

## **Surface Texture Investigation in High Speed Flat End Milling of Ti-6Al-4V**

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### **Abstract**

Aerospace alloy Ti-6Al-4V is classified as “difficult-to-cut” material. But with their low mass, high strength, and excellent resistance to corrosion, titanium alloys solve many engineering challenges. In this study, high speed end milling of Ti-6Al-4V was applied as a potential machining technique for obtaining better surface finish using small diameter tools applying high rpm to facilitate the application of micro-meter level feed and depth of cut to ensure super finishing that could avoid the need of further grinding and polishing. Machining was performed on a Vertical Machining Centre (VMC) with a high speed attachment (HES 510), using cutting speed, depth of cut, and feed as machining variables. Three level full factorial designs were followed for machining operations. Minimum average surface roughness ( $R_a$ ) value of 0.13  $\mu\text{m}$  was obtained which is within the acceptable range of avoiding grinding and polishing operations. Surface texture was investigated and no alternation in microstructures was observed and there was no presence of white layer on the machined surface. A strain hardened zone was observed beneath the machined surface with a small temperature-softened zone just below the machined surface.

### **Keywords**

End Milling, Surface Roughness, Surface Texture High Speed Machining, Ti-6Al-4V

### **1. Introduction**

The overall objective of machining research is to study the interaction of the cutting tool and the work-piece in order to optimize cutting conditions and hence minimize operational cost and maximize product quality. The techniques of High Speed Machining (HSM), while still in an initial stage of wide acceptance, have already been proven in leading aircraft manufacturing plants [1]. It has been proved that there are considerable savings in the machining time by comparing the conventional machining [2]. Because of its extensive applications in aerospace industries and the poor machinability properties, Ti-6Al-4V alloy has dominated the major research interests in metal cutting industries in the recent past. However, less attention has been given on enhance their surface finish and dimensional accuracy.

High rpm is needed when using small-diameter tools for better surface roughness in case of HSM. It is necessary to maintain proper chip load during HSM. When machining at high rpm, say 30,000 - 40,000 rpm it is necessary to maintain high feed rate, otherwise the tool to rub against the material instead of taking a cut [3]. More than 30,000 rpm cutting can eliminate much of the hand polishing and bench work that was traditionally. At high chip loads, the effect of cutting speed was proven much more prominent [4]. In this study, 3-level full factorial experimental designs of RSM were used for high speed end milling of Ti-6Al-4V. The 3-level factorial method was used to study qualitatively the 3D (three dimensional) surface morphologies/topographies for the machined surfaces of Ti-6Al-4V to determine the machining conditions that could give the highest possible surface finish and to study quantitatively the effects of the machining parameters and their interactive effects on the two dimensional (2D) surface roughness ( $R_a$ ). Response Surface Methodology (RSM) establishes the relationships between several explanatory variables and one or more responses or outcomes. The RSM is an empirical modeling approach for determining the relationship between various process parameters and responses and for establishing the significance of these process parameters on the coupled responses [5].

## 2. Experimental Details

### 2.1 Experimental setup

End milling tests were conducted on Vertical Machining Centre (VMC ZPS, Model: MCFV 1060) manufactured by ZPS of the Czech Republic. It has Vickers Acramatic PC2100 Control System. This machine allows high precision positioning as well as linear and continuous circular cutting. A precision high speed milling attachment (HES 510, Nakanishi, Japan) equipped with an electronic control unit was used which achievable spindle speed is up to 50,000 rpm. Figure 1 shows the block diagram of the experimental setup comprising the high speed milling attachment and electronic control unit with air supply system.

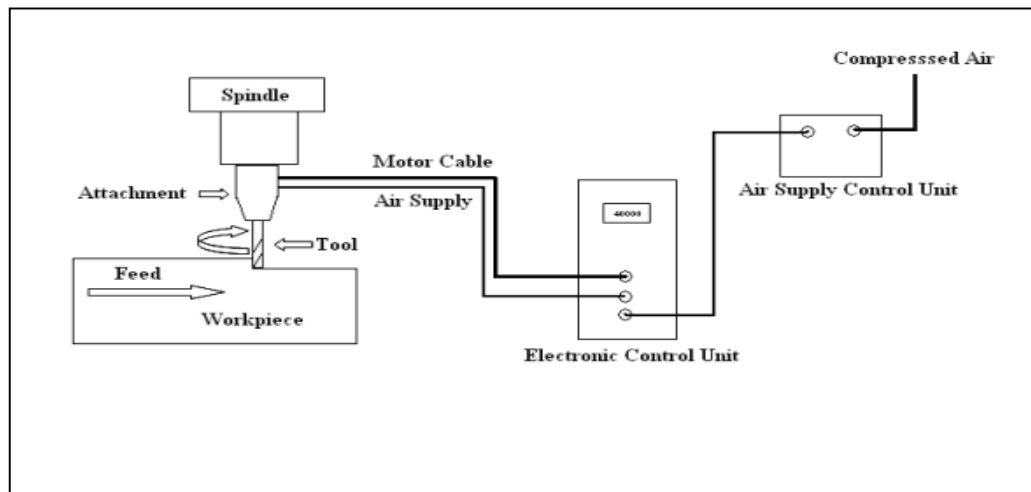


Figure 1: Experimental set-up with high speed milling attachment and electronic control unit

After machining, average roughness  $R_a$  was measured for every standard run using an optical surface profiler (Wyko NT1100). Figure 2 shows the arrangement of surface roughness measurement.

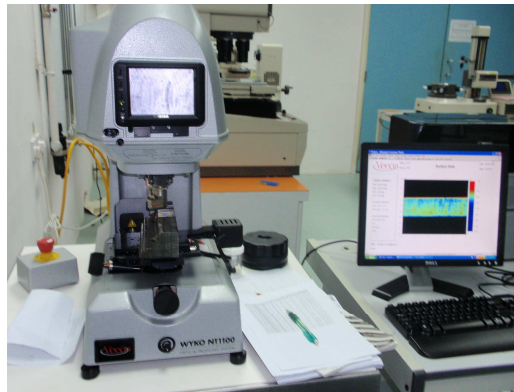


Figure 2: Surface roughness measurement.

### 2.2 Experimental Design

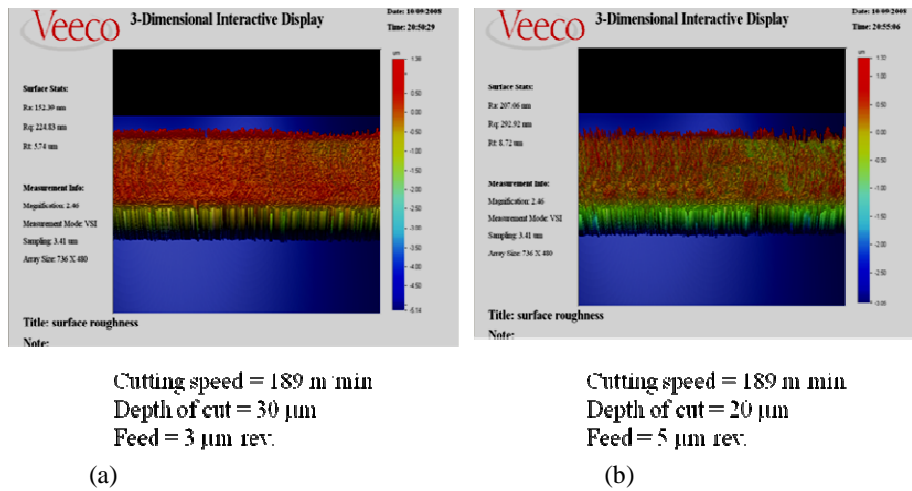
Experiments were conducted with the variations of cutting speed (126m/min to 252 m/min), Axial depth of cut (10 ( $\mu\text{m}$ ) to 30 ( $\mu\text{m}$ )) and Feed 1 ( $\mu\text{m}/\text{rev.}$ ) to 5 ( $\mu\text{m}/\text{rev.}$ ) Table 1 shows the cutting conditions and the measured surface roughness results.

Table 1: Experimental results of high speed end milling of Ti-6Al-4V

Trial No.	Cutting speed $v$ , (m/min)	Axial depth of cut $a$ , ( $\mu\text{m}$ )	Feed, $f$ ( $\mu\text{m}/\text{rev.}$ )	Surface roughness, $R_a$ ( $\mu\text{m}$ )
1	126	10	1	0.17
2	126	20	5	0.22
3	189	10	3	0.13
4	252	10	5	0.17
5	126	30	3	0.26
6	189	20	1	0.15
7	189	30	5	0.25
8	252	20	3	0.15
9	252	30	1	0.19
10	189	20	3	0.18
11	252	10	1	0.17
12	252	20	5	0.22
13	126	10	3	0.17
14	189	10	5	0.16
15	252	30	3	0.14
16	126	20	1	0.24
17	126	30	5	0.36
18	189	30	1	0.18
19	189	10	1	0.13
20	189	20	5	0.21
21	252	10	3	0.13
22	126	10	5	0.17
23	189	30	3	0.15
24	252	20	1	0.20
25	252	30	5	0.18
26	126	20	3	0.21
27	126	30	1	0.28

### 3. Investigation of Surface Texture

Under high magnification surfaces look different when they are cut under different cutting conditions. Figure 3 shows the 3D-pictures of machined surfaces obtained using Wyko NT1100 optical surface profiler during roughness measurement. It is observed that high peaks and deep valleys are prominent in surface (b) resulting higher values of  $R_a$  compared to surface (a).

Figure 3: 3D surface texture of machined surface corresponding to (a)  $R_a=0.152 \mu\text{m}$  and (b)  $R_a=0.207 \mu\text{m}$

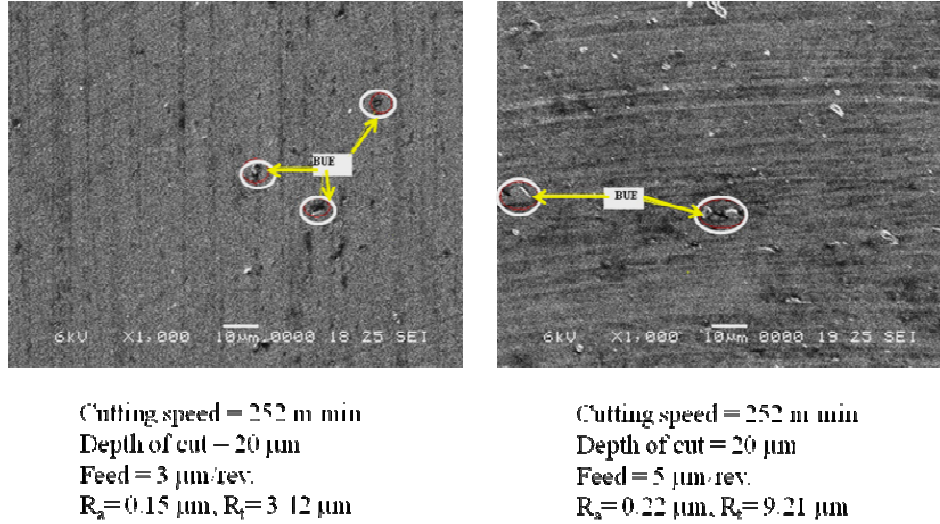


Figure 4: SEM top view of the machined surface obtained during high speed end milling of Ti-6Al-4V under dry condition

The SEM images of the machined surface at different feed values are shown in Figure 4. As the feed increased the milling mark is more visible. This happened because the distance between two adjacent peaks was larger as the feed value increased [6]. Figure 6 indicates that surface roughness is low for moderate feed value (feed = 3 μm/ rev.) and high for highest feed (feed = 5 μm/ rev.). Adhesion of built-up-edge (BUE) on the machined surface is also observed.

### 3.1 Microstructure and Micro-Hardness

The samples were cut by wire cut Electro Discharge Machining (Wire-EDM) at 90° from the machined surface to observe cross-sectional plane in order to evaluate the possible micro-structural modifications beneath the top surface. The microstructure of the material beneath the machined surface was observed under Optical Microscope (Nikon, Model: EPIPHOT-200, Japan). Obtained images (Figure 5) reveal no or little deformation of the grains beneath the machined surface. Previous studies showed that during conventional machining of titanium alloy an overheated layer of hardened material was formed on the top layers [7], generally called *white layer*. In present study no evidence of white layer was observed on the beneath the machined surface.

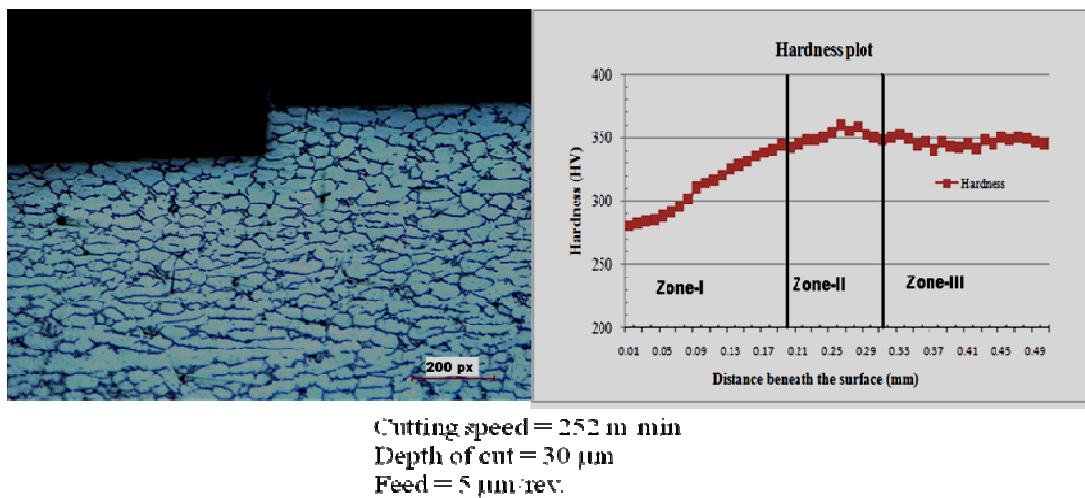


Figure 5: Microstructure and micro-hardness beneath the machined surface obtained after machining

Micro-hardness of the cross-section machined surfaces was measured by Mitutoyo (MKV-H2, Japan) Hardness Testing Machine Vicker's hardness measurement values were taken randomly up to 0.5 mm beneath the machined surface at a 0.01 mm interval. Loading time and applied load were 10 seconds and 0.3 Kg respectively. Figure 5 also shows sample hardness-depth profile for the extreme machining conditions (i.e. maximum cutting speed, axial depth of cut and feed). It is observed that extensive strain hardening has occurred. The hardened zone started from 0.20 mm and ended at 0.30 mm below the machined surface. The increase in subsurface micro-hardness was associated with plastic deformation of the workpiece surface and local deformation at the relatively low temperatures [8].

#### 4. Conclusions

High speed end milling of Ti-6Al-4V was introduced in this study as a potential machining technique to achieve better surface finish and higher integrity of the machined surface. The conclusions of the research work can be summarized as follows:

1. Surface texture investigations show that rubbing/ ploughing occurs instead of cutting resulting high roughness at very low feed values. Adhesion of chip segments and built-up-edge (BUE) is observed on the machined surface.
2. Microstructure study depicts that there is no alternation of microstructures and no evidence of the formation of the white layer observed on or beneath the machined surface even at extreme cutting conditions used in this study.
3. From micro-hardness test, a hardened zone from 0.20 mm to 0.30 mm from the machined surface as a result of strain hardening was observed.

The need of expensive and time consuming machining operations like grinding and polishing may be replaced by high speed machining.

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