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ScienceDirect
Procedia CIRP 45 (2016) 127 – 130
www.elsevier.com/locate/procedia

3rd CIRP Conference on Surface Integrity (CIRP CSI)

Influence of finish machining on the surface integrity of Ti6Al4V produced by Selective Laser Melting

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Abstract

Selective Laser Melting (SLM) is a direct manufacturing technique that allows objects to be built by selectively melting successive layers of metal powder. There is an additional finish machining step that is required to achieve close tolerances and control the surface integrity of the final surface. This paper mainly deals with studying the influence of the finish machining step on the surface integrity of Ti6Al4V parts produced by SLM technique. Three different building directions are considered. Changes in roughness, hardness of the machined surface and sub-surfaces are evaluated and compared with those of conventional hot rolled alloy. Cutting forces were also measured during milling process to study the influence of machining the SLM samples on the components of force in the three orthogonal directions. It is observed that the SLM samples show higher surface hardening behavior after machining and exert 22% greater axial force during the machining when compared to the conventional alloy.

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Keywords: Selective laser melting; Surface-integrity; Milling; Ti6Al4V

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1. Introduction

Titanium alloys have gained a lot of attention in the recent years with additive manufacturing (AM) technologies. Ti6Al4V being the most commonly used titanium alloy with its wide spread applications across aerospace, aeronautical, medical and other industries is now being developed to fit into mainstream through AM. Mainly because of its superior properties like high strength to weigh ratio, corrosion resistance and good performance at elevated temperatures [1], it is now being used to make functional parts with AM technologies. Selective Laser Melting (SLM) is one of the AM techniques adapted to make metallic parts in which parts can be created directly by selectively melting several layers of metal powder [2]. However in the view of surface quality and the manufacturing tolerances' required, these parts require finish machining (a post processing step) to produce the final functional surface. The surface integrity characteristics of the machined surface and the subsurface control the functional performance of a component to a large extent [3]. Some studies have been done on the conventional titanium alloys [4, 5, 6, 7] to understand machining induced surface integrity, whereas very little knowledge is available for parts produced by AM techniques.

In order to understand the influence of this post processing machining step on SLM parts, in this study, a face milling operation was performed and the final surface roughness and the sub-surface hardness was compared with the conventional hot rolled Ti6Al4V alloy. The cutting forces generated during the milling process were also compared. The SLM parts are built in three orthogonal orientations as it would help in understanding the influence of direction of the build process on this post processing step (Fig 1).

2. Materials and methods

The conventional sample which was used as a reference in this study was manufactured by a hot rolled process and then annealed at 750°C. .It was an α-β titanium alloy provided by TIMET.

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doi:10.1016/j.procir.2016.02.340

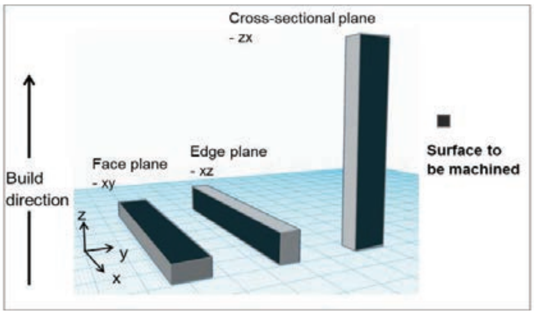

Fig. 1. SLM samples built in three different orientations.

The SLM samples tested here were built using MLab Cusing machine from CONCEPT LASER, with 100W ytterbium (Yb) fiber laser. Ti6Al4V powder according to ASTM F136-02a (ELI Grade 23) was used as the initial powder material to make the samples. The chemical composition of the conventional and SLM samples are compared in the Table 1. Optimized process parameters used for making the SLM parts are listed in Table2. Lower laser scan velocity of 400 mm/sec was used for the contours in order to have a better surface finish of the final part [8]. Simple straight line scans were used for melting each layer. The samples were built in a protective argon atmosphere on secondary support structures that help us to detach the samples from the build platform after the part is completed. The geometry of all the samples was a cuboid with dimensions of 70mm x 10mm x 6mm.

Table 1. Chemical composition of Conventional and SLM parts

Element	SLM parts Vol(%)	Conventional Vol(%)
Ti	88	89.14
Al	6.5	6.47
V	4.5	4.05
Fe	0.25	0.15
C	0.8	0.01
O	0.13	0.17
N	0.05	0.0045
H	0.012	0.0035

The samples were built with three different orientations as described in ASTM F2921, along the face plane - XY, edge plane - XZ and cross-sectional (vertical) plane ZX (Fig 1).

Once the samples were built they were removed from the build plate without any post processing heat treatment so as to study the samples in as-built condition.

As expected, the samples built on the face plane and edge plane showed some degree of deformation while the sample built on the cross-sectional plane had no observable deformation. This is attributed to excessive thermal stress produced by rapid melting and cooling during the SLM process. Though the supports help in conducting the heat away from the sample, the orientation of the sample determines the final part accuracy and quality [9].

The as-built samples were cut along the cross-section to do a micro-structure analysis which will allow us to know the orientation and the size of the grains and to compare it with the conventional hot rolled alloy. The cut samples were mechanically polished up to 1μm finish with diamond suspension and then etched with the Kroll's reagent to observe the micro-structure.

Table 2. Process parameters used for building SLM parts.

Process parameter	
Laser power (W)	95
Scanning speed (mm/sec)	900
Layer thickness (μm)	30
Diameter of laser (μm)	40

Only the side with dimensions of Length L= 70mm and width W= 10m (Fig 1) was to be machined in each of these samples. Surface roughness of the samples was measured on this side in as built condition which is shown in Table 3. Optical profilometer based on interferometry which uses white light scanning for non-contact measurements was used to measure the average roughness, Ra of the samples. Ra values of the surfaces was also measured after face milling the samples.

Table 3. As-built roughness of SLM samples on the surface to be machined

Sample orientation	Ra (μm)
Face plane	12.75
Edge plane	14.02
Cross-sectional plane	8.24

Face milling was done on the SLM samples and the conventional alloy with cutting parameters recommended for finishing operations with radial depth of cut a_p = 0.5 mm, feed rate f_z= 0.08 mm/tooth and cutting speed V_c= 55 m/min. Radial engagement of the tool was the sample width and the mill was in a central position. Coromill R300 milling cutter with AlTiN - PVD coated carbide insert grade from Sandvik Coromant was used. Dedicated round inserts were used for machining each sample to avoid the influence of the edge radius, ER wear on the force measurements. Milling was done under dry condition. The samples were mounted on a specially designed fixture that could be mounted on a KISTLER dynamometer table (type 9255B) which was used to measure the forces in the three orthogonal directions Fx, Fy and Fz. These forces correspond to the force in feed direction, cutting direction and the axial direction respectively during the face milling process (Fig 2).

To measure the machined surface hardness and hardness in the subsurface, series of indentations were performed using Nano indenter equipment from Micro Materials, UK. Berkovich indenter tip and a load of 150mN were used to make the indentations.

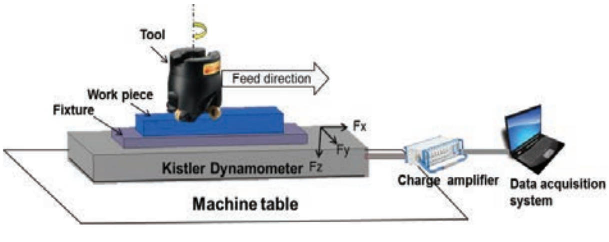

Fig. 2. Cutting force measurement setup.

3. Results and discussion

3.1. Microstructure:

Microstructure of the SLM parts is controlled by the laser scan vectors and the direction of the building process. It is evident that the high temperature gradients during the build process forms an entirely transformed α' martensitic phase. [10,11] These fine acicular α' grains are enclosed within the elongated prior-β grains which is observed to have grown along the building direction (Fig 3a-b). Hence the orientation of the prior-β grains gives rise to the anisotropy in the micro-structure. The effect of this anisotropy on the tensile properties of the samples has been studied earlier [12]. The effect of grain orientation on the milling process has to be determined. Milling is done on the plane perpendicular to the building direction for the sample built on the face plane and on the plane parallel to the building direction for the sample built on the edge and cross-sectional plane as indicated in the Fig1. The influence of the scan stratergy on the microstructure is observed in the sample built on the cross-sectional plane (Fig 3.c) where the scan vectors are visible along with the hatch spacing between them, which is about 85µm. Microstructures along the cross-section of the machined surface of samples is shown in Fig 3d,e,f,g. The conventional alloy which has a equiaxed α+β microstructure and shows some degree of plastic deformation in the layer very close to the machined surface(Fig 3g). The direction of the deformation follows the direction of the shearing during milling as indicated by the cutting velocity V_c.

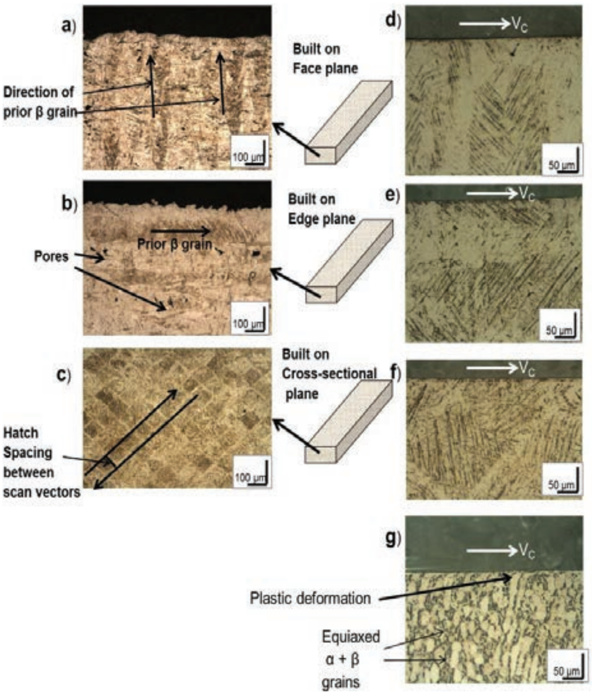

Fig. 3 Micro-structure of cross-section of the samples as-built and after machining. (a)Face plane, as built; (b) Edge plane ,as-built ; (c) Cross-sectional plane, as built ; (d) Face plane, after machined ; (e) Edge plane, after machined ; (f) Cross-sectional plane, after machined ; (g) Conventional alloy, after machined.

Unlike conventional alloy for the same cutting conditions the SLM samples in all three building orientations did not show signs of plastic deformation close to the machined surface (Fig 3d,e,f) under the same magnification of 500X. This can be explained by the finer α grain structure of about 1-2µm grain diameter in SLM samples [13], which makes it difficult to detect the deformation caused due to machining. Higher resolution microstructural analysis with EBSD, electron back scatterd diffraction may be needed for SLM samples.

3.2. Surface Roughness:

SLM samples built in the three orientations showed differences on the as built roughness values (Table 3). Though lower laser scan velocities were used for the contours to have a better surface finish, the average roughness Ra obtained is still between 8 – 14 µm in as-built state. After milling the samples the the roughness values were found to be less than 0.4µm for all the samples which is similar to those observed on a conventional sample. The Ra values measured in the feed and the cutting direction were similar (Fig 4). For SLM samples, under the same milling conditions lower Ra values were obsereved while machining the surfaces that are parallel to the building direction(edge plane and cross-sectional plane samples) than while machining the surface perpendicular to the building direction (face plane sample).

Ratio of the roughness of SLM samples to the conventional reference sample is 0.95 for face plane sample , 0.74 for edge plane sample and 0.82 for the cross-sectional sample.

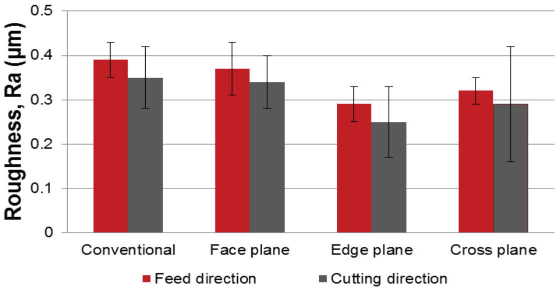

Fig. 4. Ra values of the machined surface of the samples. (V_c=55m/min, f_z=0.08mm/tooth, a_p=0.5mm)

3.3. Surface and Sub-surface hardness:

Fig 5 shows the hardness ratio of the SLM samples relative to the conventional alloy. The reference line indicates the hardness of the conventional alloy scaled to 1 at each measurement. Nano indentations were performed on two different planes i.e. on the machined surface and the sub-surface profile. Though no microstructural changes in the micrographs were observed with SLM samples after machining (Fig 3d, e, f), the work hardening of the machined layer observed on the SLM samples is more than that of the conventional alloy. On the machined surface, the sample built on cross-sectional plane showed higher hardening behavior when compared to the other two SLM samples.

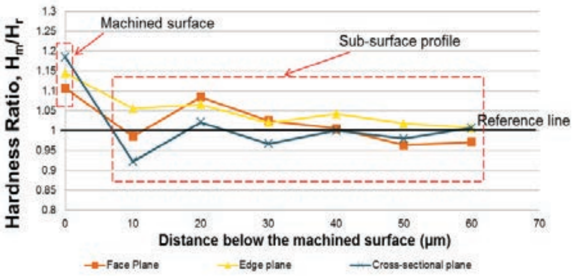

Fig. 5. Hardness ratio of SLM samples on the machined and subsurface w.r.t conventional alloy. (H_m – Hardness measured on SLM samples, H_r – hardness of reference conventional alloy).

In the sub-surface profile, at about 10 µm from the machined surface, we observe a drop in the hardness for all the samples. This is mainly because of the high cutting temperatures generated at the surface during machining titanium alloys. This temperature is retained by the surface below due to its very low thermal conductivity [5] which causes this softening effect. The sample built on cross-sectional plane showed a higher difference between the machined and sub-surface hardness at 10µm. This difference in homogeneity close to the machined surface can cause crack initiation when exposed to fatigue loading.

3.4. Cutting Forces:

The three orthogonal components of force were measured while machining the SLM samples and were compared with the conventional alloy. Figure 6 shows how these force components vary for each of the samples. It is observed that there was very little change in the feed force, Fx and cutting force, Fy for all the samples. But the axial force, Fz which is perpendicular to the surface of the sample was found to be higher for the SLM samples. SLM samples recorded about 22% higher axial force for the same machining conditions. Discontinuities in their microstructure could be a probable cause for this variation. This implies that this higher force exerted into the tool is received by the flank face of the milling insert. Elastic bouncing back effect on flank face while milling SLM samples which is higher than that of the conventional sample. This would eventually lead to higher wear rate and lower tool life and hence tool and the strategy has to be optimized for the SLM parts. This also implies that higher residual stresses could be induced while milling the SLM samples when compared to the conventional alloy.

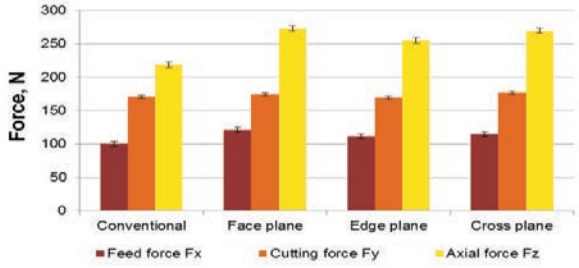

Fig 6. Forces in three orthogonal directions recorded while machining.

4. Conclusions

In this study the machining induced surface integrity on the Ti6Al4V SLM parts were compared with the conventional hot rolled alloy under finish machining condition. Based on the results the following conclusions can be drawn:

- Little or no microstructural changes were observed in the micrographs under same magnification for the machined surface on the SLM samples built in all three build orientations unlike the conventional hot rolled sample. High resolution microstructural analysis will be needed to quantify the changes caused by machining.
- Sample built on edge plane showed relatively lower Ra values after machining.
- SLM samples showed higher work hardening behavior when compared to the conventional alloy. Sample built on cross-sectional plane showed more difference in hardness between the machined surface and at the depth of 10µm.
- SLM samples exerted 22% greater axial force than the conventional sample. This in turn would lead to a higher wear rate and lower tool life.

Acknowledgements

The authors would like to thank Mikael Schuisky and his AM team from SANDVIK, Sweden for making the SLM samples.

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