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Cutting Force and Surface Finish Analysis of Machining Additive Manufactured Titanium Alloy Ti-6Al-4V

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Abstract

In this paper, the effect of machining parameters such as cutting speed and feed rate on cutting forces and surface roughness during turning of wrought and additive manufactured titanium alloys Ti-6Al-4V (selective laser melting) was studied. It was found that higher cutting speeds and feed rates resulted in high cutting forces and poor surface finish. It was also found that higher cutting forces were required for machining selective laser melted titanium alloy (SLM Ti-6Al-4V) as compared to that of conventionally produced wrought Ti-6Al-4V due to the higher strength and hardness of SLM Ti-6Al-4V. After machining, surface roughness of additive manufactured titanium alloys was found to be low as compared to wrought Ti-6Al-4V because of the high hardness and brittle characteristics of additive manufactured titanium alloys.

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1. Introduction

Titanium alloys are widely used in aerospace, automobile, marine, medical and chemical industries because of their superior properties such as high corrosion resistance, biocompatibility and high strength to weight ratio [1-5].

Conventional manufacturing of titanium alloys are always difficult and expensive due to some crucial material properties like poor thermal conductivity and high chemical reactivity [6-8]. Thus, the use of titanium alloys is

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limited in various industries due to its expensive processing route. Recently, Additive Manufacturing (AM) has gained huge attention in manufacturing sector because of its freedom of design, low material wastage and high productivity [9-12]. Various additive manufacturing processes like selective laser melting, selective laser sintering, and electron beam melting are being widely used. The main draw backs in these technologies is the poor surface quality of the fabricated components as a result of rippling effect on the molten material, staircase effect due to layer by layer fabrication and sticking of non-melted powder particles to the surface [13]. To overcome these problems, post machining of additive manufactured components are often necessary as surface finish has a great effect on the functional performance of the component. In order to successfully machine additive manufactured components to the required surface finish and tolerance, proper selection of process parameters are required.

In this research paper, the effect of machining parameters like cutting speed and feed rate on cutting forces and surface roughness during machining of additive manufactured Ti-6Al-4V is studied. Machining of wrought titanium alloy is also carried out alongside with AM Ti-6Al-4V to comparatively study their machinability characteristics.

2. Materials and methods

2.1 Materials

Ti-6Al-4V cylindrical rods used in this research were procured from Timet, France. The initial dimensions of the rod were 70mm in diameter and 600mm in length. The alloys was received in rolled condition with a post mill annealing heat treatment at 750°C (2 hrs) followed by air cooling. A cylindrical rod of 70mm diameter and 75mm length was fabricated using the SLM 125HL machine with a build chamber of size, 125x125x75mm and with a laser power of 100/200 W, YLR-Laser. The fabricated cylindrical rod is heat treated in vacuum furnace at 730°C followed by rapid furnace cooling to reduce the residual stresses developed during fabrication.

2.2 Machining trails

The turning trails were performed on Nakamura-Tome AS-200 supplied by Nakamura precision industries. The main spindle power of the machine is about 15KW with a maximum speed of 4500 rpm. The experimental set up of turning tests is shown in fig. 1. All the cutting tools used were tungsten carbide supplied from Iscar Tools Limited and were designated as IC907. It has an ISO range –P/M/K: (P15 –P40) with designation “DNGG 150401-SF”.

![Fig. 1. Experimental set up for machining trails](image)
The tools had a tough sub-micron substrate, TiAlN PVD coated grade suitable for machining heat resistant alloys, austenitic stainless steel and hard alloys at low to medium cutting speeds. The tools were double-sided 55O rhombic inserts and are recommended for super finishing operations. In order to keep the tool wear constant for all trials, it was ensured that new insert was used for each trial. Cutting forces during the turning trails were measured using a Kistler 9119AA2 three component piezo electric dynamometer attached to a Kistler 5070 charge amplifier which were in turn connected to a PC running Kistler Dynoware software for signal analysis and force output. Surface roughness of the machined surface was evaluated with the help of Taylor Hobson Form talysurf50. For each cutting condition, at least three surface roughness readings were taken to ensure repeatability. The surface roughness was measured over a sampling length of 4mm with a cut off length of about 0.8mm.

3. Results and discussion

3.1 Influence of cutting speed and feed rates on cutting forces

The effect of cutting speed and feed rate on cutting forces during machining of wrought and additive manufactured titanium alloys are shown in fig. 2. Cutting forces correlated well with the mechanical properties of the materials (as tabulated in table 1). For all cutting conditions, cutting forces observed during machining of SLM Ti-6Al-4V was higher compared to wrought Ti-6Al-4V due to the higher yield strength and hardness of SLM Ti-6Al-4V. The most probable reason can be explained as the cutting speeds increases, the heat generated at the deformation zones increases as a result of adiabatic heating due to high strain rate deformation and friction between the tool and work piece. This heat generated cannot dissipate in to the work piece because of the poor thermal conductivity of titanium alloys leading to unfriendly conditions to cut the material. Cutting forces during machining of SLM Ti-6Al-4V was completely different compared to the machining of wrought Ti-6Al-4V. In machining of SLM Ti-6Al-4V, tool wear had a greater influence on the cutting forces rather than the thermal softening characteristics of the titanium alloy as cutting forces did not decrease with speed, but increased. Feed forces showed the same trend as the main cutting forces. For all feed rates, cutting forces during machining of SLM Ti-6Al-4V was high than the machining of wrought Ti-6Al-4V. It can be seen that increase in feed rate resulted in increase in cutting forces during machining of both wrought and SLM Ti-6Al-4V. This is because when the feed rate increases, the section area of sheared chip increases because the metal resist rupture more and requires large efforts for chip removal.

3.2 Influence of cutting speed and feed rates on surface roughness

It can be seen that increase in feed rate resulted in increase in cutting forces during machining of both wrought and SLM Ti-6Al-4V. This is because when the feed rate increases, the section of sheared chip increases because the metals resist rupture more and requires large efforts for chip removal. Surface roughness of the SLM Ti-6Al-4V was low as compared to wrought Ti-6Al-4V for all cutting speeds as shown in fig. 3. This is due to the high hardness and brittle characteristics of SLM Ti-6Al-4V. Harder materials have less plastic flow on the machined surface than the softer materials. As a result, surface roughness, becomes lower for hard materials. It can be seen from the graph that the surface roughness during machining of both the alloys decreased with increase in cutting speeds. This is because at high cutting speeds the material gets softened at the deformation zones because of the adiabatic and frictional heating at the tool chip interface. In addition, at high cutting speeds the amount of adhered material decreases. Thus as a result of these phenomena the good surface quality was observed during machining at high speeds. For all the
feed rates, surface roughness of SLM Ti-6Al-4V was low as compared to that of wrought Ti-6Al-4V.

Fig. 2. Cutting forces during machining of wrought and SLM Ti-6Al-4V at various cutting speeds of 45 m/min, 90 m/min and 180 m/min at a feed rate of a) 0.05 mm/rev; b) 0.1 mm/rev; and c) 0.2 mm/rev and depth of cut 0.5 mm.
Fig. 3. Surface roughness after machining of wrought and SLM Ti-6Al-4V at various cutting speeds of 45 m/min, 90 m/min and 180 m/min at a feed rate of a) 0.05 mm/rev; b) 0.1 mm/rev and c) 0.2 mm/rev and depth of cut 0.5 mm.
When a cutting process is carried out, the basic theoretical model for surface roughness is given by the following equation:

\[ R_a = (0.0321s^2)/r \] (1)

Where, \( s \) denotes the feed rate in \( \text{mm/rev} \) and \( r \) is the tool nose radius in \( \text{mm} \). Generally, the theoretical value is less than the actual experimental value because of the violent vibration of the machine tool structure. The increase of surface roughness with feed rate is due to the vibrations and generation of heat that softens and melts the metal during machining. These melted particles are left behind the cutting tool as debris damaging the surface quality.

4. Conclusion

The following conclusions can be drawn from this experimental work:
- Cutting forces correlated well with the mechanical properties of the tested materials. Yield strength and hardness of the material has a considerable influence on the cutting forces during machining. Cutting forces during machining of SLM Ti-6Al-4V was high as compared to machining of wrought Ti-6Al-4V.
- Cutting forces increased with increase in cutting speeds during machining of SLM Ti-6Al-4V and decreased with increase in cutting speeds during machining of wrought Ti-6Al-4V. Possibly thermal softening characteristics of Ti-6Al-4V had a great influence on cutting forces during machining wrought Ti-6Al-4V whereas porosity of the SLM Ti-6Al-4V has some effect on cutting forces during machining.
- Surface roughness observed was low after machining of SLM Ti-6Al-4V as compared to machining of wrought Ti-6Al-4V most likely due to the high hardness and brittle nature of SLM Ti-6Al-4V.
- Surface roughness decreased with increase in cutting speeds due to the reduction of build-up edge formation and thermal softening at high cutting speeds that reduces the adhered materials on the tool rake face. Surface roughness increased with increase in feed rate during machining of both materials most likely due to the machine tool vibrations and thermal softening.

In-depth investigation at microstructural level, into the reasons for low machinability of SLM Ti-6Al-4V needs to be conducted. Based on the future work, some solutions using heat treatment or alloy modification to suit the design application requirements can be suggested.

References