Microstructural anisotropy in Electron Beam Melted 316L stainless steels

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Abstract. In recent years electron beam melting has been explored to establish its suitability for product manufacturing as this additive manufacturing route offers advantages which are not achieved in other similar processes. This paper focusses on the prime issues associated with 316L manufactured using electron beam melting. Location dependent microstructure and strain accumulation is found to be completely different at central and peripheral regions in a particular layer. Coarser grains as well as lesser amount of strain value is observed at central region when compared to periphery. Crystallographic texture at centre is seen as intensified <100> parallel to build direction whereas it is weak and relatively scattered (<100> and <110> both) for periphery. BD parallel plane gives a glimpse of available energy as well as repeated thermal cycling as long elongated grains were observed and lowest strained region, depicting the high anisotropic structure altogether.

1. Introduction

Austenitic stainless steel 316L has been extensively explored to establish its manufacturing following the route of selective laser melting (SLM), an important method in additive manufacturing [1-3]. Primary reasons for adopting this non-conventional approach comes because of 316L application areas that demands intricate design, near net shape products, low buy-to-fly proportion, etc. Although SLM possesses many non-traditional behaviours in 316L such as Mo- and Si- segregated dislocation cells, crystallographic texture as <100> or <110> normal to substrate, increase of both strength and ductility altogether [5], this manufacturing route exhibits some key challenges which hinders its widespread acceptance. Inherent defects common to SLM such as lack of fusion, unmelted powders, debonding of layers, trapped gases as well as anisotropic microstructure in 316L shows a large fluctuation in mechanical properties and sometimes lead to inferior products than conventional counterparts [1].

Electron beam melting (EBM), a very similar route as SLM melts metallic powder of a single layer selectively using electron beam at comparatively high power (~1 kW) and the chamber environment is kept in vacuum [2]. Salient advantages offered for EBM manufacturing which are not observed for SLM as (a) high densification level because of comparatively higher energy density when compared to SLM, (b) minimised defects like gas traps, de-bonded layers etc. (c) reduced thermally generated residual stress as substrate temperature is kept higher (nearly 800°C) (d) comparatively more homogenised and relieved microstructure as lower cooling rate (~ 10³ Ks⁻¹) provides more available time for diffusion [3]. Very few reports have been done for the case of EBM processed 316L that primarily gives attention to process-induced defects observation and inherent non-equilibrium microstructure [3,7]. A detailed investigation is needed that should answer questions related to phases, microstructure and its response combined with repeated heating and cooling of higher heated substrate on crystallographic texture.

This paper aims at establishing the response of location dependent microstructure on crystallographic texture for EBM manufactured 316L. Microstructure of various length scales as well as its location specific distribution and the key reasons contributing towards this observation has been discussed in detail. Additionally, factors that leads to differences in strain-gradient at these locations has been highlighted and discussed.
2. Experimental details

Manufacturing of 316L sample was done using electron beam where preheated and pre-alloyed 316L powder was taken as the starting material. Sample was built in the form of cylinder having the dimension as 13 mm height and 8 mm diameter and it is built vertical to the substrate. An interlayer hatch rotation of 90˚ was given and individual layers were rastered bidirectionally. After melting a particular layer of thickness 70 μm, it is lowered and powder was spread using racking mechanism for repetition of melting sequence. Substrate was maintained in a temperature range of 820 – 850˚C to minimise the thermal gradient. Densification level for this particular sample was found as 99.4% calculated using Archimedes’ principle.

A detailed microscopic characterisation was carried using Electron back scattered diffraction (EBSD) the help of FE-SEM attached with EBSD detector on both planes, parallel and normal to the build direction. Sample was scanned at two discrete locations as centre and periphery in BD normal plane to gain a clear understanding. Sample preparation was done using conventional polishing steps followed by electropolishing at 29V in electrolyte designated as A2. EBSD was done with a step size of 2 μm and nearly equivalent area was scanned for BD normal plane so that a clear comparison can be made. A commercially available software TSL 8.0 was used for data processing.

3. Results and discussion

3.1. Microstructure

Figure 1 (a-c) represents map of optical image micrograph (OIM), grain boundary character distribution (GBCD), and kernel average misorientation (KAM), respectively for the region of central portion in BD normal plane. Figure 1(d-f) represents the above-mentioned maps for peripheral portion of BD normal plane. As shown in figure 1 (a and d) morphology of grains is irregular in almost both locations. However, coarseness of grains seems higher at central portion (grain size ~140 μm) when compared to peripheral (grain size ~60 μm). Additionally, distribution of grain follows a wider range for periphery. The prime reason for this observation lies in location dependent cooling rate which happens to be more at periphery than central because heat can escape from more directions at periphery (towards sides of built sample and substrate) whereas it can escape only through substrate at central region. Moreover, figure 1 (b and e) highlights comparatively lower presence of low angle grain boundaries (demarcated as red, misorientation of 2 - 5˚) in case of central region than periphery. Distribution of medium angle boundaries (demarcated as green, misorientation of 5 - 15˚) seems identical in both cases whereas negligible number of twins (demarcated as blue, boundary of misorientation 60 ± 5˚) are observed at all locations.

A very similar trend is observed for KAM distribution that is mostly used to find the strain distribution as shown in figure 1(c and f). Central region highlights comparatively more strain-free regions as this area shows a uniform colour corresponding to minimum strain at all locations as compared to periphery that has non-uniform and higher strained regions.
Figure 1. EBSD generated microstructures for BD normal plane where (a) Orientation image micrographs, (b) Grain boundary character distribution (GBCD) map, (c) Kernel average misorientation (KAM) map represents central region and (d) OIM, (e) GBCD map, (f) KAM map represents peripheral region

Figure 2 (a-c) represents the OIM, GBCD map, and KAM map, respectively for BD parallel plane. A wide range of colour variants in OIM clearly demonstrate the fact that direction of maximum thermal gradient is not constant thereby, this clearly will affect crystallographic texture. As shown in figure 2(b) grains possess elongated shape having longer side along build direction where length/width ratio is nearly 8 (width ~90 μm and length ~700 μm). Additionally, some grains length along build direction are nearly 2.6 mm in length. These findings clearly depict the fact that higher amount of available energy during melting as well as cyclic heating/cooling cycle in sample promotes extensive growth of grains along build direction as reported by Korner et al. [2]. Moreover, this retained heat in previously solidified layers anneal out the structure as also reported previously. This finding is supported by KAM distribution for the same area as shown in figure 2(c). This KAM distribution is lower than value seen for a particular layer both at centre and periphery.
Figure 2. EBSD generated microstructures for BD parallel plane representing (a) Orientation image micrographs, (b) Grain boundary character distribution (GBCD) map, (c) Kernel average misorientation (KAM) map

Figure 3 compares the KAM plot of BD normal plane (centre and periphery region) and BD parallel plane. Central and peripheral region of BD normal plane exhibits average KAM value as 0.58 and 0.80, respectively. However, BD parallel plane exhibits a value of 0.37, the lowest KAM value out of all these locations.

Figure 3. Kernel average misorientation (KAM) distribution plot of BD normal representing the central and peripheral regions as well as BD parallel plane
3.2. Crystallographic texture

Figure 4 (a and b) shows the crystallographic texture using inverse pole figure along the build direction for central region and peripheral region of BD normal plane. The reason for adopting inverse pole figure and reference as build direction is because of two reasons: (a) texture in most AM processed alloy is observed as <100> or <110> or a combination of both and (b) build direction is the only fixed direction as other manufacturing parameters vary from case to case hence, changes considered reference direction [1]. As observed in Fig. 4(a), central region shows texture as <100> along build direction whereas texture shown in Fig. 4(b) for peripheral region represents a combination of <100> and <110> which appears to be consistent with previous reports of AM processed 316L [6]. Moreover, intensity level in peripheral region also observed to be low than central region. The key reason for these differences in texture observation is because of thermal gradient as a result of retained heat at a particular location. Peripheral region solidifies earlier than centre because of accelerated cooling thereby, chance of randomised nucleation at these locations gets high. This condition is very similar to amount of energy available to manufacture the product using AM [6]. This led to a decreased intensity of <100> and <110> planes at periphery.

![Figure 4. Inverse pole figure parallel showing texture parallel to build direction representing the region (a) centre and (b) periphery](image)

4. Conclusions

This investigation emphasises key consideration that need to be addressed for EBM manufactured 316L. Location dependent complex thermal gradient as a result of layer-by-layer manufacturing affects morphology of grains, strain distribution as well as crystallographic texture altogether. In an individual layer, regions near to periphery shows finer grains, strained structure as well as relatively weak texture when compared to regions near to centre. The key reason for this lies in increased cooling rate of peripheral regions than centre. Additionally, texture is seen as a combination of <100> and <110> parallel to build direction in peripheral regions when compared to central region.

BD parallel plane shows a representation of highly anisotropic process as length/width ration of grains is near to 8. This anisotropy comes as a result of repeated thermal cycling of layers as well as higher amount of retained heat in EBM process than similar processes.

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