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# Residual stresses when finish turning of Ti6Al4V skin produced by SLM

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## Abstract

Additive manufacturing processes is particularly interesting to reduce the weight of a part by associate lattice structures to a thin skin. 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 proposed work studied the surface integrity after finish turning of thin wall of Ti-6Al-4V part produced by SLM. An experimental design approach is used to study the effect of cutting parameters on machinability and surface integrity. The studied parameters are the cutting angle, the tool nose radius, the cutting depth, the feed rate and the cutting speed.

**Keywords:** Ti6Al4V, SLM, Turning, Residual stress

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## 1. Introduction

Additive manufacturing processes offering shapes liberty and original internal structures. A way to reduce the weight of part is to associate lattice structures to a thin skin, as a sandwich structure. Sintering Laser Melting (SLM) can be used for efficiently producing metal lattice structures with complex unit cell designs [1], providing determined mechanical properties. Internal structure can be cover by thin skin during the same manufacturing process. However, parts produced present dimensional deviations due to process accuracy and roughness due to thickness of fusion layers. Thus SLM process allows a dimensional accuracy from 40 to 80  $\mu\text{m}$ . In order to ensure a finished product with the dimensional and structural requirements of an industrial part, a post processing by machining or grinding is necessary [2]. Due to the near net shape obtained, only a finishing cutting is necessary. Moreover, machining further improves performance of additive manufactured parts compared to an as built surface [3]. SLM applied to Ti6Al4V alloy produces a material with a martensitic microstructure. Some micro cracks, due the effect of incomplete homologous wetting and residual stresses produced by the large solidification undercooling of the melt pool, are observable in the matrix [4]. When cutting SLM Ti-6Al-4V, compare to wrought titanium, it results on greater cutting and feed forces [5, 6], deepest tool crater wear [7], chip welding and build up of work material on the cutting tool [8].

The experimental study focus on the impact of tool and cutting parameters on surface integrity applied a thin skin of Ti6Al4V produced by SLM. Finish turning is performed with various cutting parameters, linked to cutting tool parameters. The cutting tests were realized by following the design experiment approach (DOA) and the results are discussed using analysis of variance.

## 2. Experimental method

### 2.1. Work material

Workpieces material used in all the experiments was a titanium alloy Ti6Al4V. This grade 5 titanium alloy is well known as a lightweight material 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 [2]. 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 HV<sub>10</sub>. The as-built microstructure of the material produced by SLM has a very fine, acicular martensitic morphology. The XRD analysis indicates the presence of hcp phase only. The hcp pattern can be attributed to both the  $\alpha$ -phase and the  $\alpha'$  martensite, as they have the same crystalline structure and very similar lattice parameters [4].

## 2.2. Micro cutting tests

Dry finish turning tests of Ti6Al4V were carried out on a three-axis CNC vertical milling centre. The HSM centre is used as a precision turning lathe by positioning sample on the spindle, see figure 1(a). The cutting tools were carbide finishing tools IFANGER MICROTURNT with cutting edge radius close to 1  $\mu\text{m}$ . Four different geometries were used to evaluate the influence of tool geometry on the experimental response. The experimental samples involved a part composed of a cylindrical lattice structure of 20 mm of diameter and cover by a thin skin of 1.5 mm. After removing a first thickness of the external surface of the cylindrical parts with a rough tool, dry turning tests were performed with a finishing tool. The three main cutting forces were measured with a dynamometric table Kistler Minidyn 9256C2. After machining, study focus on the effect of cutting parameters on surface integrity. Surface residual stresses are determinate using an X-ray diffraction technique according the  $\sin^2\psi$  method. They were measured in two directions: parallel and perpendicular to cutting direction, see figure 1 (b).

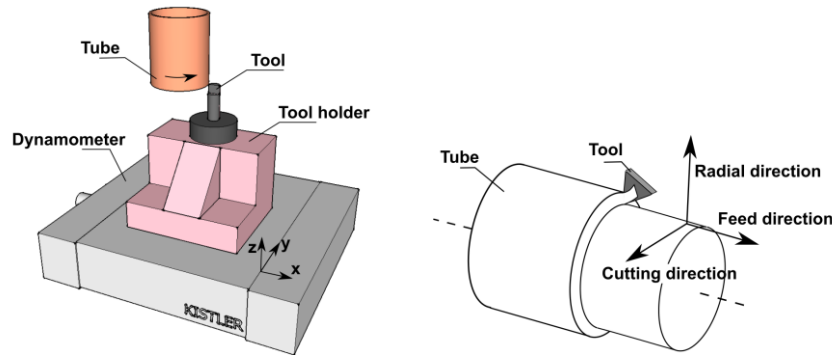


Fig. 1. (a) Experimental set up and (b) references and orientation of cutting forces

## 2.3. Experimental design and parameters

Design of experiments approach (DOE) was employed to study dry finish cutting of Ti6Al4V produced by SLM. The input parameters were the tool parameters: rake angle and tool nose radius but also the cutting conditions: cutting speed, feed rate and depth of cut. A factorial design was used for input parameters. The associated low and high levels of these parameters appear in table 1. The selected value were chosen related to finishing turning of titanium and to highlight the effect of input parameters. Effect of rake angle is few studied on micro cutting. An angle of  $0^\circ$  is compared with a positive angle of  $12^\circ$ , recommended for titanium cutting. Positive angle allows a better cutting edge acuity and affect shear angle. Tool nose radius is defined taking account of depth of cut and corresponding to finishing thickness. The effect of cutting speed is studied using a carbide manufacturer recommended speed (40 m/min) and a much greater speed (100 m/min). Feed rates are selected using a recommended feed of  $12 \mu\text{m}/\text{rev}$  and a very low feed rate, near of the cutting edge radius, potentially generating particular cutting [5]

	Rake angle ( $^\circ$ )	Nose radius ( $\mu\text{m}$ )	Feed rate ( $\mu\text{m}/\text{rev}$ )	Cutting speed (m/min)	Depth ( $\mu\text{m}$ )	Cutting force			Residual Stress (MPa)	
						Ff (N)	Fc (N)	Fp (N)	Feed	cutting
1	0	50	12	100	60	2.7	3.8	7.8	-800	-385
2	12	50	12	40	120	2.2	3.7	1.1	-375	-275
3	12	50	2	40	60	0.7	0.6	0.9	-90	-180
4	0	50	2	100	120	1.8	1.4	1.0	-275	-110
5	12	120	12	100	120	2.1	3.7	2.8	-165	-75
6	0	120	2	40	120	2.1	2.2	2.6	-350	-230
7	12	120	2	100	60	0.6	0.5	1.4	-70	-110
8	0	120	12	40	60	1.7	3.3	3.8	-465	-110
9	0	50	12	100	60	2.5	4.6	9.1	-705	-380
10	12	50	12	40	120	1.9	3.2	1.3	-345	-175
11	12	50	2	40	60	0.9	1.0	1.1	-405	-190
12	0	50	2	100	120	1.9	1.5	1.0	-300	-120
13	12	120	12	100	120	2.4	4.4	4.3	-115	-15
14	0	120	2	40	120	2.2	2.4	2.6	-255	-200
15	12	120	2	100	60	0.9	1.1	1.7	50	40
16	0	120	12	40	60	1.5	3.3	3.6	-280	-255

Tab. 1. Experimental array and results

### 3. Results and discussion

#### 3.1. DOA Results

This range of values is referred to as 95% confidence interval and a margin of error equal to 5%. The effects of each response were normalized to allow a comparison of each of them. The results of DOE are represented by the figure composed by the normal probability plot-to detect non-normality and Pareto chart indicating the significance, or not, of the responses. In order to understand the effects of the parameters on the responses, the position of the parameters indicates when they are on the right of the straight line, an increasing effect on the response, when they are on the left a decreasing effect on the response. An experimental  $2^{5-2}$  array (8 experiments) shown in table 3 with 1 repetition for a total of 16 experiments was chosen in order to improve the level of confidence with a limited number of experiments. Results were analysed based on analysis of variance by MINITAB software

#### 3.2. Cutting forces

The main effect of cutting parameters on cutting and penetration forces are analysed through figure 2. It appears that tool radius has no effect on forces measured. It also reveals the particular influence of three parameters. Cutting angle effect is systematically significant and a positive angle limits forces for the three main directions. Depth of cut is also significant, influencing greatly the undeformed chip thickness. Logically, feed effect is systematically the more significant with an increase of force with the increase of feed rate. This is particular true that the values tested are a feed of 2  $\mu\text{m}$  and 12  $\mu\text{m}$ . When introduces the effect of parameters specific cutting forces, only cutting angle and feed rate are predominant. However, contrary to cutting forces, the lower the feed rate the lower the specific cutting force. It is influenced by the value of feed rate, close to the cutting edge radius. This phenomenon corresponds to a change of effective rake angle through micro-cutting operation on the main cutting edge.

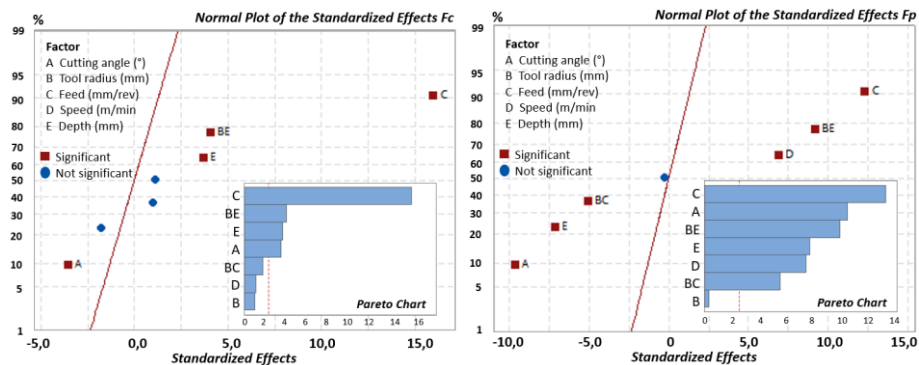


Fig.2. Normal plot of the standardized effects and Pareto chart for (a) cutting and (b) penetration force.

#### 3.3. Residual stress

Residual stresses when micro turning of Ti6Al4V are compressive stress, except for experiment n°15 that conducts to low traction residual stresses on feed and cutting direction. Compression residual stress on surface correspond to previous evaluation when turning Ti6Al4V at low cutting speed [9, 10], even higher feed rate and depth of cut. Statistical analysis, figure 3, reveals that residual stresses depend principally from tool geometry with a major influence of tool radius and cutting angle. A lower tool nose radius leads to more compressive residual stress. In addition, a positive rake angle of 12° limits compressive stress. Measurement confirms the conclusions of Edkins [10] when turning wrought Ti6Al4V that concludes negative rake angle generally produces more compressive residual stress.

It is interesting to observe the significant of feed rate on compressive residual stress and particularly on feed direction. Chip thickness is decreased gradually to zero at the trailing edge, which is the region of the tool responsible for generating the machined surface [11]. Logically the shape and the length of the minimum chip thickness is greatly influenced by tool nose radius and feed rate. A 2  $\mu\text{m}$  feed rate with a higher radius of 120  $\mu\text{m}$  leads to a long minimum chip thickness area between two successive overlaps of the tool. Contrary to, a feed of 12  $\mu\text{m}$  reduces greatly the length of minimum chip thickness. A long

trailing edge leads to create a particular thinning effect on the entire generated surface also describe as “springback” effect [12]. A combination of feed rate and tool nose radius highlights the predominance of the trailing edge area on residual stress

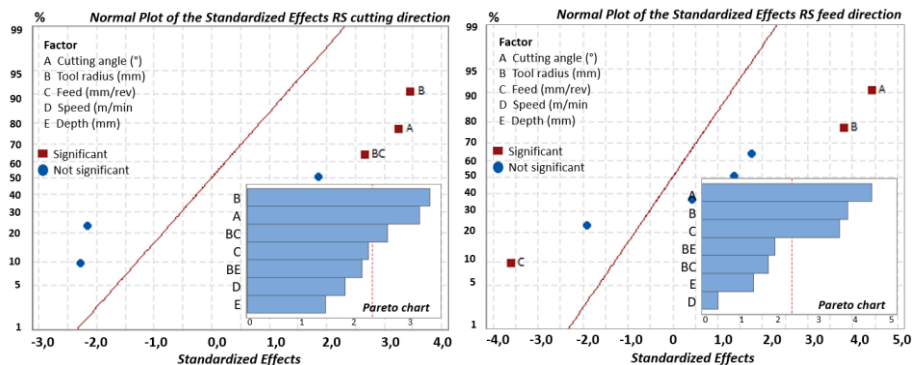


Fig.3. Normal plot of the standardized effects and Pareto chart for residual stresses in (a) cutting and (b) feed direction

#### 4. Conclusions

A SLM Ti6Al4V composed of  $\alpha$ -phase and  $\alpha'$  martensite is dry machined (finishing turning) using uncoated carbide tool with various cutting angle and tool nose radius. To investigate the workpiece surface integrity, a design of experimental approach (DOE) is used. The main results are summarized in the following: (i) Cutting speed has the lower influence on forces, compared to geometrical parameters as tool parameters, feed and depth of cut; (ii) Specific cutting force highlight the incidence of a low feed rate, near the cutting edge radius; (iii) Residual stresses are principally compressive and influenced by the tool parameters. A lower tool nose radius leads to more compressive residual stress. In addition, a positive rake angle of  $12^\circ$  limits compressive stress.

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