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Micro cutting of Ti-6Al-4V parts produced by SLM Process

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Abstract

Parts produced by Selective Laser Melting (SLM) presents a roughness due to thickness of fusion layers but also to partially sintered particles stuck to the edge of the parts. In order to ensure a finished product with the dimensional and structural requirements of an industrial part, a post processing by machining is necessary. The aim of the proposed study is to compare the machinability of Ti-6Al-4V obtained by SLM process and that of a cast alloy. Micro-cutting tests are conducted to examine the effect of operating conditions on cutting forces, chip formation and on surface and sub-surface microstructure. .

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Keywords: Sintering Laser Melting, Micro cutting, Titanium

1. Introduction

Processes of rapid prototyping and manufacturing represent a unique potential for innovation and attain now their matureness. Today, many industrial actors enrich a market composed of various technologies allowing to produce functional prototypes and little series of metallic parts with high mechanical properties. One of the most promising methods is Selective Laser Melting (SLM). The SLM process is based on a high energy laser that melts a belt of powder particles. The process allows producing near net shape parts with a dimensional tolerance of 40 to 80 µm with a roughness induced by the thickness of powder deposition layer but also by the sticking of partially melted powder.

In order to obtain a functional product with dimensional and structural requirement of industrial parts, finishing machining or grinding is necessary [1]. Hybrid processes were developed to reply to this issue, based on a principle of addition of material followed by the removing of material on the same machine. The deposition process allows reaching a "near net shape" and the process of machining a "final form". Hybrid processes involve methodologies to decompose the necessary phases [2] and the modification of existing milling center for plastic [3] and metallic parts [4, 5]. Recently, equipments are available for industrial manufacturing (DMG Lasertec, Hermle MPA40 3D). Hybrid processes become economically competitive when deposited materials are rare, expensive and difficult to machine [5]. To a certain extent, this problematic is applied to titanium alloys, ranked among the most difficult to machine materials [6]. This finding is related to the material properties: high mechanical tensile strength retained at high temperature; low modulus of elasticity, low thermal conductivity; high chemical reactivity. The machining of Ti-6Al-4V is however possible, even without lubrication [7]. Titanium alloys are easily damaged during machining. The damage appears as micro cracks, build up edge, plastic deformation, heat affected zones and tension residual stresses [6]. While Ti-6Al-4V rough dry cutting, elongation of the beta grains shows an important plastically affected area, influenced by the increase of the cutting speed [8]. A comparative microstructure phenomenon is observed [9] with titanium parts obtained by additive manufacturing (Selective laser Sintering). Chips allow to observe physical and thermal phenomena induced by machining. The chip shape and microstructure are deeply linked to those phenomena. Specially while cutting Ti-6Al-4V [10, 11] besides its additive

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manufacturing [12], chips show an evolution in the behaviour of the cut related to the cutting speed and feed rate.
To improve the quality of SLM parts with a finishing by cutting tool, it is interesting to study their machinability. This experimental work will study the chips generation in order to understand not only the related mechanisms but also the machined surfaces integrity.
A particularity of the study is to focus on micro cutting with orthogonal test, conducted with a Ti-6Al-4V titanium alloy obtained by SLM process. A comparison with hot worked material is realized. Various cutting conditions are tested by varying the feed rate and the cutting speed. Impact on cutting forces, chip and microstructure will be investigated.

2. Material and Experimental set up

2.1. Material

Workpieces materials used in all the experiments were an alpha beta titanium alloy Ti-6Al-4V. This grade 5 titanium alloy is well known as a lightweight material for aerospace structure combining very good metallurgical and physical properties. Ti6Al4V presents a high strength to weight ratio, a low density, elevated temperature properties up to 400°C, and a low modulus of elasticity [6].

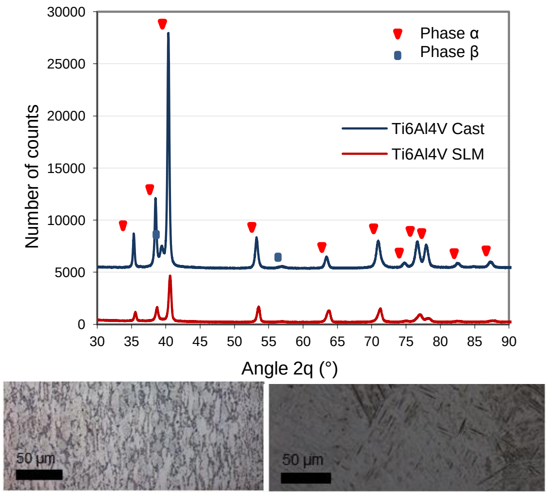

Fig. 1. (a) XRD pattern of the cast and of the SLM produced material and microstructure associated to (b) cast titanium and (c) SLM titanium

For a comprehensive comparison of the machinability of SLM samples, two different samples were prepared.
First, a bar of an alpha beta titanium alloy Ti-6Al-4V was used. The microstructure of the hot worked and annealed material considered in this work is shown in figure 1(b), where an α-globular phase in a β matrix is observable. The presence of the β-phase (8 per cent) is confirmed by X-ray diffraction (XRD) analysis, figure 1(a). The measured hardness is 315 HV10+/-0.5.
Secondly, SLM samples were produced using a SLM280HL machine. A power of 175W and a scan speed of 775 mm/s were used. Titanium melting is performed in an argon protective atmosphere. Process parameters lead to full density of the part and a hardness of 357 HV10+/-1.5. The as-built microstructure of the material produced by SLM has a very fine, acicular martensitic morphology, figure 1(c). The XRD analysis indicates the presence of hcp phase only. The hcp pattern can be attributed to both the α-phase and the α' martensite, as they have the same crystalline structure and very similar lattice parameters [13].

2.2. Experimental Set Up

Orthogonal micro cutting tests of Ti-6Al-4V were carried out on a three axis CNC vertical milling center ROEDERS RP600 with a spindle speed up to 36000 rpm. The HSM center is used as a precision turning lathe, see figure 2.
The experimental samples involved a tubular part with an initial outer diameter of 20 mm. The assumptions of micro-cutting must be taken into account: the uncut chip thickness must be small compared to the width of cut, to be able to neglect the boundary effects, and the width should not be too large to consider a constant cutting speed along the cutting edge. Considering the limits, an average diameter of 19 mm and a thickness w of 500 µm are chosen. This thickness is calculated for a speed variation along the cutting edge inferior to 10 %. The tube was first turned internal and external by roughing tools, to obtain the desired tube width and a limited workpiece run-out.
Orthogonal cutting conditions were obtained by removing the end of the tubular part of the samples with a tool, mounted on a dynamometric table Kistler Minidyn 9256C2 fixed on the machine table and associated with a Kistller amplifier 9017. The cutting tools were micro turning tools IFANGER MTNY 41015-R-TiAlN with a nominal rake angle of 8°. The cutting edge radius was measured using an Alicona Infinite Focus 3D microscope and was close to 1.3 µm [14].

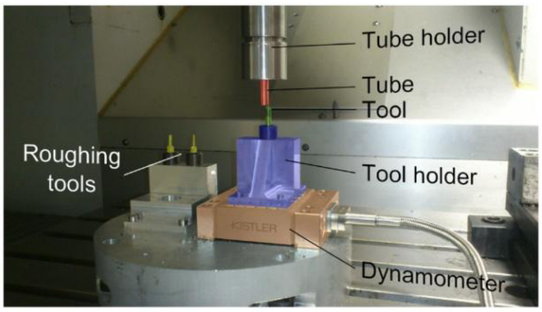

Fig. 2. Experimental set-up for tube turning.

Table 1. Cutting conditions.

	Set 1	Set 2
Cutting speed (m/min)	6,12,18,30,42,60,78,102,500	60
Feed rate (µm/rev)	10	1,2,3,5,7,10,20

Cutting conditions for experiments are defined according to the technological limitations of the milling machine. Experiments were carried out to observe the effects of cutting conditions. The first series studies the effect of cutting speed Vc, varying from 6 to 500 m/min with a constant feed of 10 µm/rev. The second series studies the effect of uncut chip thickness varying from 1 to 20 µm/rev, with a constant speed of 60 m/min.

3. Results and discussion

3.1. Cutting forces

Experiments are defined to observe the effects of cutting conditions on cutting and feed forces, reported in figure 3.
When turning Ti-6Al-4V parts, produced by SLM process, cutting and feed forces are systematically higher than when turning cast Ti-6Al-4V. The cutting force difference varies from 3% at the lower feed rate to 24 % at the higher feed rate. Also, the feed force difference varies from 21% at the lower speed to 10% at 100 m/min. For a cutting speed of 500 m/min (un-represented), cutting and feed forces are equal to respectively 11 N and 17 N for feed and cutting force and for the two type of sample.
For a cutting speed lower than 12 m/min, forces are greatly superior, especially in feed direction. It reveals a modification of cutting behaviour around 10 m/min. Cotterell and Byrne [15] consider a modification of cutting comportment around 20 m/min.

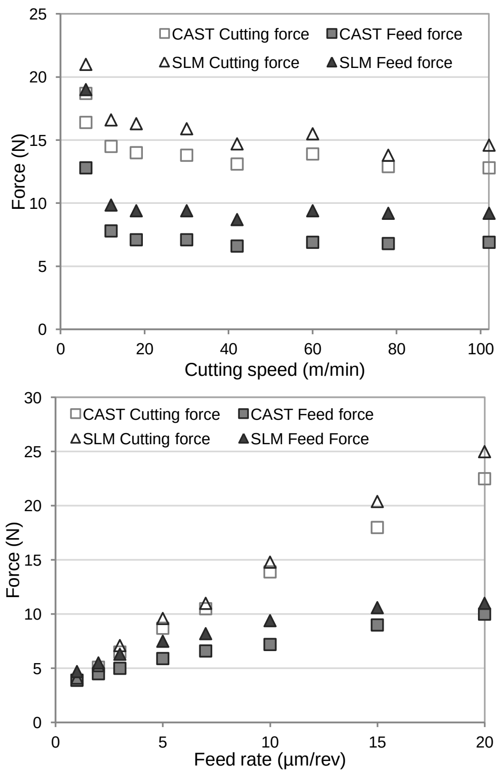

Fig. 3. Comparison of cutting and feed forces when turning cast and SLM Ti6Al4V for various conditions.

Also, for both materials a modification of feed force variation is observed for a thickness of cut lower than 3 µm, modifying the main friction coefficient. This phenomenon is influenced by the cutting edge radius [16]. For higher feed rate, the edge radius is negligible. Reasons for this behaviour are an uncut chip thickness larger than cutting edge radius, erasing cutting edge radius contribution on cutting forces and an uncut chip thickness larger than affected layer thickness, erasing affected layer contribution [14]

3.2. Chip morphology

A selection of macro observation of chips forms for cast and SLM titanium are presented in figure 4.
The two materials present the same chips formation. For the constant cutting speed of 60 m/min, chip is conical helical. The lower uncut chip thickness results in a snarled conical helical chip and higher feed rate leads to long chip.
For the constant uncut chip thickness of 10 µm, chips shape changes from a long conical helical chip at 6 m/min, to a snarled conical helical chip at 102 m/min. For the higher speed of 500 m/min, chip is a snarled ribbon but fragile.
Compared to the uncut chip thickness, the cutting speed appears as the most important factor in determining the chip formation when orthogonal cutting Ti-6Al-4V. It mainly affects the frequency of segmentation, the shear angles and the crack length as discussed by [17].

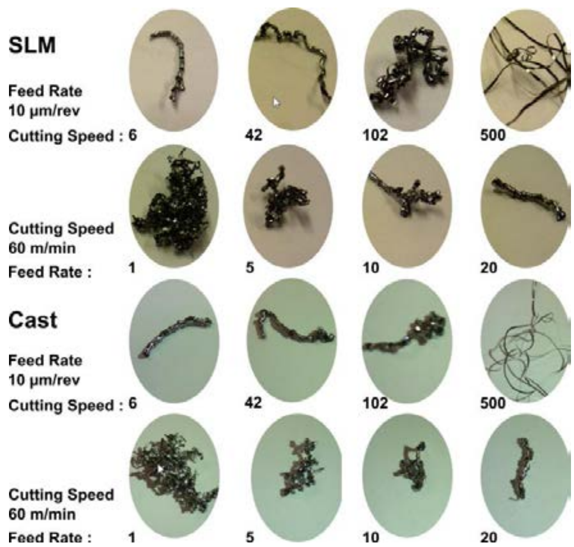

Fig. 4, Comparison of chip morphology when turning cast and SLM Ti6Al4V for various conditions.

Microscope observations of chips reveal a similar deformation for the two material states. Segmentation appears but is limited whatever the cutting speed and tested feed rate. Chips are un-regularly serrated in form and in frequency. No particular crack appears.
Contrary to literature [10, 17] precision turning is performed

and uncut chip thickness is near the grains size. Also, deformed chip thickness (t2) is related to the chip deformed area due to the contact between tool and chip.

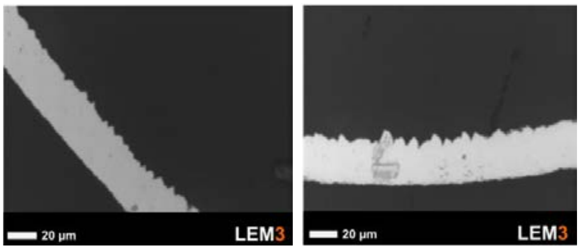

Fig. 5. Comparison of chip structure when turning cast and SLM Ti6Al4V (60 m/min and 20 µm/rev.

The evolution of deformed chip thickness t2, useful to understand the mechanism of chip formation, is presented in figure 6. Evolution is the same with cast and SLM titanium. For the minimum cutting speed and for an un-deformed chip thickness of 10µm, t2 is equal to 20 µm. With the increase of cutting speed, t2 is reduced and tends to a limit value around 15 µm for cutting speeds higher than 100 m/min.

Also, variation of feed rate influences linearly the evolution of t2 respectively from 5 µm to 30 µm for an uncut chip thickness of 1 µm and 20 µm. The ratio t2/t1, giving information about cutting shear angle vary from 5 to 1.5. And so, higher feed rate leads to a higher shear angle φ.

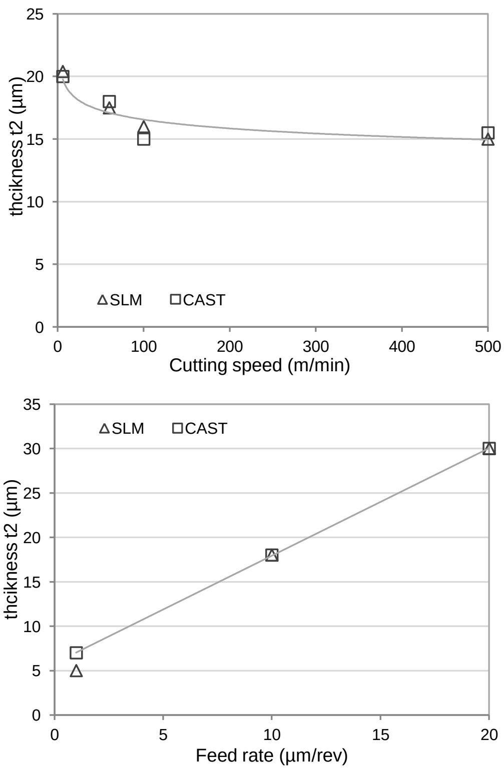

Fig. 6. Maximum chip thickness evolution with (a) cutting speed (t1=10µm) and (b) feed rate (Vc=60 m/min).

3.3. Microstructure

Subsurface microstructures in the direction of cutting and for the higher feed rate of 20µm/rev were studied and compared figure 7. The observed microstructures are different as previously observed, figure 1. Figure 7 does not reveal particular microstructure deformation. Micro cutting allows a non-affected subsurface.

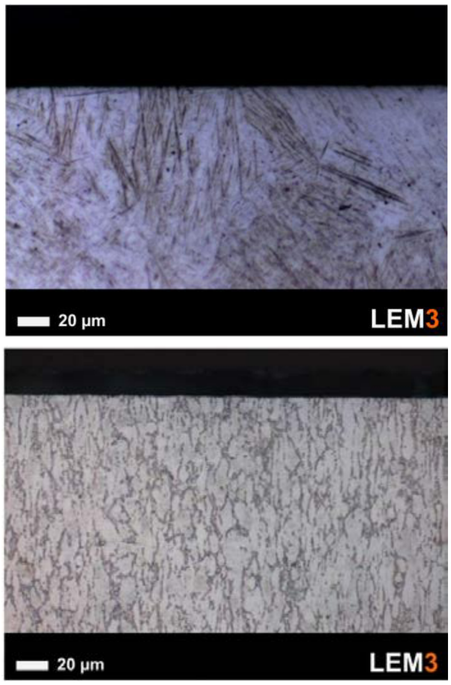

Fig. 7. Subsurface microstructure for a cutting speed of 60 m/min and a feed rate of 20 µm/rev, (a) cast and (b) SLM Ti6Al4V.

4. Conclusions

This paper presents results of machinability when micro cutting of a Ti-6Al-4V obtained by SLM process. Cutting forces, chip morphology and formation and subsurface microstructure are studied and compared with traditional cast Ti-6Al-4V. Even if the two materials present different microstructures, some analogies can be formulated.

(1) Cutting and feed forces are greater with SLM Ti-6Al-4V, from 3 to 24% for the cutting condition used. However, the forces evolutions are similar with a specific regime. For a cutting speed lower than 12 m/min and for a thickness of lower than 3 µm, particular phenomenon is present with an increase of forces and of main friction coefficient.

(2) When micro cutting, chip does not suffer from severe deformation as observed in macro cutting.

(3) Chip morphologies are similar for the two material states. For both, evolution with cutting speed and feed rate are comparable in term of segmentation and deformed chip thickness.

(4) Subsurface microstructures are not particularly affected by cutting.

Acknowledgements

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