TUTA/IOE/PCU

Journal of the Institute of Engineering, 2018, ***14(1):*** *115-121*

Printed in Nepal

Experimental Study on Surface Integrity of Titanium Alloy Ti6Al4V by Ball End Milling

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Received: *Jan 10, 2018* ***Revised:*** *Jan 28, 2018* ***Accepted:*** *Feb 5, 2018*

Abstract: Titanium alloy, Ti6Al4V, has been widely used in aerospace, automotive, biomedical, and chemical industries due to its exceptional strength to weight ratio, high temperature performance, and corrosion resistance. However, machinability of Ti6Al4V is poor due to high strength at elevated temperatures, low modulus, and low thermal conductivity. Poor machinability of Ti6Al4V deteriorates the surface integrity of the machined surface. Poor surface integrity causes high machining cost, surface defects, initiate cracks, and premature failure of the machined surface. Thus, it is indispensable to obtain better surface integrity when machining titanium alloy Ti6Al4V. Cutting parameters such as cutting speed, feed rate, and depth of cut have significant effect on the surface integrity when machining titanium alloy Ti6Al4V. Hence, this study investigates surface integrity of Ti6Al4V by ball end milling at different cutting speeds, feed rates, and depth of cuts. Microstructure of subsurface is studied at different cutting speeds, feed rates, and depth of cuts. The results show that the depth of deformation of subsurface increases with increase in the cutting speed, feed rate, and depth of cut.

Keywords: Ball end milling, titanium alloy-Ti6Al4V, surface integrity, experimental method

1. Introduction

The quality of a machined surface is becoming more and more important to satisfy the increasing demands of sophisticated component performance, longevity, and reliability. Structures for military and commercial aerospace, automotive, and other capital goods industries are being subjected to more severe conditions of stress, temperature, and hostile environments. In response to the above need, there is a continued increase in the development and use of heat resistant, corrosion resistant and high strength alloys in the wide variety of structural applications. Ti6Al4V is one of the alloys of titanium that is best suited for these types of applications [1]. Ti6Al4V is extensively used in aerospace components because of the combination of high strength to weight ratio, excellent fatigue properties, fracture toughness, and corrosion resistance [2]. Some of its physical and mechanical properties are given in table 1 and table 2 in the next Section.

2. Challenges in Machining Titanium Alloys Ti6Al4V

The use of titanium alloys are increasing in several fields. But the cost of titanium alloys are expensive than other metals due to the complex extraction process, difficult melting process, and hard fabrication and machining. Titanium alloys are known as difficult-to-cut metal because of the properties of the materials. Titanium alloys are chemically reactive and weld to the cutting tools during machining. Titanium alloys have low thermal conductivity that generates large amount of heat at tool/workpiece interface resulting in premature tool failure and poor machinability. The low modulus of elasticity and high strength at elevated temperature of titanium alloys make machinability of titanium alloys more challenging [2]. The poor machinability is the reason for poor surface integrity of machined titanium alloys. So, there is necessity to conduct research studies to improve machining and surface integrity of titanium alloys.

Table 1: Typical physical properties for Ti6Al4V [5]

Properties	**Value**
Density	4.42 g/cm^3
Melting Range	1649 ºC±15ºC
Specific Heat	560 J/kg.ºC
Volume Electrical Resistivity	170 ohm.cm
Thermal Conductivity	7.2 W/m.K

Table 2: Typical mechanical properties of Ti6Al4V [5]

Hardness, Brinell	**334 HB**	**Estimated from Rockwell C**
Hardness, Knoop	363 HK	Estimated from Rockwell C
Hardness, Rockwell C	36 HRC	
Hardness Vickers	349 HV	Estimated from Rockwell C
Tensile Strength, Ultimate	950 Mpa	
Tensile Strength, Yield	880 Mpa	
Modulus of Elasticity	113.8 Gpa	
Poisson's Ratio	0.342	

3. Surface Integrity

Surface integrity refers to the quality and the performance of a component obtained after machining. Surface integrity consists of the mechanical properties (residual stresses, hardness etc.), metallurgical states (phase transformation, microstructure etc.) and topological parameters (surface finish, surface roughness etc.). The components for aircraft and aircraft engine need the greatest reliability and surface integrity is the most important parameter that is used to determine the quality of the machined surface [4]. In most of the cases, the smoothest surface finish is required to prevent premature fatigue and failure of the components [3]. So, surface integrity is very important because it ensures durability, sophisticated performance and reliability of components. After machining processes various aspects of surface integrity are affected. These are listed below:

a. Mechanical properties such as residual stresses and hardness

b. Topography properties such as textures, waviness, and surface roughness

c. Metallurgical state such as microstructure, phase transformation, grain size and shape, inclusions etc.

4. Experimental Design

The study aims to investigate surface integrity of Ti6Al4V generated from ball end milling process. For the milling experiments, milling parameters such as the cutting speed, feed rate, and depth of cut are selected. The cutting parameters influence on the surface integrity of Ti6Al4V. Hence, the study focuses on the influence of the cutting parameters on surface integrity of Ti6Al4V in terms of microstructure. The factors influencing the results of the experiments are cutting tool, cutting speed, feed rate, depth of cut, and milling process. All the experiments are conducted in dry condition so that the effect of cutting parameters can be clearly understood. Ball end milling is selected for the experiments because it is extensively used in manufacturing tools and dies and machining complex three dimensional contours with a smooth finish. It can ensure the durability of the cutting tools, and can be used for milling wide range of materials, from plastics to titanium and steel alloys.

Seco Tools' solid carbide ball nose end mill cutter, JABRO-Solid^2, is selected as the cutting tool for the experiments because it is suitable for usage at high temperature, high strength, and high stress. It has 12 mm diameter, 3 flutes, 10º rake angle, and NXT coating. The samples of cutting tools are shown in Fig. 1.

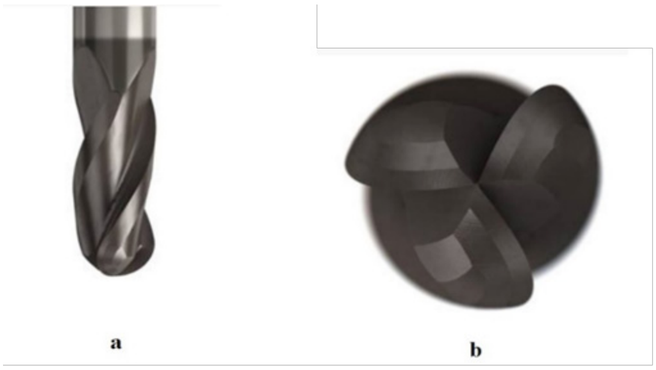

Fig. 1: Cutting tool (a) tip of the cutting tool (b) flutes of the cutting tool

The cutting parameters comprise of high cutting speed, and low feed rate and depth of cut to prevent severe impact on the surface integrity. Cutting speed of 151 m/min, 207 m/min, and 301 m/min, feed rate of 0.1 mm/tooth and 0.05 mm/tooth, and depth of cut of 0.1 mm and 0.03 are selected for the experiments. The details about experiment design is shown in table 3.

In the Fig. 2, the experimental setup can be seen. The cutting tool is fixed to the tool holder. The workpiece is fixed to the fixture firmly. Then, everything is checked to ensure the safety and smooth operation. The cutting speeds, feed rates, and depth of cuts are inputted and then the milling process is started. The cutting parameters are same as in table 3. Chips are produced during milling process and the chips are collected on either sides of the work piece and fixture.

Table 3: Table showing detailed Experimental Design

S.N	Cutting Speed V (m/min)	Feed Rate V_f (mm/min)	Feed rate f_z (mm/tooth)	Cutting depth (mm)
1	207	1650	0.1	0.1
2	207	1650	0.1	0.03
3	207	825	0.05	0.1
4	207	825	0.05	0.03
5	301	2400	0.1	0.1
6	301	2400	0.1	0.03
7	301	1200	0.05	0.1
8	301	1200	0.05	0.03
9	151	1200	0.1	0.1
10	151	1200	0.1	0.03
11	151	600	0.05	0.1
12	151	600	0.05	0.03

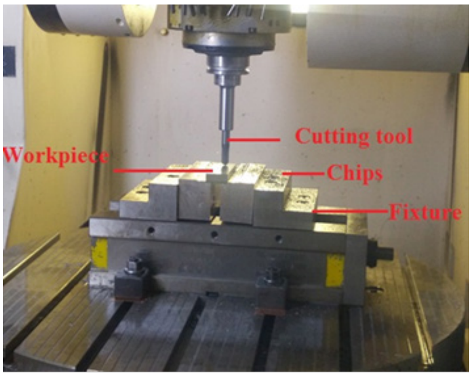

Fig. 2: Experimental Setup

5. Microstructural Alteration Measurement and Analysis of Result

In order to observe microstructure alteration of machined Ti6Al4V, the metallographic specimens are prepared, the specimens are polished and chemically etched so that the microstructure of the specimens are revealed. Then Leica DM4 M, optical microscope is used to observe the microstructure of the specimens. The microstructure of the specimens are taken at the magnification 20×, 50×, and 100×. The analysis is conducted to observe depth of deformation beneath the machined surface.

5.1 Sectioning of the Specimens

The workpiece is too large (85mm × 30mm × 15mm) and it is extremely difficult to polish the whole surface and then to observe under optical microscopy. Thus, it is necessary to cut the specimens into smaller size. MAXCUT abrasive blade - MAX-I series is used to section the workpiece. The work piece is cut into 5mm × 5mm × 15mm from the top of machined surface to the bottom of the workpiece.

5.2 Mounting of the Specimens

The primary reason for mounting specimens is to better hold the part to be grinded and polished, and to provide protection to the edges of the specimens. Mounting of the specimens is done using phenolic black resin and hot pressed by PRESI Mecapress 3.

5.3 Abrasive Grinding of the Specimens

The specimen surface and subsurface is damaged after machining and sectioning. The purpose of abrasive grinding is to remove this damage and to restore the microstructural integrity of the specimen for accurate analysis. The process to abrasion of the specimen surface by coarse abrasive particles, Silicon carbide (SiC) paper, is abrasive grinding. PRESI Mecatech 334 is used for abrasive grinding. The abrasive particles are specified in terms of grit size, with larger numbers indicating finer particles. The details about the different grits size papers used and other necessary conditions for abrasive grinding of the specimens is listed in table 4.

Table 4: Conditions for abrasive grinding

Abrasive/Surface	Lubrication	Force/Sample	Speed (Head/ Base)	Time
P240 grit SiC Paper	Water	15 N	100/150 rpm	3 minutes
P240 grit SiC paper		10 N	100/150 rpm	3 minutes
P800 grit SiC paper		10 N	100/150 rpm	2 minutes
P1200 grit SiC paper		5 N	100/150 rpm	2 minutes

5.4 Polishing of the Specimens

The surface of the specimens after abrasive grinding contained scratches. It is necessary to remove all the scratches in order to observe and measure the microstructure features of the specimens. Hence, polishing of the specimens are done. The details of the polishing specimens are listed in the table 5.

5.5 Chemical etching of the Specimens

In order to observe smaller particles and other microstructure features of the material it is essential to perform chemical etching of the specimens. Thus, Kroll's reagent is used as an etchant. The specimens are reacted with Kroll's reagent for 5 seconds. The composition of Kroll's reagent is as follows:

Hydrofluoric acid (HF): (40%): 10 ml
Nitric Acid (HNO_3): (62%) 6 ml
Distilled water: 100 ml

Table 5: Conditions for polishing specimens

Abrasive/Surface	Lubrication	Force/Sample	Speed (Head/Base)	Time
9 micron DIAMAT diamond on TEXPAN polishing pad	Diamond suspension gel2 + monocrystalline 9 µm	5 N	100/150 rpm	3 minutes
3 micron DIAMAT diamond on GOLDPAD polishing pad	Diamond suspension gel2 + monocrystalline 3 µm	5 N	100/150 rpm	3 minutes
0.03 micron Nanometer alumina on ATLANTIS polishing pad	SPM 0.03 µm non crystallising	5 N	100/150 rpm	3 minutes

The A1 region is directly beneath the machined surface and extend to the depth of only few microns. This region is characterized by the grains undergoing severe deformation by extension and rotation. The A2 region lies beneath A1 region and this region is characterized by the rotation and realignment of the grains only. The A2 region extends up to region A3 where the grain structure is similar to the bulk material. The grains in the A3 region do not undergo deformation, and grain realignment. The deformation regions are shown in Fig. 3.

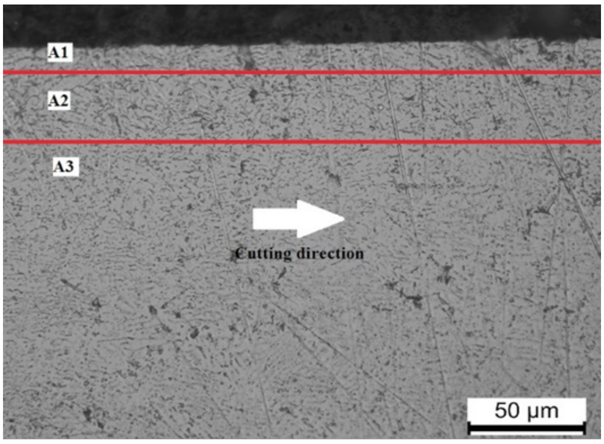

Fig. 3: Deformation regions (5 µm)

In the Fig. 4, three micrographs are shown and the influence of the cutting speed on the depth of deformation can be seen in these micrographs. At the cutting speed of 151 m/min, feed rate of 0.1 mm/tooth, and depth of cut of 0.1 mm, the depth of deformation measured is about 5.5 µm. At the cutting speed of 207 m/min, feed rate of 0.05 mm/tooth, and depth of cut of 0.03 mm, the depth of deformation measured is about 9.7 µm. The depth of deformation at the cutting speed of 301 m/min, feed rate of 0.1 mm/tooth, and depth of cut of 0.1 mm is equal to 12 µm. Hence, the depth of deformation increases with the increase in the cutting speed.

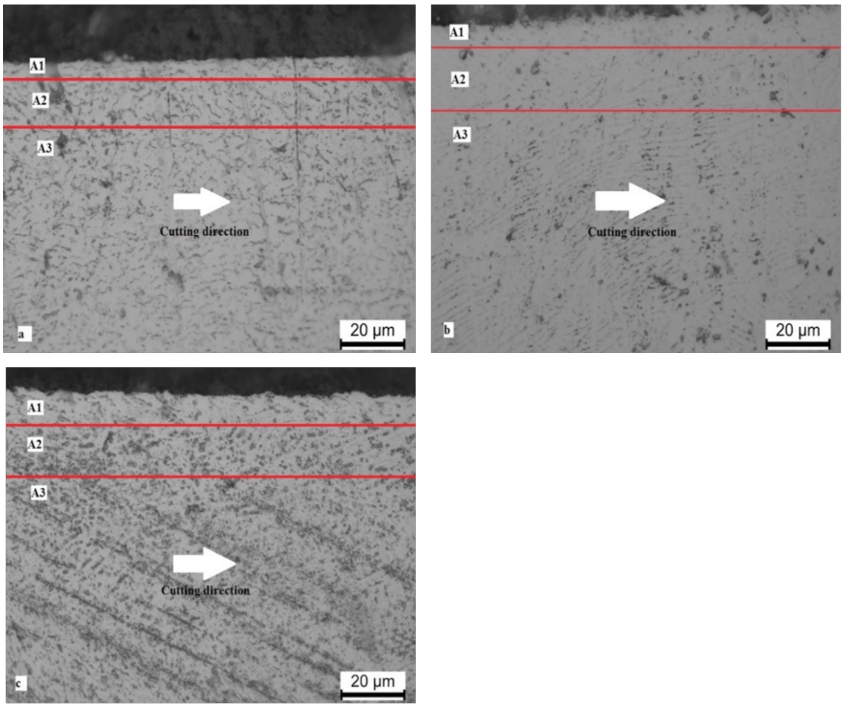

Fig. 4: Micrograph showing depth of deformation (a) at cutting speed of 151 m/min, 0.1 mm/tooth feed rate, 0.1 mm depth of cut (b) at speed of 207 m/min, 0.05 mm/tooth feed rate, 0.03 mm depth of cut (c) at speed of 301 m/min, 0.1 mm/tooth feed rate, and 0.1 mm depth of cut.

6. Conclusion

The conclusions for the research are as follows: a) the depth of deformation at the subsurface beneath the milled surface increases as the cutting speed, feed rate, and depth of cut increases, b) the effect of milling is limited to small depth of subsurface.

Acknowledgement: This research was supported by National Natural Science Foundation Project, Project Number: NSFC No. 51675339, Enhanced Twinning Mechanism of Titanium Alloys in Machined Surface Created from High-Speed Machining under Cryogenic Condition.

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