are comparable with those of the commercially available SLM systems and are characteristic of the SLM process that has an inherent brittle martensitic microstructure resulting in a high yield stress, a high ultimate tensile strength but a relatively low ductility (<10%) [15-17]. The UTS and YS of the Aeroswift as-built specimens are higher than those of cast and wrought but their elongation is far less, this however should be improved by post processing [3,5,11]. Conventional manufacturing methods produce <1000MPa UTS and YS and >8% elongation.

Table 1: Tensile mechanical properties of SLM as-built Ti6AlV specimen.

	UTS (MPa)	YS(MPa)	Elongation (%)
Aeroswift	1211.66 ± 3.11	1067.91 ± 26.31	4.34±2.33
SLM [5]	1216+-8	1125+-22	6+-0.4
EOS M270[5]	1219+-20	1143+-30	4.89+-0.6
ASTM F1472 As-cast[18]	>758	>860	>8
ASTM F1108 Wrought[18]	>930	>860	>10

The SEM images of the fracture surfaces are shown in figure 3 below. Low magnification shows a cup and cone fracture. Pores are visible and contribute to the cracking of the material. At high magnification figure 2b) dimples are visible, these are associated with pore coalescence and ductile type of fracture [19]

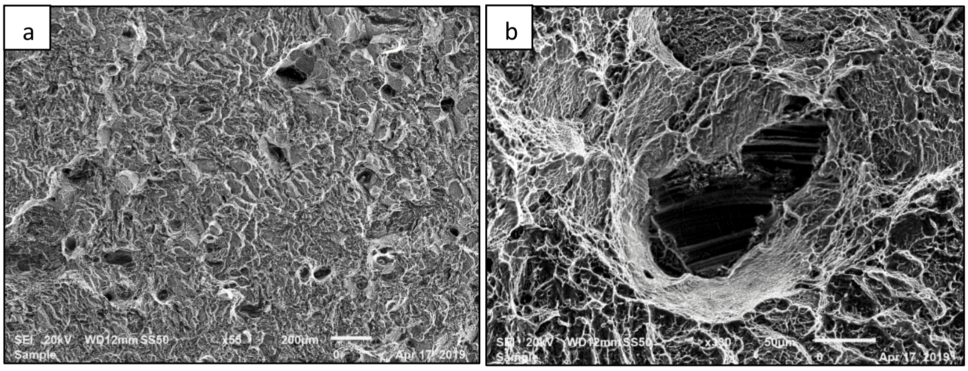

Figure 3: SEM images of the tensile fracture surface a) Pores b) Dimples

3.2 Crack growth properties

The crack growth of the Aeroswift as built specimen as well as the stress relieved specimen is given in figure 4. The as built specimen fractured after 41000 cycles and the crack had grown up to almost 8mm. The stress relieved specimen fractured only after 220000 cycles and had a crack growth length of 19mm. This indicates the influence of temperature on crack growth properties and the improvement of the properties temperature provides.

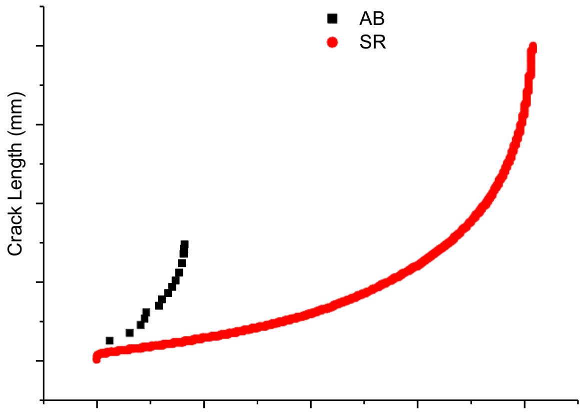

Figure 4. Graph showing the relationship of crack growth in distance with the number of cycles.

Testing for this material processed by additive manufacturing had not been done before on this machine, thus the testing load had to be determined using the specimen. After three rounds of testing that included increasing and decreasing the load depending on the rate at which the crack was growing, the load needed for this material for a recordable rate was established. Two of the test specimen were used for the load determination and thus only one set of results is reportable at the time of submission of this manuscript.

3.3 *Distortion Results*

The distortion results of the Aeroswift cantilevers are compared to a study by Vrancken at al. [11] and are depicted in figure 5. The Vrancken at al results represent two sets of data, one is of 25mm cantilevers built at no preheating (NP) and the other built at 200˚C preheating temperature, the same temperature as this study. The results show that spreading (distortion) of the cantilever for the Aeroswift specimen (72 mm) starts from 12cm from the cantilever base and the spread, Δl is 3.526 mm. From the Vrancken et al. study, the amount of spreading between no preheating and 200˚C preheating is evident but is not substantial. The distance ratios are shown in table 2, they were used to normalize the distance at which distortion begins in each case. This helps in comparing the data as parallels since the cantilever lengths were different. The bigger the ratio, the larger the distance between the cantilever base and the point at which distortion starts.

At the same preheating temperature, distortion starts after a larger distance for Aeroswift specimen than Vrancken et al. results. The test qualified the preheating temperature as no delamination of the parts occurred, even thin parts like those of the cantilever teeth which are very prone to delamination [6].

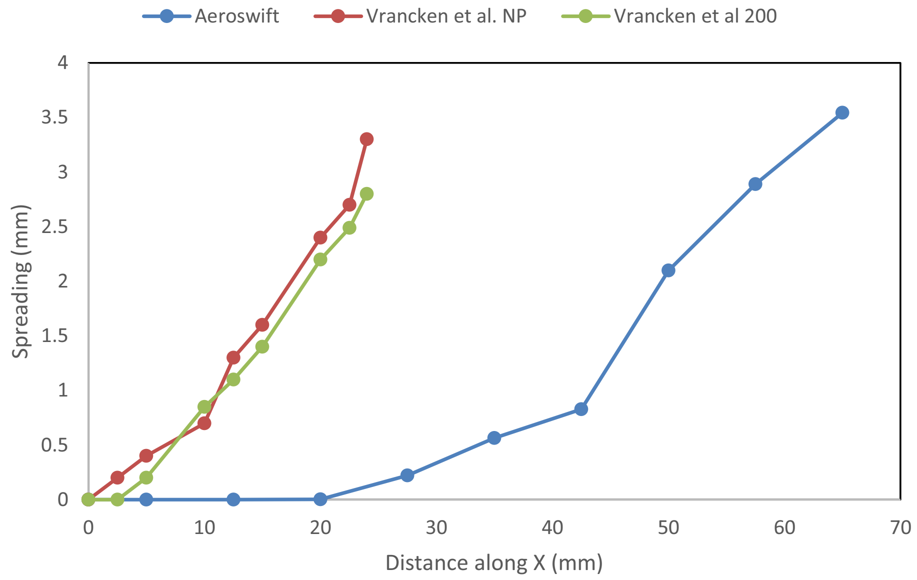

Figure 5. Cantilever spread results at 200˚C preheating

Table 2. Start of distortion ratios

	Tot. Length (mm)	Start of distortion from base (mm)	Ratio
Aeroswift	67	12.5	0.186567
Vrancken et al. NP	25	1	0.04
Vrancken et al. 200˚C	25	2.5	0.1

4. Conclusion

Preheating at 200˚C on the Aeroswift yields tensile properties similar to those of other SLM commercial systems. The UTS and YS are better than those produced by conventional methods but the elongation is less than that of cast and wrought parts. The cantilever spread indicates the presence of residual stresses at this temperature but no delamination was experienced. Further testing is to be done to confirm crack growth behavior at this preheating temperature. The study was useful in informing the operational ability of the Aeroswift machine and to the roadmap to producing capable and high integrity parts. Future work will look into implementing higher preheating temperatures to effectively reduce distortion causing residual stresses and improve static and dynamic mechanical properties without post process heat treatments.

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