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Characterization of selectively laser melted Ti-6Al-4V micro-lattice struts

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Abstract

This paper presents a characterization study of titanium alloy (Ti-6Al-4V) micro-struts manufactured using selective laser melting (SLM). Previous test results from sandwich structures with titanium alloy micro-lattice cores showed that the material experienced brittle fracture failure, although it had a reasonable specific strength. Therefore, the microstructure present in the struts has been investigated in order to understand its influence on the mechanical behaviour. Conclusions on the way forward for improved mechanical behaviour, by the use of subsequent heat treatment and careful control of the manufacturing process can then be identified.

Keywords: selective laser melting; titanium alloy; micro-lattice; sandwich structure

1. Introduction

The University of Liverpool has investigated the use of selectively laser melted (SLM) micro-lattice structures within a number of engineering areas including medical devices and aerospace mechanical structures, such as lightweight sandwich constructions [1, 2]. Previous work reported that the specific strength of titanium alloy (Ti-6Al-4V) micro-lattice structures is competitive with that of aluminum honeycomb [3] and this is especially true if the energy density is high (higher laser powers and long exposure times) during the SLM process, with optimum results being obtained with a laser power of 200 Watts and an exposure time of 1000 μs. This combination of parameters for the Ti-6Al-4V micro-lattice structure core resulted in a more localized impact area in the sandwich constructions as compared to aluminum honeycomb core [4]. A more localized impact area means that a smaller area is affected by

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impact damage, and this is preferred by the aircraft manufacturer [5]. However, it has been observed that the impacted area of the Ti-6Al-4V micro-lattice structure core experienced brittle failure, with struts showing almost flat fracture surfaces. Since plasticity is an important criterion for energy absorbency in load bearing structure performance, especially in aerospace applications [6], the failure of these Ti-6Al-4V micro-lattice structures needs to be further studied and analyzed. Therefore, the investigation into the behavior of the basic micro-strut build is an important part of current research, as the properties and failure of the micro-struts is thought to predict the behavior of the micro-lattice. An explanation of the brittle fracture failure observed needs to be found, and in parallel, the elastic properties of the structures need to be determined by the use of a reliable micro-strut test.

1.1. Micro-lattice strut

The micro-plastic and -elastic properties of SLM Ti-6Al-4V micro-lattice structures can be quantified [1] from their basic building block which is the micro-strut. Fig 1(a) shows a BCC Ti-6Al-4V micro-lattice block with 2.5 mm unit cell size, while Fig 1(b) graphically shows a BCC unit cell with 8 micro-struts protruding from a node at the centre. When subjected to impact or compression load, it was found that fracture occurred in the end part of certain struts, near the node region. As reported by Shen [7], the SLM Ti-6Al-4V micro-lattice block fails on a 45° diagonal plane as shown in Fig 2. The failure of the strut ends can be clearly observed in the scanning electron microscopy (SEM) image in the figure.

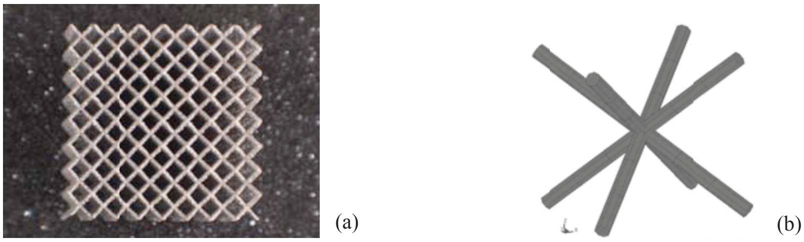


Fig. 1. (a) side view of 20 mm X 20 mm X 20 mm BCC Ti 6Al 4V micro-lattice structure block; (b) graphic illustration of a BCC unit cell with 8 struts [2]

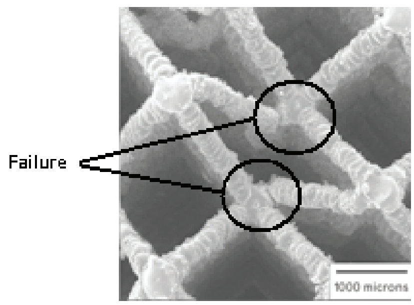


Fig. 2. SEM image of 200W X 1000µs SLM Ti-6Al-4V micro-lattice block which shows failure at certain point in the strut, near node area [7]

Previous work on the SLM processing of stainless steel micro-lattice structures [1] highlighted the possibility that the 'cast' microstructure may contribute to the less ductile behavior. It has been suggested that a similar problem may occur with Ti-6Al-4V and that this issue could be clarified by examining the microstructure present. The effect of microstructure on behavior is also implied in other research work [8, 9], where the strength of SLM Ti-6Al-4V products varied with the microstructure formed and the phases present, while the microstructure varied with the SLM process parameters used and any subsequent heat treatment. In this paper, the microstructure of the SLM Ti-6Al-4V micro-struts was studied and reported, with an objective of clarifying the SLM Ti-6Al-4V micro-lattice failure issues that have not been resolved in previous research work.

2. Material

SLM Ti-6Al-4V micro-struts were produced from the same powder material as the micro-lattice structures in previous research [7], which was Titanium Powder Grade 5 ASTM produced by TLS Technik GmbH & Co., Germany. As the micro-struts in the BCC architecture of the micro-lattices was at a 35° angle to the horizontal, the single struts were manufactured at a 35° build angle, with the maximum length being limited to 43 mm by the manufacturing process. Fig 3 shows an image of the as-manufactured SLM Ti-6Al-4V micro-strut. For microstructure studies, metallurgical samples of the micro-struts were prepared by hot-mounting in conductive resin using a 20 mm diameter mould. They were then polished following a standard metallurgical procedure, before being etched and observed under optical microscopy and SEM, incorporated with electron dispersive spectroscopy (EDS) for element analysis mapping.

Fig. 3. A 43 mm micro-strut of SLM Ti-6Al-4V manufactured at the University of Liverpool (200W X 1000μs)

3. Geometry, Microstructure and Element Analysis of Micro-strut

Fig 4(a) shows the circular cross-section of an as-manufactured SLM Ti-6Al-4V micro-strut build at 35° to the powder bed, diameter approximately 380 μm. The optical micrograph Fig 4(b) shows a longitudinal cross-section of a micro-strut, with micro-voids within the strut, and a dendritic structure, similar to the welded structure of titanium alloy. Needle like structures are present within the grains due to the solid state transformations that occur on cooling. This structure is different to that normally used with heat treated Ti-6Al-4V [10].

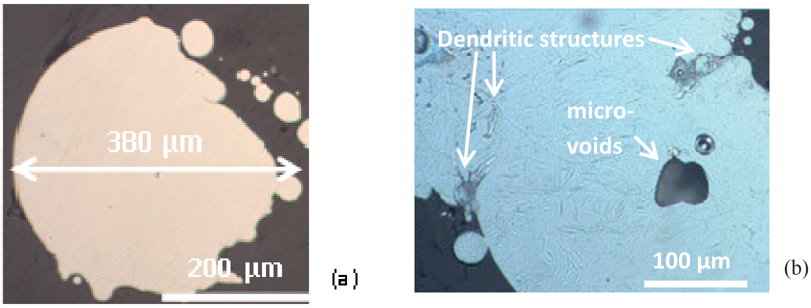


Fig. 4. (a) Optical microscopic view of circular cross-section; (b) Microstructure of longitudinal sectioned; both figures are the as-manufactured SLM Ti-6Al-4V single strut built at 35° angle laser beam at 200 W laser power and 1000 μs laser exposure time

Within the microstructure were regions that although dendritic looked very different from the bulk of the material (Fig 5).

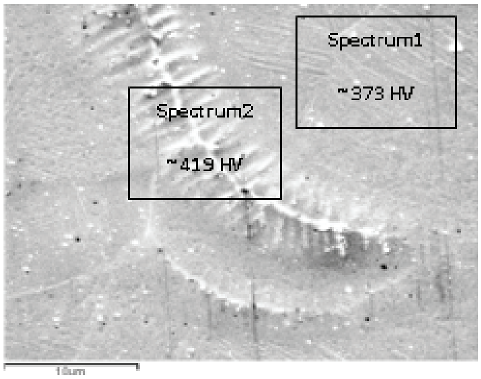


Fig. 5. A focused SEM image of dendritic structure with indicated points for spectrum 1 and 2 in elemental analysis (SLM Ti-6Al-4V micro-strut with 200W X 1000µs)

Elemental analysis of these regions (Fig 6, spectrum 1) showed that compared to the bulk (Fig 7, spectrum 2) they were rich in elements not normally found in Titanium Powder Grade 5 ASTM [7]. These included relatively high amounts of iron (Fe) and chromium (Cr). It is likely, therefore, that these structures are due to the cross contamination of the powder bed with 316L stainless steel which is also used in this SLM machine. It is likely that this contamination occurred during the manufacturing stage rather than powder preparation and may have come from the powder feed system as the argon gas atmosphere is carefully filtered [11]. Since most of these dendritic structures were found at boundaries and within inter-layer areas these phases probably form due to segregation during freezing rather than by precipitation in the solid state and are likely to form part of the last liquid to freeze. It is also suspected that the dendrite formation affects the mechanical properties as if they are brittle or soft they will form a weak point in the micro-strut initiating cracking across the strut in that region, the strut only being as strong as the weakest point. It was found that these structures were significantly harder (419 HV compared with 373 HV) that the bulk of the structure. It has not yet been possible to determine the phases present in these regions.

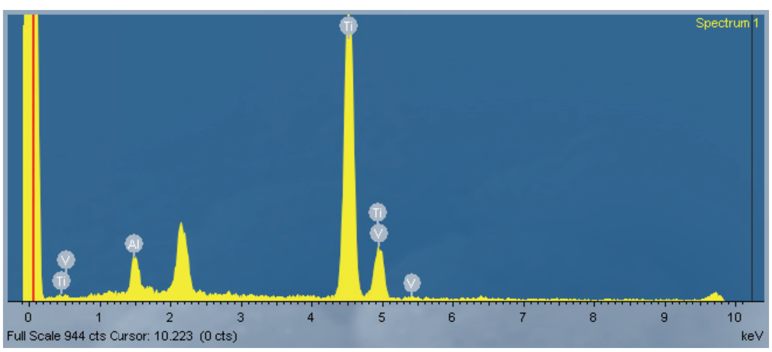


Fig. 6. The EDS plot of spectrum 1 for elemental analysis of as-received micro-strut confirmed with Ti-6Al-4V elements

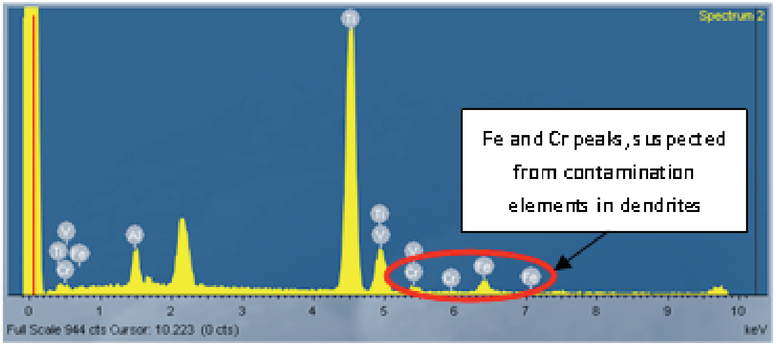
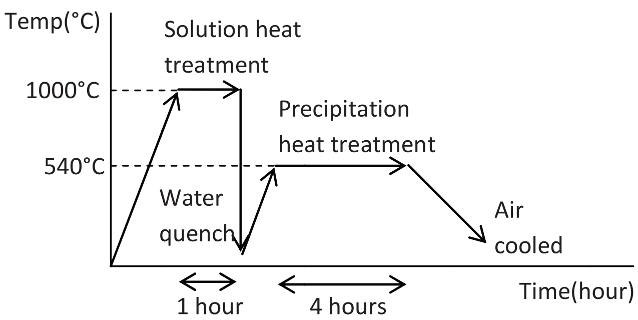


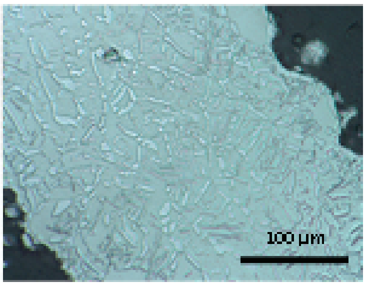
Fig. 7. The EDS plot of spectrum 2 for elemental analysis of as-received micro-strut showed the existence of Fe and Cr peaks, suspected due to contamination

4. Heat Treatment on SLM Ti-6Al-4V micro-strut

A simple heat treatment process was used to study how the microstructure affected the mechanical properties of the struts. Fig 8(a) schematically illustrates the heat treatment process while Fig 8(b) shows the resultant microstructure, which is closer to that normally used and in which any segregation of elements has been redistributed. The heat treatment was done in a normal furnace but with the sample sealed within an evacuated quartz tube. The heat treatment led to a somewhat coarser microstructure with the formation of α and β regions, the removal of the chromium and iron rich regions and the removal of the needle structure. Results from EDS analysis showed that normal amounts of Fe were present, as expected in Ti-6Al-4V, while no Cr was detected throughout the sampled area, as the overall contamination was below the detection limit of the EDS system. This change in the microstructure on heat treatment has produced a more uniform structure and is therefore likely to produce struts without regions of weakness; however the heat treatment has not induced significant grain growth so that the struts are one grain wide. The presence of a large grain size within such small struts would significantly affect their strength. Further analysis to understand the heat treatment effect on mechanical properties of SLM Ti-6Al-4V micro-lattice structure is now being carried out.



(a)



(b)

Fig. 8. (a) Schematic of heat treatment process on SLM Ti-6Al-4V micro-strut; (b) resulted microstructure of heat treated specimen showed balance α/β phase of Ti-6Al-4V

5. Conclusion and Ongoing Study

In this study the diameter of the SLM Ti-6Al-4V micro-struts was determined from the transverse cross-section geometry. The characterization of the microstructure has led to the observation of dendritic structures due to cross contamination with other powders, which had caused uneven mechanical properties along the micro-struts. Elemental analysis identified the problem of contamination and it is likely to be a significant problem with this technology if the equipment is used with more than one powder. It has been shown that heat treatment can significantly change the microstructure dispersing the contamination and creating a uniform microstructure, but without causing excessive grain growth that would have a deleterious effect on the mechanical properties. Based on these results, the current ongoing study focuses on effect of contaminant on mechanical properties of SLM Ti-6Al-4V micro-lattice structure and looking forward in ways to improve the condition.

Acknowledgements

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