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An Experimental Investigation of High-Speed End Milling of Ti-6Al-4V Alloy

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ABSTRACT

Cutting of titanium alloys has been a subject of high interest for research projects worldwide, especially due to the widespread application of those materials within the aerospace industry. Titanium alloys are recognized as extremely difficult to cut materials for a number of their innate characteristics, like their high-temperature strength and low thermal conductivity. Poor machinability of those materials is said to the generation of high temperatures at the chip-tool interface and formation of serrated chips, which end in low chip-tool contact length and high fluctuation of cutting force working on the tip of the tool. Such dynamic loading behavior leads to instant failure of the tooltip and consequently poor surface finish in machining. Many researchers have actively administered innovative research to enhance tool life, MRR, improvement of surface finish, and elimination of chip serration to reduce chatter and vibration during machining. However, less success has been achieved in improving surface finish and tool life. This study aims to optimize the cutting parameters to achieve the finest possible surface finish in conjunction with a reasonable tool performance in high-speed end milling of Ti-6Al-4V using uncoated tungsten carbide tools. The experiment design was supported by the response surface methodology (RSM). Empirical Mathematical models were developed for output response – Surface Roughness in terms of the machining parameters. Based on the developed model, optimization was conducted using RSM. The influence of input parameters, namely, cutting speed, axial depth of cut, and feed, were analyzed, and their optimum combinations for minimum surface roughness, were identified. It is observed that with the rise in spindle speed (from 16000 to 22000 rpm) and the lowering of feed rates (from 26 to 38 mm/min), the possibility of finding the best surface roughness from the contour graph increases. A Scanning Electron Microscope (SEM) was applied to study the cutting-edge wear behavior, chip morphology, and texture of the machined surface.

Keywords: *Ti-6Al-4V, HSM, RSM, Uncoated tungsten carbide.*

1. Introduction

Titanium alloy Ti-6Al-4V is that the most ordinarily used alpha-beta alloy developed. It accounts for quite 50% of whole Titanium usage within the world, with aerospace industries utilizing quite 80% of these usages. Titanium alloys are utilized in airframe structures and reaction-propulsion engine components due to their medium weight, high structural properties, e.g., high strength-to-weight ratio, high fracture resistance, stiffness, toughness, and fatigue maintained at elevated temperature and unusual resistance to erosion at temperatures below 932°F. However, the unique combination of the above properties is liable for the poor machinability of Ti-6Al-4V. More heat is generated due to elevated mechanical properties. However, due to this group of materials' low thermal conductivity, more heat is concentrated at that chip-tool interface during the application of machining operation, resulting in high-temperature development at the chip-tool interface also as at the shear zone, causing instant tool failure.

Numerous studies focused on the causes of the titanium alloy's poor machinability, which reveal the subsequent causes: 1. High thermal stresses at the leading edge thanks to low cooling by the chip, tool, and work-piece [1]. 2. High-pressure load on the leading edge through the reduced contact surface [2]. 3. Tool failure by chipping due to high dynamic components of cutting force and self-induced chatter [3]. 4. The hazard of exoergic (spatters) reaction of the chip with atmospheric oxygen [4]. 5. Strong affinity to adhesion thanks to the warmth accumulation within the cutting zone involving tool failure [5].

"High-Speed Machining (HSM), for any materials, are defined because of the cutting speed above which shear localization builds completely within the primary shear zone" [6]. Effectiveness, productivity, and efficiency of the machining operations are often improved by varying feed rates following cutting velocity resulting in high chip-removal rates with comparatively small cutting tool diameters [7]. The success of HSM machining relies on several parameters, including gear dynamics, power, work material, feed capabilities, and torque of the machine. HSM is predicated on a high metal removal rate, short production time, better surface finish, and high dimensional accuracy [8]. For an equivalent surface speed, rpm is a different supported tool diameter. Fig.1 shows how surface speed for high-speed machining varies with workpiece material [9].

Numerous research works are conducted on developing the machinability of titanium alloys within the past few decades to accelerate material removal rate and gear life to scale back machining cost. However, less attention has been given to the enhancement of surface roughness quality and dimensional accuracy in a machining process.

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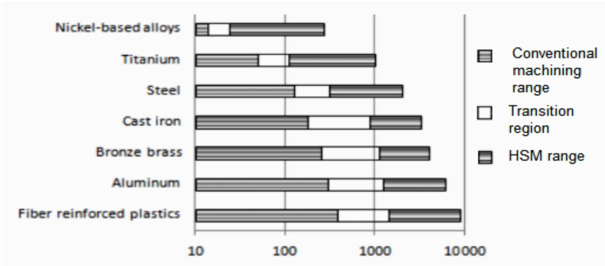

Fig.1 "Cutting speed ranges for machining of various materials" [9].

High-speed machining (HSM) is the procedure targeted to shorten the lead and production times. HSM generally employs low diameters of tool and gear geometries that allow low feed per tooth, enhancing surface finish without compromising the fabric removal rate. HSM is predicted to account for a highly effective rate due to high rotational speed (n) and correspondingly high feed (f) per minute, reasonable depth of cut, and high linear cutting speed (v). HSM exerts better linear cutting speed (v), as cutting force decreases with linear cutting speed and lower cutting force, which results in lower feed per tooth. Thus, HSM ensures stress-free components with burr free-high-quality surface finish.

This paper investigates the consequences of feed rate, cutting speed, and depth of cut on surface roughness, tool wears morphology, and chip characteristics during high-speed end milling operation of Ti–6Al–4V on a CNC Router machine using uncoated tungsten carbide end mill cutter.

2. Experimental Procedure

2.1 Workpiece Materials

During this research work, Ti-6Al-4V has been selected as the workpiece materials. The workpiece's chemical composition, mechanical and thermophysical properties are listed in Table 1 [10] and 2 [11], respectively.

Table 1 "Normal chemical composition of Ti-6Al-4V alloy (wt. %)" [10]

Content	Max	Min
Al	6.8	5.5
V	4.5	3.5
Fe	0.3	-
O	0.15	-
Si	0.15	-
C	0.1	-
N	0.05	-
H	0.015	-
Titanium	Balance	

Table 2 "Mechanical properties and thermo-physical data of Ti-6Al-4V alloy" [11]

Thermal conductivity (W ⁄m°K)	Hardness (HRC)	Re (MPa)	Density (g ⁄cm^3)	Rm (MPa)
7,3 TA	36	910	4,43	1000

2.2 Cutting Tool Materials

The diffusion rate resists the life of the uncoated tungsten carbide tool used to machine Ti-6Al-4V alloy at the tool–chip interface. A severe factor obstructing the machinability of Ti-6Al-4V is their property to react with the cutting tool, thereby provoking dissolution wear during the machining operation. The recommendation was to conduct machining of Ti-based alloys with uncoated tungsten carbide cutting tools. They perform better due to the relatively higher chip-tool contact length during machining. Amin et al. [12] conducted a study on HSM of Titanium Alloy - Ti–6Al–4V using 2 mm and 4 mm diameter uncoated carbide tool for the comparison of their performance in terms of minimum surface roughness and found that the 2 mm diameter uncoated carbide tool was more convenient for HSM of Titanium Alloy Ti-6Al-4V. Based on their findings, during this study, a 2 mm diameter uncoated tungsten carbide end mill was used for investigating the influence of cutting parameters in HSM of Titanium Alloy, Ti-6Al-4V. Mechanical and thermophysical characteristics of the tool material are listed in Table 3 [13].

Table 3 "Mechanical properties and thermo-physical data of tungsten carbide" [13]

Content	Value
Density (Kg/m3)	1,477
Expansion coefficient at 100° (μm/m·°C)	90.1
Specific heat capacity	2,563
Thermal conductivity at 24° (W/m·K)	15.48
Hardness (HRC)	75-120
Young's Modulus (GPa)	550-650

2.3 Experimental Design Using RSM

Several experimental design options are available, including the central composite design (CCD), Box-Behnken, Plackett Burman, and full factorial. Among these 2-level full factorial is the most useful response surface method (RSM), requiring sufficient experiments to provide minimum error [12]. Most researchers have used central composite and rotatable design in order to reduce experimentation. The models developed were based on only a few experimental results [14]. Experiments were designed to support the three-factor two level small factorial design concept of RSM. The machining variables were feed rate, spindle speed, and DOC (depth of cut). The response that was considered for model development was average surface roughness.

The experiment was conducted on a CNC routing machine with a high-speed milling attachment, using which end milling operations were performed. The spindle speed ranged from 10000 to 25000 rpm was used during the experiments. The selection of the spindle speed range is formed considering the grouping of the high-speed machining and consistent with the cutter's strength used in the experiment. Table 4 represents the coding of independent variables for the machining operation of Ti-6Al-4V using carbide tools. Experimental works were carried out in dry conditions with a 2 mm diameter, 4-flute uncoated tungsten carbide end mill.

2.4 Design of Experiments (DOE)

Response surface methodology (RSM) is a technique that can be used to develop an improved and optimized process using a collection of statistical and mathematical techniques [15]. Response Surface Methodology (RSM) was conducted to plan experiments, with the view to developing regression models. Design Expert package version 12.0.5 was applied for conducting the above purpose. Ranges of the three variable machining parameters are shown in Table 4.

Table 4 Intervals of the three experimental parameters of Ti-6Al-4V machining using carbide tool

Levels	A: Spindle Speed, rpm	B: Feed Rate, mm/min	C: DOC Depth of cut, µm
Low	10000	20	10
High	25000	50	30

2.5 Measurement of surface roughness

Average surface roughness was measured on a surface roughness tester machine - Mitutoyo Surftest SJ-210. The roughness on the machined surface was weighed vertical to that feed signs after each cut. The average of three readings of response parameter -surface roughness for each of the 20 different runs, combined with a different combination of cutting parameters (Spindle Speed, Feed Rate, and DOC) (showed in Table 5) was taken in order to ensure a more reliable value of the surface roughness. The given surface roughness tester is provided with auto-calibration, which will be initiated with a numerical value.

2.6 Chip Analysis

Titanium alloys have an odd behavior of forming serrated chips, which may be classified as catastrophic shear chips, while most other materials tend to form a continuous chip with uniform thickness. Chip investigation was conducted on a Scanning Electron Microscope (SEM). JEOL JSM-7610F Plus SEM was used in this study for studying the tool wear and chip morphology in HSM of Ti-6Al-4V.

3. Experiment results

The results obtained from the surface roughness tests were used for model development using DESIGN EXPERT package version 12.0.5. Table 5 shows the machining combinations, and therefore the measured roughness on the machined surface. It calculates the consequences of all model terms and “std” in the 1st column representing the machining order followed strictly during the machining operation.

3.1 Surface roughness

Table 5 Experimental results for the surface finish in the end milling operation of Ti-6Al-4V.

Std	Run	A: Spindle Speed, rpm	B: Feed rate, mm/min	B: Feed rate, mm/teeth	C: Depth of cut, µm	Response Surface finish, µm
7	1	16500	35	0.53	20	0.107
10	2	16500	35	0.53	20	0.112
5	3	16500	60.226	0.91	20	0.392
2	4	16500	35	0.53	20	0.115
3	5	5568.3	35	1.57	20	0.438
11	6	10000	20	0.50	10	0.369
8	7	23000	50	0.54	10	0.369
14	8	23000	50	0.54	30	0.527
4	9	10000	50	1.25	30	0.581
1	10	16500	35	0.53	20	0.12
20	11	10000	50	1.25	10	0.554
17	12	10000	20	0.50	30	0.264
18	13	23000	20	0.22	30	0.134
6	14	16500	9.7731	0.15	20	0.148
9	15	23000	20	0.22	10	0.287
13	16	16500	35	0.53	36.8	0.244
19	17	16500	35	0.53	3.18207	0.246
12	18	27431.7	35	0.32	20	0.224
15	19	16500	35	0.53	20	0.119
16	20	16500	35	0.53	20	0.121

3.2 Chip Investigation

Komandwi, Schroeder, Bandhopadhyay have confirmed serrated chips' formation within titanium alloys machining, & Hazra, 1982 [16]. Within the primary shear zone, an area increase in temperature is observed, which causes a decrease in strength at this zone. Shear to form a chip occurs at this narrow zone, on the brink of a shear plane when the developed stresses go beyond the materials' yield strength. This successively causes local temperature thawing and rotation of the shear plane, causing serrated chips.

At these speeds, the chips have morphologies almost like those encountered within the machining operation of Ti-6Al-4V at comparatively high speeds. It is noted from Fig. 2 that at a relatively lower cutting speed (corresponding to 16500 rpm), the chip formation is regular, with the serrated nature of the continual chips. On the contrary, Fig. 3 shows that at higher cutting speed (corresponding to 23000 rpm), the chips formed have a gummy nature due to their high heat exposure at the chip-tool interface. A combination of lower speed and better feed rate appears to favor the formation of regular serrated teeth, while upper speed and lower depth result in the chips' gumminess. Comparing the effect of depth of cut on surface roughness with that of feed based on the ANOVA analysis, it is found that the effect of DOC negligible.

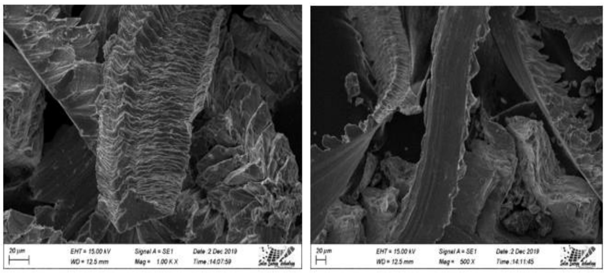

Fig.2 SEM photograph of the chip (A: 16500 rpm, B: 60.2269 mm/min, C:20 µm).

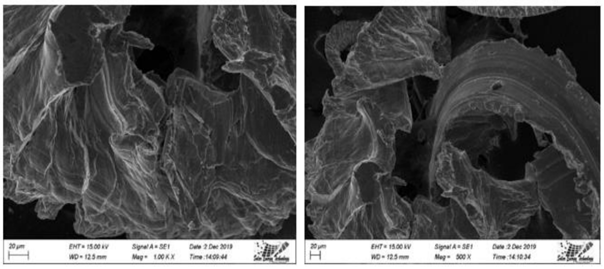

Fig.3 SEM photograph of the chip (A: 23000 rpm, B: 20 mm/min, C: 30 µm).

3.3 Tool Wear Morphology

The vital components that remain in Ti-6Al-4V alloys (Ti and Al) have an extreme chemical alliance with the foremost tool materials. There is comparatively high contact stress, high allied motion between the cutting tool, the chips, and heat within the high-speed milling process. A thin flow zone, a thin chip, and a comparatively low chip-tool contact length are the prime causes for the high-temperature developed at the chip-tool interface during machining of Ti-6Al-4V [17].

The tool's cutting edges were viewed under the SEM under several cutting combinations to study the influence of spindle speed, which has the foremost influential outcome on cutting tool wear. Fig. 4 shows the intact edges of a new tool, Fig. 5 expresses the cutting edges' circumstance after the machining operation of a fixed length of workpiece applying the lowest rpm of 5568.35. The feed rate was 35 mm/min, and therefore the DOC (depth of cut) was 20 µm. Fig. 6 shows the cutting edges' condition again after applying a new cutting tool for cutting at a better rpm of 16500, the feed rate and DOC (depth of cut) were as within the previous case. Finally, fig. 7 represents the condition of the tool edges when another new cutting tool was applied for cutting at a still higher rpm of 23000 with the feed rate and DOC an equivalent as within the previous two cases, and eventually Fig. 8 shows the condition of the tool applied for cutting at the very best rpm of 27431.7 with slightly lower feed but higher DOC of 20 mm/min, 30 µm respectively. In this study, one particular cutting tool was used for one operation only.

It can be concluded that the foremost dominant factor deciding tool life is cutting speed. The foremost favorable speed for the given feed value of 35 mm/min and DOC value of 20 µm appears to be 16500 rpm as at higher spindle speed values, such as at 23000 rpm and 27431.7 rpm, tool wear is nearly catastrophic. Reasonable tool life is predicted when machining would be conducted at 16500, like 104 m/min of linear cutting speed for the tool's given diameter or below. It may be noted from Fig. 1 that for titanium alloys, the high-speed range starts from slightly below 100 m/min. Thus, the cutting speeds applied were within the HSM range for Ti-based alloys during the experimental run (Fig. 1). Therefore, tool failure's main mechanism appears to be adhesion and attrition due to the chip analysis section's gummy behavior as discussed within the chip analysis section and microchipping and brittle failure modes (Fig. 5 – Fig. 8). A particular cutting tooth (among the 4 teeth) was identified with a white circle at the noncutting zone (the tooth is shown with a circle mark in the left of fig. 4 to fig. 8). The tooth condition was monitored before and after machining under high SEM magnification (Fig 4 – Fig 8).

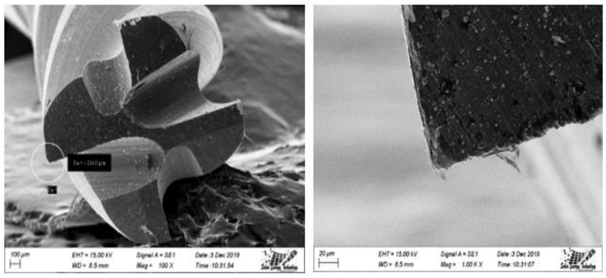

Fig.4 SEM photograph of the unused tool.

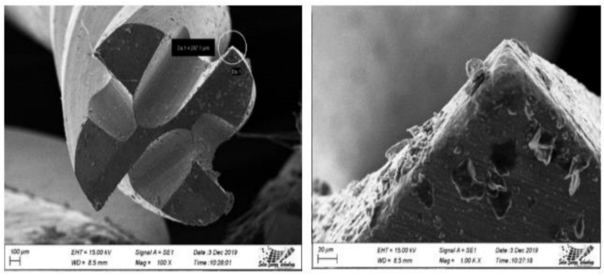

Fig.5 SEM photograph of used tool (A: 5568.35rpm, B: 35 mm/min, c: 20µm).

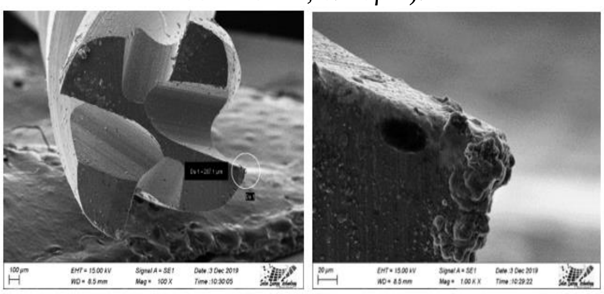

Fig.6 SEM photograph of used tool (A: 16500 rpm, B: 35 mm/min, C**:** 20 µm).

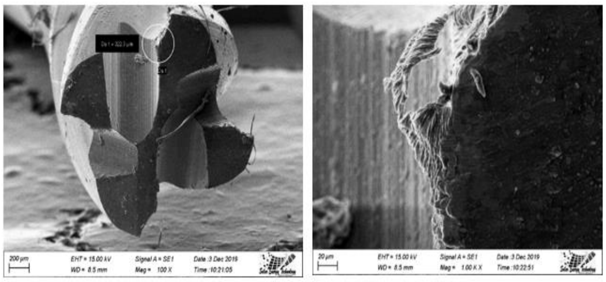

Fig.7 SEM photograph of used tool (A: 23000 rpm, B: 20 mm/min, C:30 µm).

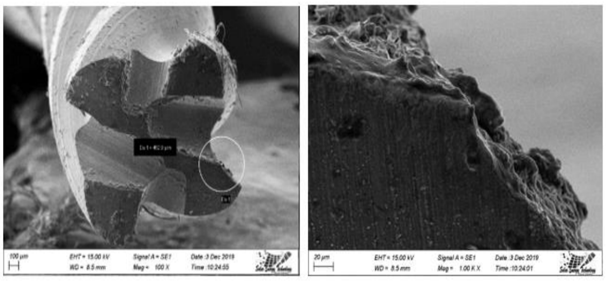

Fig.8 SEM photograph of used tool (A: 27431.7rpm, B: 35 mm/min, C: 20µm).

4. Surface Roughness Optimization

RSM has been conducted to get the minimum measure of average surface roughness. RSM may be an amalgamation of statistical and mathematical techniques used for the analysis during which the desired outputs (response) (surface finish) are influenced by different input parameters (factor) (feed rate, DOC, cutting speed). Therefore the desired outcome is to optimize the output by varying the input parameters together. For conducting this RSM, choice of input parameters, their interval (Table 4), and complete experiment trails are required (Table 5).

According to the fit and summery tests, the quadratic model was suggested. The fitted surface finish model for the machining operation of Ti-6Al-4V was found to be as:

$$\text{Surface Roughness} = 1.58010 - 0.000084 \times \text{Spindle Speed} - 0.023727 \times \text{Feed Rate} - 0.039666 \times \text{Depth of Cut} + 0.000369 \times \text{Feed Rate} \times \text{Depth of Cut} + 2.26910\times10^{-9}(\text{Spindle Speed})^2 + 0.000330 \times (\text{Feed Rate})^2 + 0.000655 \times (\text{Depth of Cut})^2 \quad (1)$$

In Fig.9, the contour graph has been developed supported the regression model developed using the experimental data. It is observed that the rise in spindle speed (16000 to 22000 rpm) increases the possibility of finding the best surface roughness from the contour graph. At an equivalent time, lower feed rates (26 to 38 mm/min) also provide better surface roughness. So, for fine surface finish, the spindle speed range should be 16000 to 22000 rpm, and therefore the feed rate range should be 26 to 38 µm at a lower depth of cut.

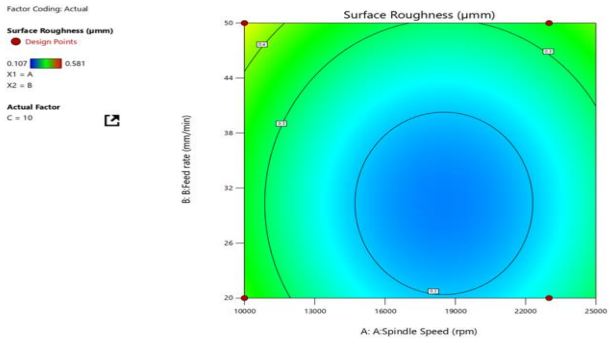

Fig.9 Contour Graph as a function of spindle speed and feed rate during the HSM of Ti-6Al-4V.

5. Surface Texture Investigation

Surface texture may indicate the standard of a surface and is explained as a component that interprets the machined surface's particular structure. This section aims to review the machined surface texture in HSM of Ti-6Al-4V alloy. The machining process applied for the surface finish was end milling, performed on a CNC routing machine. Surftest SJ-210 calculated the machined surface finish values. Machined surfaces were also analyzed using scanning microscopy (SEM) after the machining process. Fig.10 – 14 shows the machined surface's SEM views at several feed rates, spindle speed, and DOC. These surface finish values measured under those conditions are indicated within the figures for the corresponding conditions for simple comparison.

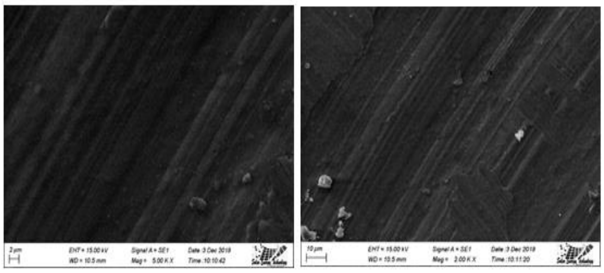

Fig.10 SEM photograph of machined surface (A: 10000 rpm, B: 50 mm/min, C:10 µm, Average Surface roughness: 0.554 µm).

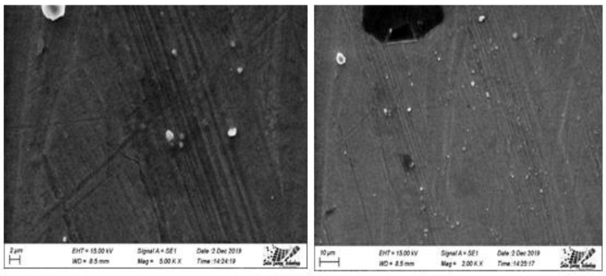

Fig.11 SEM photograph of machined surface (A: 16500 rpm, B: 35 mm/min, C: 20 µm, Average Surface roughness: 0.107 µm

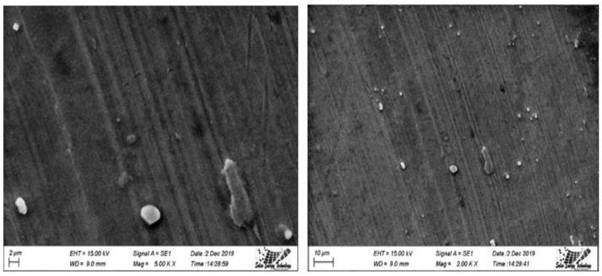

Fig.12 SEM photograph of machined surface (A: 16500 rpm, B: 60.2269 mm/min, C: 20 µm, Average surface roughness: 0.292 µm).

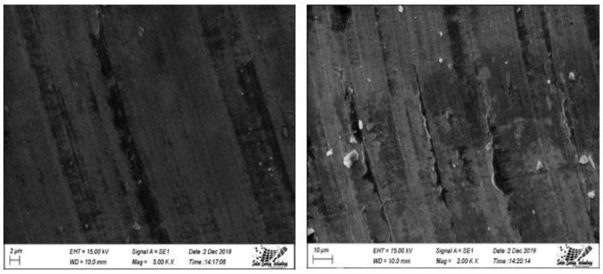

Fig.13 SEM photograph of machined surface (A: 16500 rpm, B: 35 mm/min, C: 3.18207µm, Average surface roughness: 0.246 µm).

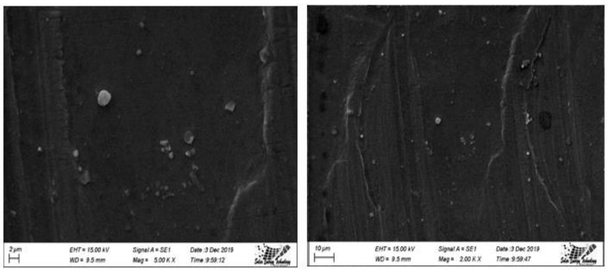

Fig.14 SEM photograph of machined surface (A: 23000 rpm, B: 50 mm/min, C:10 µm, Average surface roughness: 0.369 µm).

Fig 10 – Fig 14 shows the surface condition's visual representation under different combinations of machining parameters.

Fig.10 represents the surface profile at the lower value of rpm and DOC and better feed value. The surface finish (0.554 µm) is outside the optimum range.

Fig.11 represents the surface profile at the intermediate grade of spindle speed (16500 rpm), a better value of feed rate (35 mm/min), an intermediate value of depth of cut (20 µm). The surface finish of 0.107 µm is one of the lowest attained within the experiment. Fig.11 and Fig. 12 compare the effect of feed rate at the spindle speed of 16500 rpm and DOC of 20 µm. A rise in the feed rate from 35 mm/min to 60 mm/min led to a rise in the surface finish from 0.107 µm to 0.292 µm. Fig. 11 and Fig. 13 indicate DOC's effect on the machined surface finish; application of too low DOC results in poor surface finish due to a phenomenon referred to as 'ploughing'. The surface finish dropped from 0.107 µm to 0.246 µm due to an application of the lowest depth of three 3.18207µm in situ of 20 µm. Fig. 14 shows the surface profile at high speed (23000 rpm), at which tool failure was prominent.

Chip droplets (white inclusions) on the final surface area due to gummy chip formation.

6. Conclusion and recommendation

In this paper, the HSM of Ti-6Al-4V was investigated to realize a suitable finish of the final machined surface. Chip characteristics and tool wear were investigated within the HSM process of Titanium alloy Ti-6Al-4V. Influences of input parameters, namely, spindle speed, axial DOC, and feed, were studied. A mathematical model was generated for surface roughness. The chip, tool, and surface texture of the final surface were also investigated using SEM.

The following conclusions were drawn from the work:

1. Input parameter, namely, cutting speed, plays the influential preface in cutting tool wear in HSM of Ti-6Al-4V.
2. Input parameters, namely, feed rate and DOC, have a considerable outcome, while cutting speed has a negligible effect over the average surface finish.
3. The spindle speed value of 16500 rpm (V = 104 m/min) offers the best result considering tool performance and surface finish. The average surface finish value found at this condition was 0.107 µm, which indicates that the surface will not require a further grinding operation.

4. Gumminess of the chip results in the spread of chip droplets on the machined surface, observed at higher spindle speeds above 16000 rpm (corresponding to the linear speed of 100 m/min).

7. References

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