Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 00 (2019) 000–000

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

International Conference on Sustainable Materials Processing and Manufacturing, SMPM 2019, Sun City Resort, South Africa, 08 – 10 March 2019

Residual Stress Modelling and Experimental Analyses of Ti6Al4V ELI Additive Manufactured By Laser Engineered Net Shaping

A.S. Ngoveni[a]*, A.P.I. Popoola[a], N.K.K. Arthur[b], S.L. Pityana[b].

[a]*Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, South Africa.*

[b]*National Laser Centre, Council for Scientific and Industrial Research, South Africa.*

Abstract

This paper focus on the experimental analyses and modelling of the residual stresses build up during laser additive manufacturing by Laser Engineered Net Shaping. Currently, additive manufactured parts employ heat treatment for the reduction of internal stresses, but then additional advantages are also possible from heat treatment. The experimental analyses focus on stress relieving heat treatment temperatures to reduce the residual stresses during laser processing of LENS Ti6Al4V ELI specimens. LENS parts out of Ti6Al4V ELI will illustrate the mechanical property possibilities resulting from the selected stress relieving heat treatments in this study. The primary aim of heat treatment in this case of Ti6Al4V ELI is the reduction of internal stresses. Due to the mechanical behaviour of Ti6Al4V as built additive manufactured parts, the heat treatment seems to be necessary to increase the mechanical behaviour, such as the fatigue performance and the breaking elongation. Optical Microscope, Scanning Electron Microscope and Vickers hardness test was employed to carry out detailed study of the resulting microstructures and Hardness. The model by COMSOL Multiphysics was employed to predict the residual stresses of as built LENS Ti6Al4V ELI and to better understand the residual stresses amounts in the Ti6Al4V ELI alloy that need to be minimized by heat stress relieving heat treatment methods. The results included the β-phase that formed in the stress relieving heat treatment process that was transformed to martensite α during the cooling process and a fine basket-weave structure emerged. The microhardness of LENS Ti6Al4V ELI alloy gradually decreased with increasing stress relieving heat treatment temperature. The computed model revealed the maximum stress of $1.78\text{x}10^9$ MPa, the Model strongly recommended the LENS process parameters suitable to obtain Ti6Al4V ELI samples with minimal residual stresses and a further possible method to alleviate the attained residual stresses in the model to the desired elasticity.

Peer-review under responsibility of the organizing committee of SMPM 2019.

Keywords: Additive manufacturing; Laser Engineered Net Shaping (LENS); Microstructure evolution; Residual stresses, Heat treatment and Modelling.

---

* Corresponding author. Tel.: 012 382 4663.
E-mail address: syd.ngoveni@gmail.com

Peer-review under responsibility of the organizing committee of SMPM 2019.

1. Introduction

Additive manufacturing (AM) is a process, which involves heating, melting and solidification of an alloy by moving the heat source such as laser in a layered manner, there is a significant thermal gradient which originate around the melt pool since the temperatures required to melt a metal are extremely high. Therefore, as the material cools down and shrinks, residual stresses develop because the thermal strains which exceed the yield point of the material, which is mainly controlled by the magnitude of the thermal gradients in the solidified metal as also addressed by [1] & [2]. It is advisable that the process parameters for additive manufacturing be closely monitored and controlled to reduce and produce samples with minimal residual stresses. Also, the Post Heat treatment of samples manufactured by additive manufacturing methods have been recommended by several authors such as the study of [3] to reduce the residual stresses produced from laser additive manufacturing (LAM).

Vrancken et al. [3] investigated the heat treatment of Ti6Al4V produced by Additive manufacturing. This work showed that optimization of mechanical properties via heat treatment of parts produced by the additive manufacturing was profoundly different compared to conventionally processed Ti6Al4V. The authors performed several heat treatments on Ti6Al4V produced by the selective laser melting (SLM) with an original α microstructure. The influence of temperature, time and cooling rate were distinguished. According to [4], the Mechanical properties are very much dependent on the maximum heat treatment temperature, with rising maximum temperature.

Residual stresses can be effectively relieved by heating during manufacturing and by stress-relieving heat treatment in a furnace after manufacturing [5]. The study by [6] also discovered that Post-heat treatment reduces the stresses more than optimising the parameters for the island-scanning strategy.

Ti6Al4V is the most commonly used titanium alloy due to its outstanding engineering properties. During the past decades, titanium alloys have developed as an increasingly important structural material for high quality and weight sensitive components according to Banerjee & Williams [7]. The relatively high cost of titanium, however, predetermines this material for applications with specific requirements, in aircraft industry.

The length and periods required to model AM processes and to predict the final workpiece characteristics are indeed very challenging as also indicated by Megahed et al. [8]. The proposed Models must span length scales resolving powder particle sizes as well as the build chamber dimensions. Depending on the scan speed, the heat source interaction time with feedstock can be as short as a few microseconds, whereas the build time can span several hours or days depending on the size of the workpiece and the AM process used [8]. Models also have to deal with multiple physical aspects such as heat transfer in solids and phase changes as well as the evolution of different material properties and residual stresses throughout the build time. The modeling task using COMSOL is therefore a Multiphysics endeavor for a complex interaction of multiple systems.

This study is aimed at improving the performance of 3D printed titanium aerospace component fabricated by LENS technology using stress relieving Heat Treatment. This study makes use of stress relieving heat treatment temperatures to investigate the residual stresses that build-up during (AM) using LENS on the titanium alloy grade 23 (Ti6Al4V ELI). Modeling towards this study will advance the capability to quantify the influence of the LENS process variables on resulting component properties. Experimental analyses to work out the influence of stress relieving heat treatment on the resulting microstructures and hardness is included in this study.

2. Methodology

2.1 Experimental Analyses

A grade 23 titanium alloy (Ti6Al4V ELI), which is a two-phase ($\alpha+\beta$) commercial titanium alloy, was used for fabrication of the parts by the Laser Net Shaping (LENS) system in this work. The chemical composition of the powder was as follows: Ti – balance, Al – 6.31%, V – 4.09%, O – 0.12%, N – 0.009%, H – 0.003%, Fe – 0.20%, and C – 0.005%, all in weight %.

Set of processing parameters applied using LENS system, are detailed in Table 1. Block Ti6Al4V ELI samples were manufactured by LENS and Heat treated at 650 ^{0} C, 750 ^{0} C and 850^{0} C for 2 hours and oven cooling to obtain samples with minimal residual stresses plus structural stability, ductility, machinability and dimensional in the heat treated parts. The Ti6Al4V ELI samples was characterized using the Optical microscope (OM), Hardness (Hv) and Scanning Electron Microscope (SEM) to determine the influence of using stress relieving heat Treatment on the microstructural behavior and hardness of Ti6Al4V ELI alloy.

Table 1: LENS processing parameters

Sample No.	**Laser Power (W)**	**Laser Scan Speed (mm/s)**	**Powder Feed Rate (g/min)**
A	300	16.9	3.25

The laser power was investigated at 300 W; Laser scanning speed investigated at 16.9 mm/s and the powder feed rate is investigated at 3.25 g/min. The as-built LENS Ti6Al4V ELI was compared with the resultant microstructures and hardness at different heat treatment conditions.

2.2. Numerical Modelling

Numerical modeling was computed to substantiate the LENS process parameters used to manufacture Ti6Al4V ELI specimens experimentally so to predict the residual stresses and give direction to alleviate the residual stress build up.

It has been seen in the COMSOL software that depending on the scan speed, the heat source interaction time with feedstock can be as short as a few microseconds, whereas the build time can span several hours or even days depending on the size of the workpiece and the AM process that is used. The model was obtained following the same LENS process parameters shown in Table 1.

The following equations were used to obtain the 2D model, the first equation shows the movement of the laser with distribution during the LENS additive manufacturing of Ti6Al4V ELI. However, this was shown in the Model for the first three layers.

Laser: Laser1*(t<time) + LaserOff*(t>=time)*(t<2*time) +
Laser2*(t>=2*time)*(t<3*time) + LaserOff*(t>=3*time)*(t<4*time) +
Laser3*(t>=4*time) (1)

The equation below displays the mesh velocity for powder distributions, it is an illustration of how the powder has been distributed into the molten pool. This was the first stage of modelling, after defining the parameters and geometry in COMSOL Multiphysics software and which assisted in determining the formation of the thermal gradients in the LENS additive manufacturing. The complete model was aimed to show how the laser is moving as the powder is deposited into the molten pool. The model was expected to show the residual stress built up based on the process parameters that were used experimentally to manufacture the samples.

Mesh Vel: Pd1*(t<time) + PowderOff*(t>=time)*(t<2*time) +
Pd2*(t>=2*time)*(t<3*time) + PowderOff*(t>=3*time)*(t<4*time) +
Pd3*(t>=4*time) (2)

3. Results and Discussion

The following micrographs obtained by optical microscope (OM) indicated how the as-built LENS samples are before and after heat treatment. Studying these micrographs at different LENS process parameters provide the direction as to where to expect the minimal residual stresses in the manufactured sample before and after the heat treatment is performed in the Ti6Al4V ELI samples.

The following OM microstructures were manufactured using the LENS process parameters shown in Table 1 and heat treated at 650 ^{0} C, 750 ^{0} C and 850 ^{0} C respectively.

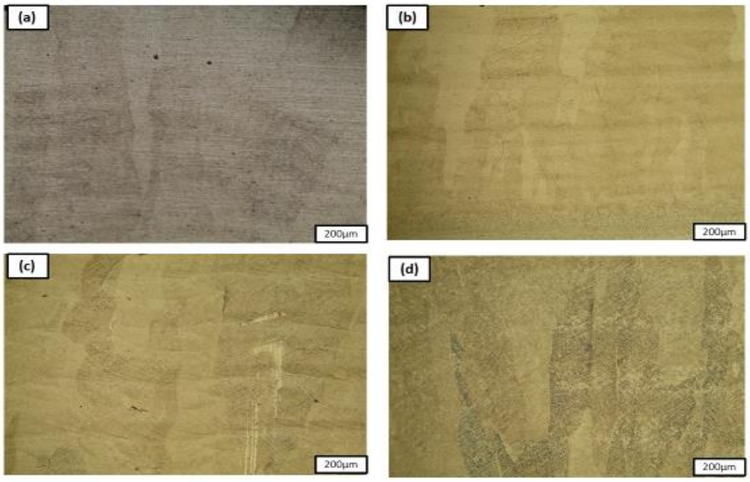

Fig. 1: OM mages (a)-is the as-built part, (b) – heat-treated at 650^{0} C, (c)-heat-treated at 750^{0} C, (d)-heat-treated at 850^{0} C

Fig. 1(a) shows the microstructure of low level of porosity in the as-built part. However, the resulting micrographs of the heat treatments in Fig. 1(b), 1(c) and 1(d) shows a further enhancement of the microstructural behaviour. The columns and the building direction of the laser are more visible in the heat treated parts.

The internal acicular martensite α′-phase of the LENS Ti6Al4V ELI is converted into the α-phase and forms a lamellar (α+β) mixture, which gradually increases in structural size with increasing temperature when studying the microstructures in Fig. 1 at their different stress relieving heat treatment conditions.

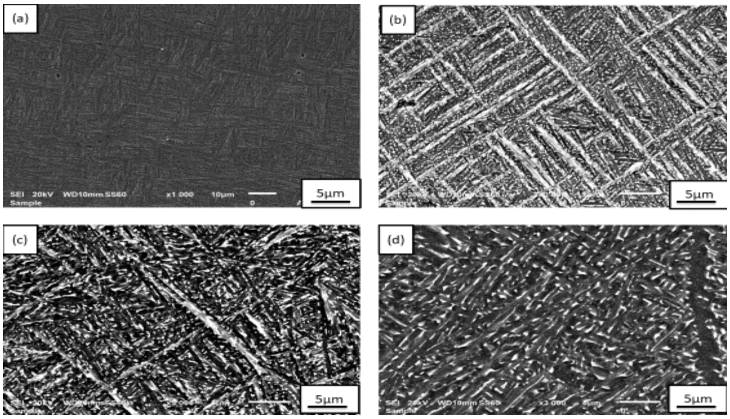

Fig. 2: SEM mages (a) – is the as-built part, (b) – heat-treated at 650^{0} C, (c) –heat-treated at 750^{0} C, (d) – heat-treated at 850^{0} C at 5 µm

Fig. 2 show a magnified SEM of Basket-weave microstructure. The as-build LENS Ti6Al4V ELI phases present are more obvious after heat treatment at 650 ^{0} C and 750 ^{0} C. After heat treatment at 850 ^{0} C, the β phase fraction is increased compared to the SEM image at 650 ^{0} C and 750 ^{0} C. The columnar grain sizes as well are enlarged at 850 ^{0} C and shows a fine martensitic structure that has been transformed into a mixture of (α+β), in which the α-phase is present as fine needles in the microstructure.

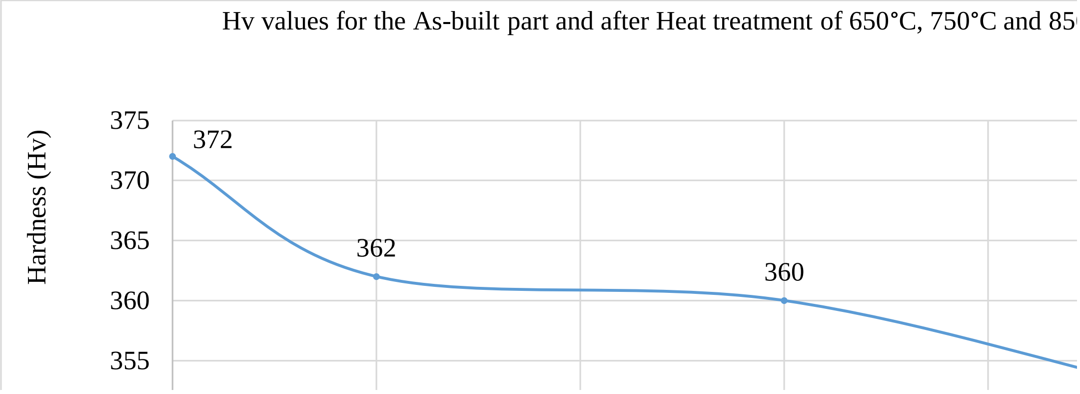

Fig. 3: The microhardness curve of LENS formed Ti6Al4V ELI before and after heat treating at stress relieving Temperatures.

Fig. 3 show a decrease in hardness value with increasing stress relieving temperature. The study by Vrancken et al. [3] indicated that, a decrease in hardness suggest a better plasticity of the material. The hardness values obtained are in the range of 350-374 Hv.

The obtained 2D model for the as built LENS Ti6Al4V ELI is shown in Fig. 3.

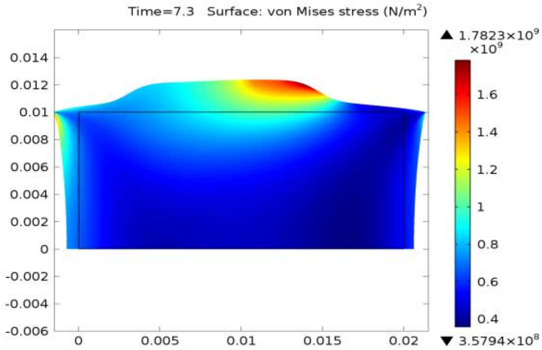

Figure 3: 2D Model Showing Residual stress of the LENS Ti6Al4V ELI additive manufactured part.

Fig. 3 shows the maximum stresses of $1.78x10^{9}$ N/m^{2} or MPa in the as built LENS Ti6Al4V ELI sample. Minimized residual stresses of the as build LENS Ti6Al4V ELI can further be achieved by performing the stress relieving heat treatment at 650 °C and 750 °C for 2 hours and oven cooling. It is recommended for future studies to compute the stress relieved model, to better realize the significance of modelling heat treated samples. Relieved residual stresses lead to the plasticity of the material and make Ti6Al4V ELI alloy better machinable while increasing the lifespan of the alloy. Just as previous study by Vrancken et al. [3] & Kruth et al. [6] indicated, that at 650 °C and 750 °C, the residual stresses can be minimized significantly.

4. Conclusion

The following conclusions were reached in this study.

- The side view of non-heat-treated Ti6Al4V ELI, produced by LENS, revealed long columnar grains which grow through multiple layers and were oriented in the building direction.
- Following the heat treatment conditions, the internal acicular martensite α′-phase of the LENS Ti6Al4V part was converted into the α-phase and forms a lamellar (α+β) mixture, which gradually increased in structure size with increasing temperature.
- The β-phase that formed in the stress relieving heat treatment process was transformed to martensite α during the cooling process and a fine basket-weave structure emerges, which improved the microhardness of the alloy and better plasticity.
- The microhardness of LENS Ti6Al4V ELI alloy gradually decreased with increasing stress relieving heat treatment temperature. However, the study by Zhao et al. [9], indicated that, when heat treating above 900 ^{0} C, the microhardness increases significantly with increasing temperature.
- The computed model revealed the maximum stress of 1.78x10^9 MPa at laser power of 300 W, Scanning speed of 16.9 mm/s and powder feed rate of 3.25 g/min. The Model, strongly recommend the LENS process parameters suitable to obtain Ti6Al4V ELI samples with minimal residual stresses and a further possible method to alleviate the attained residual stresses in the model to the desired elasticity.

Acknowledgements

This work was benefited from the cooperation between the Tshwane University of Technology (TUT) and Council for Scientific and Industrial Research, South Africa National Laser Centre, (CSIR-NLC).

References

[1] P. Aggarangsi, J.L Beuth. Localized preheating approaches for reducing residual stress in additive manufacturing. In Proc. SFF Symp, Austin, 2006, pp. 709-720.

[2] I. Van Zyl, I. Yadroitsava, I Yadroitsev. Residual stress in ti6al4v objects produced by direct metal laser sintering. South African Journal of Industrial Engineering. Vol 27(4) 2016, 134-141.

[3] B. Vrancken, L.Thijs, J. Kruth, J. Humbeeck. Heat treatment of Ti6Al4V produced by Selective Laser Melting: Microstructure and mechanical properties. Journal of Alloys and Compounds, 541 (2012) 177-185.

[4] D .Greitemeier, F. Palm, F. Syassen, T. Melz. Fatigue performance of additive manufactured TiAl6V4 using electron and laser beam melting. International Journal of Fatigue, 94 (2017) 211-217.

[5] M. Shiomi, K Osakada, K. Nakamura, T. Yamashita, F. Abe. Residual stress within metallic model made by Selective Laser Melting process. CIRP Annals — Manufacturing Technology, 53(1) 2004, pp. 195-198.

[6] J.P. Kruth, J. Deckers, E. Yasa, R. Wauthle. Assessing and comparing influencing factors of residual stresses in selective laser melting using a novel analysis method. Proc IMechE Part B: J. Engineering Manufacture, 0(0) 2012, pp. 1-12.

[7] D. Banerjee, J.C. Williams. Perspectives on titanium science and technology. Acta Materials, 61 (2013) 844-79.

[8] M. Megahed, H.W Mindt, N. N'Dri, H. Duan and O. Desmaison. Integrating Materials and Manufacturing Innovation (2016) 5:4.

[9] Z.Y. Zhao, L. Li, P.K. Bai, Y. Jin, L.Y. Wu, J. Li, R.G. Guan, & H.Q. Qu.. The Heat Treatment Influence on the Microstructure and Hardness of TC4 Titanium Alloy Manufactured via Selective Laser Melting. *Materials.* 2018, 1-12.