13th International Research/Expert Conference
"Trends in the Development of Machinery and Associated Technology"
TMT 2009, Hammamet, Tunisia, 16-21 October 2009

SURFACE INTEGRITY ANALYSES IN HIGH SPEED INCLINED MILLING OF THE TITANIUM ALLOY TI-6AL-4V

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ABSTRACT
The aim of this work is to provide an in-depth understanding of the surface integrity produced by various machining conditions and workpiece inclination angles using high speed finish ball end-milling of the titanium alloy Ti-6Al-4V.
Inclined milling with hemispherical-end tool generates a variation of the effective cutting speed which depends on additional parameters of the cut such as the inclination angle and the tool path, and other operational parameters: radial depth of the cut a_e*, feed per tooth* f_z *as well as the feed direction. It is suitable to claim that the machining directions and strategies also influence the tool life and the machined surface integrity.*
The surface integrity is not only based on surface roughness but also focus on surface hardness, microstructure, plastic deformation of machined surface, residual stress and surface defects.
For a range of workpiece inclination angles, measurements of surface roughness of machined surface and residual stress were taken. All cutting tests were conducted in dry conditions and performed on a vertical five-axis CNC milling machine, using an uncoated carbide tool.
Keywords: Ball end milling; Surface integrity; Workpiece inclination angle; Ti-6Al-4V;

1. INTRODUCTION
Cutting of titanium alloys has always been a topic of great interest to industrial production and scientific research worldwide. Titanium alloys are extremely difficult-to-machine materials, their machinability is generally considered to be poor due to several of their inherent properties [1,2]. Namely, they have low thermal conductivity and high chemical reactivity with many cutting tool materials. Their low thermal conductivity increases the temperature at the cutting edge of the tool. Hence, on machining, the cutting tools wear very rapidly due to high cutting temperature and strong adhesion between tool and workpiece material [2]. Additionally, the low modulus of elasticity of titanium alloys and their high strength at elevated temperature further impair their machinability. Ti-6Al-4V is the most commonly used alloy, it is an extensively employed material for aerospace and other components that operate at high temperatures and in corrosive as well as hostile environments; such as, aerospace and missile parts, gas turbine engines, steam turbines, chemical and petrochemical

equipment [1,2]. In all these applications, resistance to fatigue, creep, corrosion and distortion depends on the characteristics of the machined surfaces. Titanium alloys are generally used for a component which requires the greatest reliability and therefore the surface integrity must be maintained. Therefore, when machining any component it is essential to satisfy surface integrity requirements.

Surface integrity is defined as the inherent or enhanced condition of a surface produced in a machining or other surface generating operation [3]. The nature of the surface layer has a strong influence on the mechanical properties of the part. When machining any component, it is first necessary to satisfy the surface integrity requirements. Surface integrity produced by a metal removal operation includes the nature of both surface topography as well as surface metallurgy.

The present work, therefore, focuses on the investigation of the surface integrity parameters recorded after high speed end milling of titanium alloy Ti-6AL-4V using uncoated carbide tool and dry machining condition.

2. EXPERIMENTAL PROCEDURES

This investigation was carried out on a high speed vertical center Deckel Maho DMU 50 evolution five-axis CNC milling machine with a maximum power of 16KW and a maximum spindle speed of 18000 rpm. The workpiece material used in the machining trials was titanium alloys alpha-beta Ti-6AL-4V, the chemical compositions and physical properties of workpiece material are given in Table 1 and 2. Machining was performed with a 16 mm diameter ball nose end mill tool holder fitted with two uncoated carbide inserts. The cutting tools and tool holder for machining Ti-6AL-4V were recommended by the tool supplier. Cutting parameters held constant were: axial depth of cut, a_p= 0.4 mm, radial depth of cut a_e= 0.5mm, feed per tooth f_z= 0.15mm/tooth and revolution speed N=3000 rev/min; dry cutting; cutting method: up milling; cutting direction (when operating at inclined milling): vertical upwards (Figure 1).

Table 1 - Chemical composition (%) of Ti–6Al–4V Alloy

Element	Ti	Al	V	Fe	O	C	N	H
%	Balance	6	4	0,3	0,2	0,08	0,05	0,01

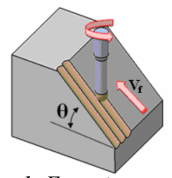

Figure 1. Experimental configuration of the cutting test

Table 2 - Physical properties of Ti–6Al–4V Alloy

Hardness (HRC)	Density (g/cm^3)	Modulus E (MPa)	Elongation (%)	Tensile strength (MPa)	Thermal conductivity (W/m°K)
36	4,43	910	14	1000	7,3

The workpiece machined surface was measured using a 3D measurement station STIL Micromeasure 2, which is optimized for roughness measurement and 3D micro-topography, in the feed and across feed directions.

The specimens were polished and etched for 10 seconds in a Kroll solution, in order to study possible metallurgical changes below the machined surfaces using an optical microscope equipped with a camera. Adjacent specimens were used for measuring residual stress distribution below the machined surface. Measurements were performed using an X-ray diffraction technique. Measurements were taken below the machined surface at 10 µm intervals between successive readings.

3. RESULTS AND DISCUSSIONS

3.1. Workpiece surface roughness:

There are many parameters used in the literature and industry related to surface roughness. For the 2D surface roughness parameters, the most popular of these parameters is average roughness. It is quoted as R_a symbol. Mathematically, R_a is the arithmetic value of the departure of the profile from centerline along sampling length. [4,5] For the 3D surface roughness parameters, the most used parameters are, S_a and S_q, respectively, the arithmetical mean of the surface and root mean square roughness. In this investigation, these three parameters were studied.

Figure 2. (a) shows the comparison of R_a values, measured in feed and across feed directions, for each of the three machining configurations (three different workpiece inclination angles). As can be seen, the R_a (along feed direction) values range from 0.366 to 0.725µm and the R_a (across feed direction) values range from 0.722 to 1.66µm. The ratio of maximum to minimum for the measures taken across the feed direction is considerably larger than that obtained for the measures taken along the feed direction, implying that the effect of cusp height, in deteriorating the surface quality, is more pronounced in pick feed direction than in along the feed direction.

The analysis of the results of the micro-geometrical topography of surface (Figure 3), and the 2D/3D parameters characteristic of the profile of the machined workpiece (Figure 2), show the improvement of the machined surface texture quality when it is machined with a workpiece inclination angle of 25°. For the parts machined with a normal or quasi-normal tool on the surface to machine, the result of the analysis of the surface quality reveals a bad micro-geometrical quality as shown at Figure 3(a).[5]

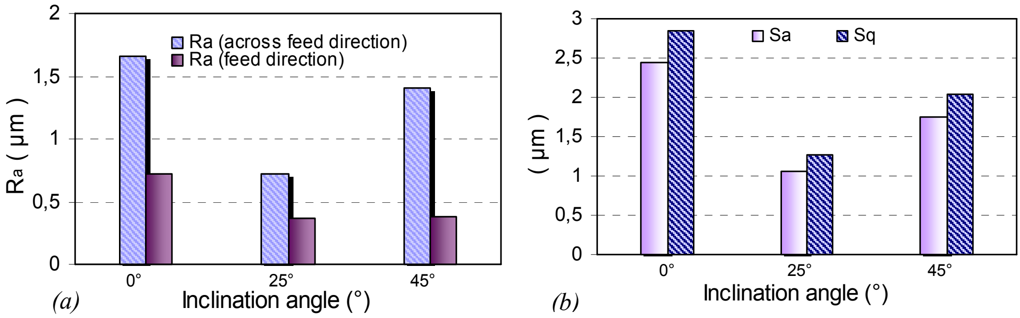

Figure 2. Surface roughness parameters of the three machining configurations;
(a)2D parameter: R_a; (b)3D parameters: S_a and S_q

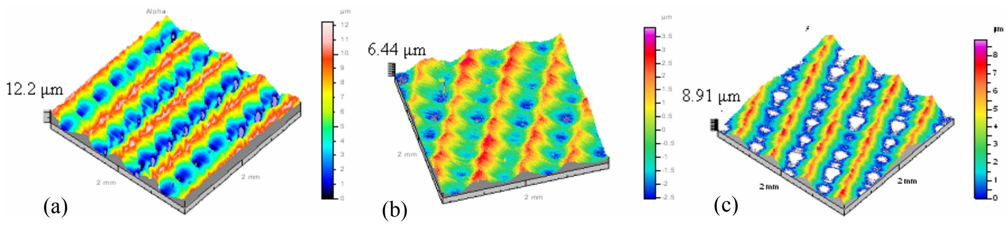

Figure 3. 3D surface topographies for various workpiece inclination angles
(a) $\theta = 0°$, (b) $\theta = 25°$, (c) $\theta = 45°$

3.2. Workpiece residual stress and microstructure:

Figure 4. shows the results of residual stress measured for the three workpiece inclination angles experimented. From the figures, the residual stress show different depth profiles for different workpiece inclination angles. The residual stress at the machined surface and the maximum residual compressive stress induced beneath the machined surface are different greatly. Stresses were highly compressive, up to 500 MPa, which can be explained by the likely overriding mechanical rather than thermal effect. The three plots follow the same tendency of decreasing compressive stress with increasing depth beneath the machined surface. It can be seen that increasing the workpiece angle, which induce the increase of cutting speed [5,6], caused the mean level of compressive stress to decrease, probably due to the absence of the rubbing effect which occurs at the centre of the ball nose end mill and tends to induce compressive residual stresses. Figure 5.(a) shows a micrograph of the surface in the feed direction which clearly illustrates a bending of the material's grain structure in the machined surface. In contrast, this microstructural defect wasn't apparent for the second configuration (θ=25°) figure 5. (b) Furthermore, no phase deformation was observed in the three configurations.

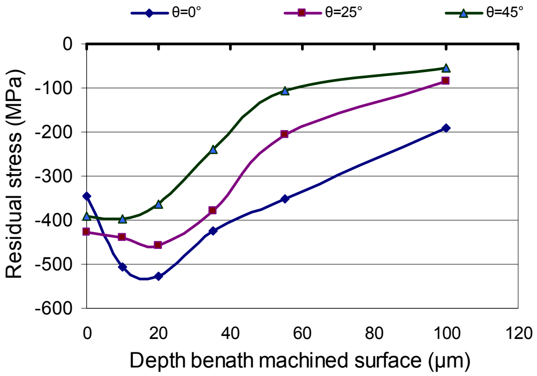

Figure 4. Effect of different workpiece inclination angles on workpiece residual stress depth profiles

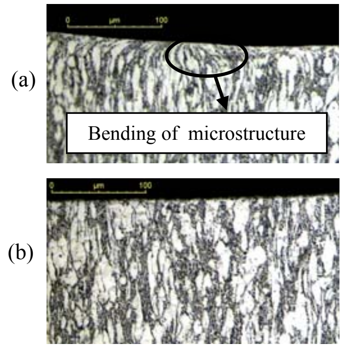

Figure 5. Microstructure of workpiece, (a) trial 1: θ=0°; (b) trial 2: θ= 25°

4. CONCLUSIONS

A series of end milling titanium Ti-6Al-4V experiments were conducted to comprehensively characterize surface integrity in various workpiece inclination angles and machining parameters. The major conclusions may be summarized as follow:

- Workpiece inclination angle proved to be an influential parameter for surface roughness. In this study, θ=25° provided best surface finish because of avoidance of cutting at tool's center and tool deflection phenomena which is important at θ=45°.
- At the higher workpiece angle, the mean compressive stress decreased slightly due to the absence of the rubbing effect which occurs at the center of the ball nose and mill and tends to induce compressive residual stresses.
- Machining without workpiece inclination angle (θ=0°) produced bending of the material's grain structure in the machined surface. This, didn't appeared at θ=25° and θ=45°.

5. REFERENCES

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