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Abstract

The Laser Metal Deposition (LMD) is an additive manufacturing process which is gaining good competence in manufacturing and repairing complex functional parts. However, the produced parts require conventional machining operations in order to enhance the surface quality and the material properties. Due to the highly localized heat input experienced by the sample during the building process, significant variation of the local material properties can appear within the produced components. This could affect the machinability of the parts produced by the LMD process. This study aims to investigate the milling process and its effect on the resulted surface integrity of Ti-6Al-4V components produced by the LMD process. The heat treatment was performed in order to homogenize the microstructure of the material. The conventional Ti-6Al-4V was taken as a reference material sample. Depending on the cutting process parameters, the cutting forces and the surface roughness of the machined LMD parts were 10-40% and 18-65% respectively higher than the conventional samples. The compressive residual stress in the machined LMD samples were 11-30 % higher than the conventional specimen. These differences are related to microstructure and grain size differences between the tested parts.

Keywords: Laser Metal Deposition; Ti-6Al-4V; Milling; Surface integrity.

1. Introduction

Ti-6Al-4V is one of the most widely used material in aerospace area where high performance and mechanical properties are required. The main factor of the usage is its low density, good strength-to-weight ratio, high toughness and good corrosion resistance [1]. Thus, it meets most of the aerospace requirements and it is used in several aircraft components such as aircraft structure, aero-engine fan and pylon [2]. Nevertheless, Ti-6Al-4V alloy presents low thermal conductivity, high strength and resistance. This implicates low machinability and expensive machining costs of this material.

In the aerospace area, around 80-90% of forged materials are removed to achieve a final part thus representing 60% of the total production cost [3]. Non-conventional techniques could be performed in order to overcome this limitation. In this case, Additive Manufacturing (AM) is an emerging technology that allows manufacturing complex parts with high quality and material properties. The AM parts are produced with dimensions and shapes that are relatively closer to the final functional component, thus requiring significantly minimal machining steps. Therefore, AM technologies represent a good alternative solution for producing components in the aerospace area, where low buy-to-fly ratio is commonly required. Recently, Fraunhofer IPT introduced the use of AM technology in the production chain of near-net-shape components [4]. Another powerful competence of the AM is the ability of repairing high value components.

In this context, Laser Metal Deposition (LMD) process proved its unique potential in repairing parts such as turbine blades [5]. This allows to save energy and reduce the material waste compared to the production of a new engine. Nevertheless, the surface of the AM parts is characterized by rough quality, dimensional inaccuracy and thus requires a finishing operation [6]. Machining processes such as milling process need to be performed in order to satisfy the surface quality and tolerance requirements [7]. Most of the studies proved that the mechanical and microstructural properties of the AM parts exhibit great variations compared to those produced by conventional methods such as wrought or cast. Nevertheless, there is still a lack of knowledge about the machining process of the AM components. Recent studies show that there is a difference between machining the conventional and additive parts concerning machining mechanisms, tool wear and the generated surface integrity [7-14].

In this framework, the aim of this paper is to investigate the effect of finish milling process parameters on the surface integrity of the Ti-6Al-4V alloy produced by the LMD process. The cutting forces, surface roughness, microstructure and residual stress were studied under different conditions.

2. Experimental methods

2.1. Materials and LMD process

The material under investigation was the alpha-beta titanium alloy grade 5. The samples were produced by two different methods: LMD and wrought processes.

The LMD samples were supplied by BeAM-France using a 5-axis Magic 800 CNC machine. The LMD process deposits a metal powder through a nozzle and melts it simultaneously using a laser beam (Fig. 1-a). A base plate of Ti-6Al-4V alloy is required in order to support the build samples. The base plate is mounted above the machine table which can be rotated around the X and Y axes. The machine is equipped with a coaxial nozzle that can move in the three-dimensional axes (X, Y and Z). The nozzle contains a laser source, the fed powder, a carrying gas and a secondary gas (Fig. 1-a). Carrying gas is required in order to feed the powder to the melt pool and the secondary gas simultaneously shapes the powder jet at the output of the nozzle. The corresponding specifications and the deposition parameters are presented in Table 1. The powder, of a spherical shape with a diameter of 45-90 µm, was supplied by AP&C using a gas atomization process.

The wrought material was provided by VSMPO-AVISMA Corporation in the form of plates. The conventional samples were subjected to annealing heat treatment at 780°C maintained for 1h15min followed by air cooling. The chemical compositions of the conventional and the powder Ti-6Al-4V are presented in Table 2.

Different Ti-6Al-4V parts were used during this study: rectangular parts with a dimension 10 mm x 10 mm x 10 mm for the microstructural analysis and 14 mm x 12 mm x 60 mm for the machining tests. The position and orientation of the LMD samples on the build platform are depicted in Fig. 1-b. The AM samples used in the machining tests were built in the Z-axis. Preparation steps were performed in order to remove the rough surfaces (1 mm in each face) and to ensure a radial engagement a_e = 10 mm during the milling tests (Fig. 2).

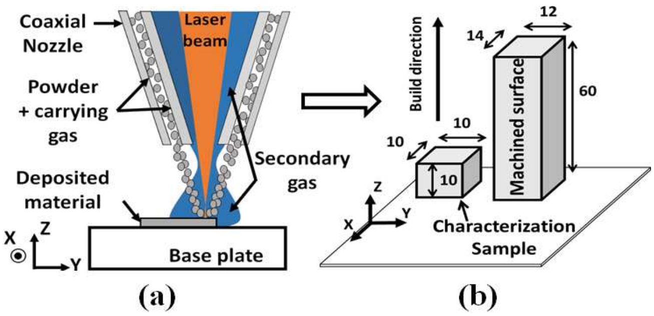


Fig. 1. Schematic representation of (a) the LMD process and (b) the AM produced samples.

Table 1. Processing parameters and specifications of the LMD process.

Parameters	Specifications
Laser Power (W)	1630 W
Laser Wavelength	1070 nm
Laser Source model	YLS-2000 from IPG LASER
Nozzle	MacroCLAD 24VX
Spot size	2.25 mm
Carrying gas flowrate	6 L/min
Shaping gas flowrate	10 L/min
Scanning speed	2000 mm/min
Powder Flowrate	12 g/min
Atmosphere	O_2 content < 1.5 ppm H_2O content < 70 ppm

Table 2. Chemical composition of the conventional and the LMD powder Ti-6Al-4V.

El.	Al	V	Fe	O	C	N	H	Ti
Wrought % wt	6.29	4.14	0.21	0.18	0.017	0.003	0.004	Bal
Powder % wt	6.42	4.01	0.2	0.14	0.02	0.02	0.002	Bal

2.2. Face milling process

The finishing face milling process was conducted on a DMU 60T CNC milling center. The cutting tool was a Sandvik Coromant® round insert Coromill R300-1032E-PL grade 1010 coated with AlTiN. The carbide insert was mounted on R300-035C3-10H tool holder. The samples were mounted on a special clamping system and the centered milling process was conducted along the parts length as shown in Fig. 2. The feed rate f_z and the depth of the cut a_p were varied in order to investigate their effect on the cutting process and the surface integrity. A full factorial design of experiment (DOE) was used to design an experimental matrix. Three levels were selected for each parameter and the total experiments are given in Table 3. The central point (E5) was replicated three times during the machining process. The cutting speed was fixed at 55 m/min and the tests were performed in a dry condition.

Fig. 2. Schematic of the face milling test.

Table 3. Experimental plan for the milling tests.

Exp Name	f_Z (mm/tooth)	a_P (mm)
E1	0.05	0.5
E2	0.15	0.5
E3	0.25	0.5
E4	0.05	1.25
E5	0.15	1.25
E6	0.25	1.25
E7	0.05	2
E8	0.15	2
E9	0.25	2

2.3. Surface integrity analysis

Characterization samples were carefully cut and subjected to polishing steps and chemical etching using Kroll's reagent to reveal the microstructural features. The residual stress was analyzed by the mean of X-Ray Diffraction using $Sin^2\Psi$ method. The "D8 discover Bruker" equipped with a Cu-Kα source tube was used for the measurements. The surface finishing quality was controlled using R_a criteria by the mean of VEECO WYKO NT1100 optical profilometer. The surface roughness was measured along the feed direction shown in Fig. 2. Three measurements at different locations for each machined surface were made and an average value of the R_a was considered.

3. Results

3.1. Microstructural observation

The optical micrographs of the conventional wrought material and the LMD as-build alloy are respectively shown in Fig. 3-a and b. The AM specimen was cut parallel to the XY plane specified in Fig. 1. A clear difference is observed between the produced microstructural morphologies and grain sizes. As observed in Fig. 4-b, the morphology of the LMD part was a mixture of Widmanstätten and basket-weave which is a typical observation in most AM processes [15]. In addition, the base plate and the powder were not preheated during the LMD process. Thus, high cooling rates occurs during the building process leading to β phase transformation into fine α lamellae and a metastable acicular martensitic α' phase by a diffusion-less transformation [16]. In order to homogenize the microstructure of the AM parts, a Hot Isostatic Pressing (HIP) process was conducted. A high temperature of 920°C and a pressure of 102 MPa were maintained for 2 hours under Argon gas atmosphere. This simultaneously provided a heat treatment and removed internal defects of the AM parts. The high temperature and pressure were maintained for 2 hours which contributed to the lath's growth as shown in Fig. 4-b and the elimination of the material's defect [17]. In addition, the heat treatment resulted in the diffusion of the α' into α and β phases. Widmanstätten and Basketweave morphologies composed of two phases, namely α lamellae (dark area) and β lamellae (white area) were clearly visible after the heat treatment (Fig. 4-b). The machining process was performed on the heat treated samples in order to limit the effect of the material defects and porosities of the as-build material [18].

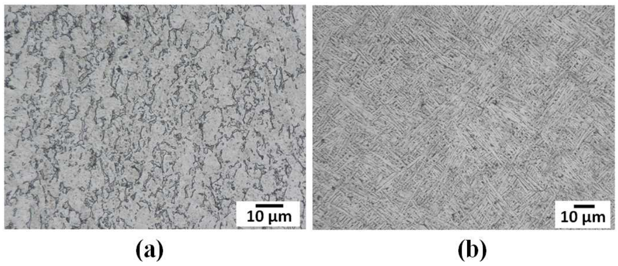


Fig. 3. Optical micrographs of the (a) reference wrought alloys and (b) LMD as-build (section parallel to XY plane).

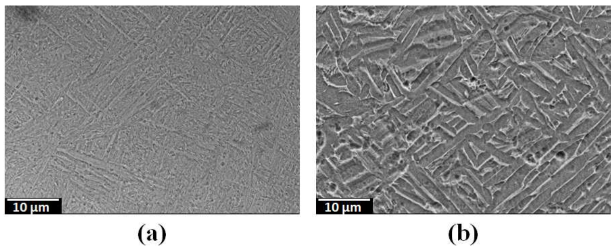


Fig. 4. SEM observations of the LMD parts (a) in the as build state and (b) after the HIP treatment (section parallel to XY plane).

3.2. Cutting forces

The cutting forces measured in the different cutting parameters for the two tested materials are presented in Fig. 5.

During this work, the resultant cutting force F (Eq. 1) was considered.

$$F = \sqrt{Fx_0{}^2 + Fy_0{}^2 + Fz_0{}^2} \quad (1)$$

The cutting forces showed a quasi-linear increase when the feed rate and the depth of cut increased. These two parameters determine the chip thickness and the amount of the removed material which have a direct effect on the insert load. In addition, the cutting forces of the LMD samples were higher than those of the conventional alloy. The difference between the forces was dependent on the machining process parameters and varied between 10% to 40%. This trend was observed in several studies focusing on the machinability of AM Ti-6Al-4V alloy [8,9,11]. The higher forces may be explained by the different microstructural characteristics of the LMD and conventional parts which affect the material properties. Indeed, the coarse equiaxed grains of the conventional alloy are characterized by a lower resistance to plastic deformation [19] and low yield stress compared to finer grains that are found in the AM parts. The higher cutting forces are a result of a greater load on the cutting tool which could lead to a low machinability of the material and higher tool wear.

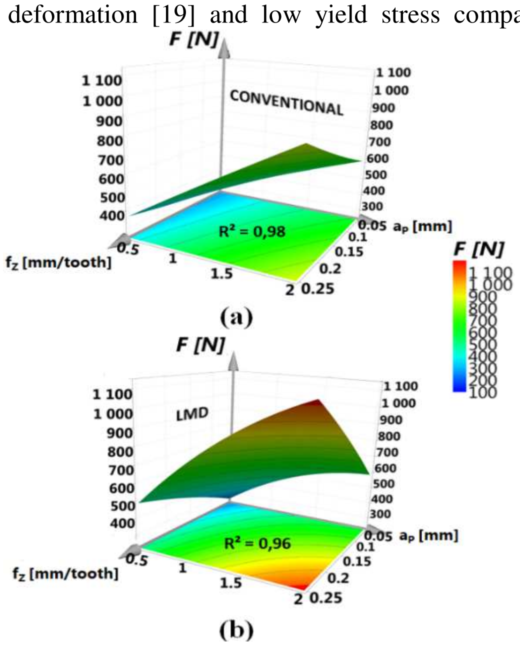


Fig. 5. Surface response of the resultant cutting force of the (a) conventional and (b) LMD samples.

3.3. Surface roughness R_a

The contour plots of the surface roughness R_a for the LMD and conventional machined parts are shown in Fig. 6. Although the tested materials have almost the same composition, several differences were found. Depending on the machining process parameters, the surface finish quality of the LMD parts were found to be inferior of around 18-65% compared to the wrought ones. The lowest R_a value of the LMD part was ~38% higher than the conventional one. This can be attributed to the different microstructures produced by the two manufacturing techniques (LMD and wrought). This result was found in previous studies focusing on the induced surface quality of the AM machined parts [12,13]. Generally the surface roughness was found higher with the increase of the feed, which corresponds to previous findings [20,21].

It is also worth to note that the surface roughness evolution is different depending on the part nature. According to Fig. 6-b, the surface roughness of the LMD parts was higher for the lowest feed value (i.e. 0.05 mm/tooth) followed by an average improvement of ~33% when f_z ~0.15 mm/tooth. This difference could be related to the change in the cutting regime depending on the chip thickness. Indeed, the material is ploughed and highly deformed when the chip thickness is less than a specific value called the minimum undeformed chip thickness, as reported by M. Shaw [22]. In this case, a material rubbing takes place instead of cutting and the chip is hardly formed. The material is squeezed between the flank face and the machined surface which results in an extensive side flow (i.e. in the feed direction) [23]. The resulting side flow contributes to a deterioration of the surface finishing quality thus increasing the surface roughness values [24]. The minimum chip thickness depends on several factors such as tool edge preparation, cutting tool material/microgeometry, the work material as well as the cutting conditions [23].

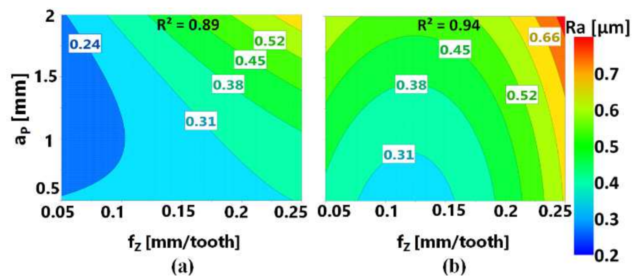


Fig. 6. Surface roughness R_a of the (a) conventional and (b) LMD machined samples (contour plot).

The resulting variation was not observed for the conventional material which indeed indicates that the minimum chip thickness is reached at the lowest value of the feed which is 0.05 mm/tooth. This implicates that the minimum chip thickness of LMD parts is expected to be higher than the conventional one.

3.4. Affected layer

The microstructure of the machined surfaces was cut parallel to the machining direction and examined using optical microscope for three different feeds (Fig. 7). The observation revealed a microstructure alteration near the machined surface in terms of grain's size and shape as a result of the machining process. A thin layer of plastically deformed material was observed near the external surface between the dashed lines shown in Fig. 7. The grains and laths were clearly deformed and stretched along the cutting direction with no phase transformation being observed. The measurement of the affected LMD depth was higher of around 50% compared to the conventional at low and medium range of feed. The result may be related to the difference in microstructure which causes different machinability behavior. The results were evident that the feed values influence the affected depth. The general phenomenon observed is that the higher value of the feed leads to an increase of the affected layer depth for the conventional specimen. Nevertheless, a different behavior of the affected depth occurred between the AM and conventional parts. The affected depth of the LMD specimen at the lower feed of 0.05 mm/tooth was higher of around 9% and 42% than that of 0.15 mm/tooth and 0.25 mm/tooth respectively. This resulting difference could be related to the effect of the minimum chip thickness. As discussed in section 3.3, when the chip thickness is lower than the minimum chip thickness, a large amount of material is ploughed instead of being cut. This condition resulted in an extensive plastic deformation against the machined surface [23] thus increasing the deformed depth.

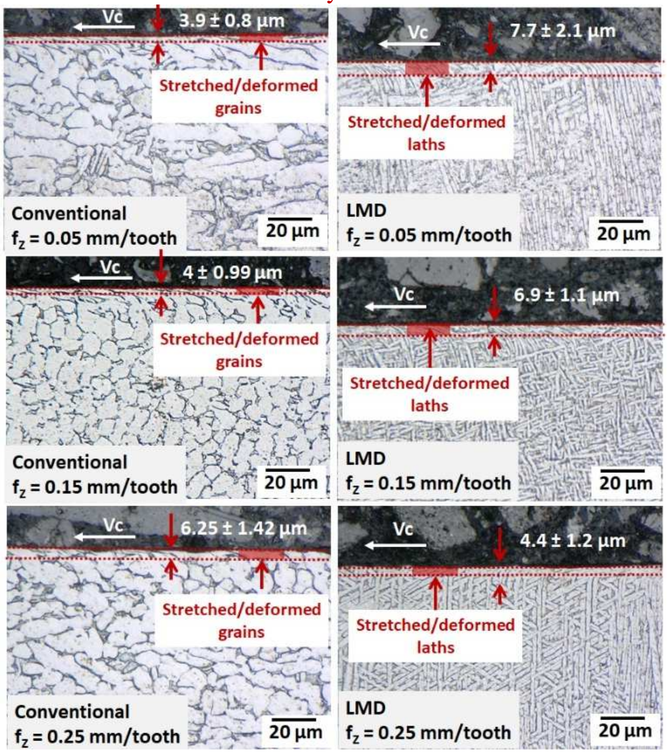


Fig. 7. Optical observation of the microstructure altered by the machining process (a_p = 2 mm) for the conventional wrought and the LMD samples.

3.5. Residual stress

The measured residual stress in the machined surfaces of the LMD and wrought parts in the cutting/feed directions are presented in Fig. 8 and Fig. 9 respectively. Residual stress is generated due to plastic deformation or metallurgical transformation during the machining process [25].

The mechanism of forming the residual stress is due to the combination of the thermal and mechanical loadings imposed by the cutting tool. The compressive residual stress in all the cutting conditions could be related to the dominant mechanical deformation due to relatively low cutting conditions (finishing conditions). The LMD machined parts constituted 11-30% more compressive residual stress compared to the conventional alloy in the lowest and highest ranges of feed. In addition, the results displayed that the residual stresses were highly influenced by the feed. The depth of cut presented less impact (maximum variation of 50 MPa) on the residual stress profiles compared to the effect of the feed (variation can attain 200 MPa). The highest compressive residual stress in the feed and cutting directions was observed when machining the LMD part at low feed values (i.e. 0.05 mm/tooth) as shown in Fig. 8-b and Fig. 9-b. The ploughing mechanism instead of cutting mechanism caused high plastic deformation on the machined surface as observed in Fig. 7 and reported in section 3.4. This ploughing mechanism may be responsible for the increase of the compressive residual stress at low feed values. Nevertheless, the residual stress constituted few expected variations due to the non-uniformly surface deformations as reported by [21]. This is mainly due to the presence of the asperities and peak-to-valley on the machined surfaces indicating that the material is not uniformly deformed.

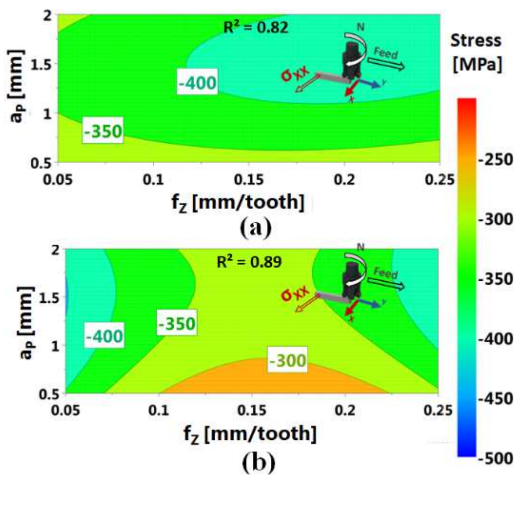


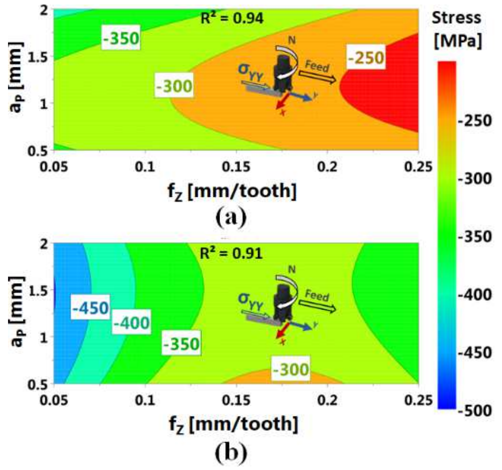
Fig. 8. Residual stress of (a) the conventional and (b) LMD parts measured in the cutting direction σxx (contour plot).

Fig. 9. Residual stress of (a) the conventional and (b) LMD parts measured in the feed direction σyy (contour plot).

The XRD spot used to measure the residual stress covers around 2 mm of diameter and an average residual stress was estimated. This could affect the residual stress measurements [21]. In general, higher compressive and more homogeneous residual stress values in the cutting and feed directions were obtained in the LMD machined surfaces.

4. Conclusions

This paper presented an investigation concerning the surface integrity induced by the machining process of LMD and conventional Ti-6Al-4V parts. Different machining results were acquired despite of the samples being taken from the same alloy. The following findings can be concluded:



- The microstructure of the produced parts was different depending on the production processes (LMD and Wrought) and heat treatment. This difference has an impact on the machining process.
- LMD parts constituted 10% to 40% higher cutting forces than the conventional alloy. This is attributed to the finer grains and different microstructure morphology.
- The surface finishing of the LMD parts was 18-65% rougher than the conventional specimens. Furthermore, the lowest surface roughness values of the AM components were obtained typically being 40% higher than the lowest value of the conventional samples.
- A plastically deformed layer was observed as a result of the machining process regardless of the processing conditions. The measured depth being affected was overall 50% higher for the LMD parts in the low and medium feed range.
- The compressive residual stress results induced by the machining of the LMD samples were 11-30% higher than the conventional for low and medium range of feeds.
- The overall conclusion is that the LMD Ti-6Al-4V is characterized by different behavior in terms of the surface integrity results compared to the conventional material. The distinct surface integrity responses were related to the different microstructural characteristics. Thereby, the cutting/ploughing regime was influenced by the minimum chip thickness. This work proves that the cutting conditions choice should consider the production process (wrought and AM) in order to have a good balance between the surface quality and residual stress.

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