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Micro-Milling of Ti-6Al-4V Alloy with Uncoated and cBN coated Micro-Tools

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Abstract

Micro-manufacturing of miniature components in titanium alloys is rapidly increasing due to demand in medical devices and implants, precision components, micro systems and other fields. Micro-milling is an effective process for direct fabrication of titanium components. This paper presents some experimental investigations on micro-milling of Ti-6Al-4V alloy with uncoated and cBN coated micro-end mills. Micro-milling of straight channels are conducted and surface roughness, burr formation and tool wear are measured. A performance comparison of the micro-end mills is also provided. An experimental design is utilized to analyze the influence of process parameters on the quality of fabricated channels. Multi-criteria optimization studies are also conducted to identify the process parameters which minimize the surface roughness and burr formation concurrently.

Keywords:

Micromachining, Micro tool, Titanium, Optimization

1. INTRODUCTION

The micro-milling process possesses several advantages such as ease of use, process flexibility, low set-up cost, variety in work materials and high material removal rates and is one of the most promising methods for rapid fabrication of parts with complex three dimensional features in high relative accuracy and precision [1,2]. Micro-milling is often defined as end-milling with micro-tools in diameter 1 mm or less and in some cases 500µm or less [3]. Nevertheless, such process scaling down for using end mills smaller than 1 mm results in encountering several problems related to the size effect, minimum chip thickness, poor surface quality, severe burr formation, rapid tool wear and sudden tool breakage.

In micro-milling, tool edge radius (r_β) is often between 3 µm and 10 µm and comparable to the feed per tooth or undeformed chip thickness (t_u) which is typically between 1 µm to 20 µm. This situation results in well known size effect and consequential high effective rake angles promote elastic-plastic deformations on the work material with increased difficulty in material separation, more dominant ploughing than shearing and higher than normal shear flow stress due to increasing strain rate and changing dislocation density [4].

A minimum chip thickness is required often about 0.3-0.4 times of the edge radius for chip formation [5]. No chip is formed when the undeformed chip thickness is below this minimum chip thickness during tool rotation where the undeformed chip thickness, i.e. $t_u(\phi)$, varies from zero to full feed per tooth value of f_z in micro-milling. At a particular cutter rotation angle (usually around 30°-50°), denoted as chip formation angle (ϕ_{CFA}), a minimum chip thickness is achieved and a chip begins to form as illustrated in Fig. 1. This phenomenon associated with ploughing dominated action and elastic recovery causes higher cutting forces, poor surface roughness, excessive burr formation and rapid tool wear especially at lower feed rates which makes the micro-milling process inefficient and unproductive [6].

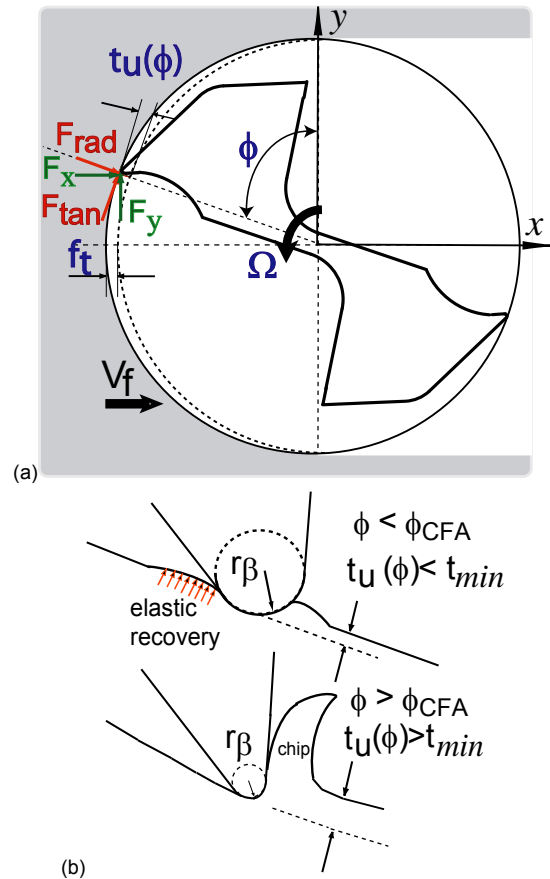


Figure 1. Micro-milling (a) full-immersion configuration and resultant force vectors and (b) minimum chip thickness where no chip or a chip formation is achieved.

Controlling the machined surface quality in micro-milling is a major challenge, since surface topography of micro-features is in a sub-micrometer order and affects functional performance of the micro-product. Burr formation can occur when micromachining hard materials due to increased tool wear. Deburring micro-features is expensive and can result in microstructural damage. Burr formation is very difficult to avoid; however, selecting appropriate process parameters and tool geometry can minimize this effect [7]. Consequently, obtaining the desired surface quality and process performance in micro-milling is considered challenging.

The titanium alloy Ti-6Al-4V offers superb strength properties, corrosion resistance and biocompatibility and is an ideal material for micro-products. However, this alloy also possesses difficulty in micromachining often related to high tool wear associated with the reactivity of titanium (Ti) with tool materials and resultant burr formation [7].

In micro-milling, fine grain carbide micro-tools fabricated mostly in tungsten carbide with a cobalt material matrix (WC/Co) are used. In these micro-tools, sharp cutting edges cannot be fabricated easily due to the limited edge strength; hence often an edge roundness with a radius between $1\mu\text{m}$ and $5\mu\text{m}$ is applied. On the other hand, influence of coatings to improve machining of titanium alloys [8] and particularly advantages of Cubic Boron Nitride (cBN) coatings in cutting of Ti-6Al-4V alloy in reducing friction and increasing wear resistance are also reported [9].

In this research, micro-tools with cBN coatings on WC/Co are experimented for possible improvements in micromachining of Ti-6Al-4V alloy. The process performance in using uncoated and cBN coated micro-tools is compared in terms of surface finish, burr formation and tool wear. In addition, a multi-criteria process optimization approach is proposed for identifying micro-milling parameters that may result in most desirable surface roughness and minimum burr formation.

2. MICRO-MILLING EXPERIMENTS

Uncoated and cBN coated tungsten carbide tools in micro-milling of Ti-6Al-4V alloy have been tested at the same dry cutting conditions. In these tests, three different nominal diameter ($\phi 635\mu\text{m}$, $\phi 508\mu\text{m}$, $\phi 381\mu\text{m}$) two-flute flat-bottom micro-tools in fine grain tungsten carbide (grain size of $0.2\mu\text{m}$ - $0.5\mu\text{m}$) manufactured by Richards Micro Tools Company have been used.

The cBN material has outstanding properties such as high hardness and wear resistance. However, the cBN material has lower toughness and is not suitable for forming inserts into complex shapes such as micro-end mills.

For this reason, cBN material is explored as a coating material for machining applications [9-11]. According to a study conducted by Bewilogua et al. [11], the sputtering process on a boron carbide (B_4C) target provides a cBN layer with a thickness around $2\mu\text{m}$ - $4\mu\text{m}$ on the tungsten carbide (WC/Co) substrate (see Fig. 2).

In this study, micro-tools are coated with the cBN material by magnetron sputtering system at the Metal Forming Center of Excellence, ATILIM University in Turkey at a deposition pressure of 3×10^{-3} Torr, heater temperature of 100°C , fixed magnetron power of 900W , argon to nitrogen gas ratio of 5/1, and at the lowest bias voltage to obtain uniform cBN coatings on tungsten carbide substrate.

All fresh micro-tools were inspected with digital microscopy and the mean edge radii of $3 \pm 0.5\mu\text{m}$ for uncoated WC/Co and $5 \pm 0.5\mu\text{m}$ for cBN coated micro-tools were measured (see Fig. 3).

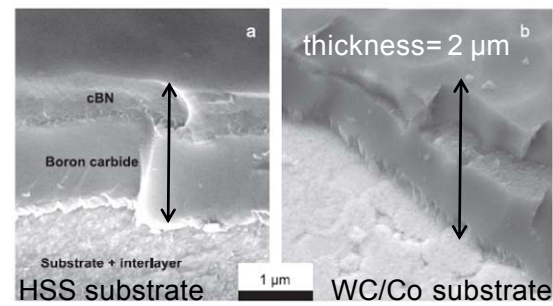
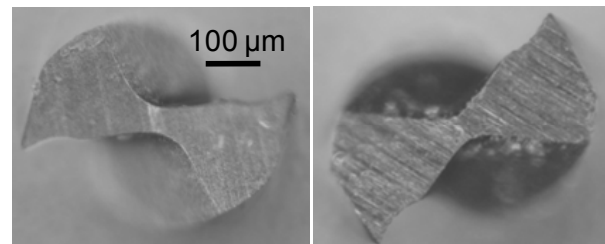


Figure 2. Images of the cBN coating layers on (a) HSS substrate and (b) WC/Co substrate (pressure= 0.3 Pa , bias voltage= -100 V) [10].



(a) cBN coated micro-tool (b) Uncoated micro-tool
Figure 3. Images of the micro-tools uncoated and coated obtained with digital optical microscopy.

An experimental set-up as shown in Fig. 4 has been prepared. A rectangular block of Ti-6Al-4V titanium alloy workpiece (36 HRC in hardness) was clamped on the fixture mounted on the table of the in-house developed micro-milling machine. The workpiece surfaces were precisely ground to insure flatness and alignment. The flat end-mill tools were mounted directly to the ceramic-bearing-electrically-driven precision spindle (NSK ASTRO-E 800) with the tool overhang of 18 mm . Full-immersion (slotting) micro-milling of 12 mm straight channels were conducted with various levels of cutting parameters.

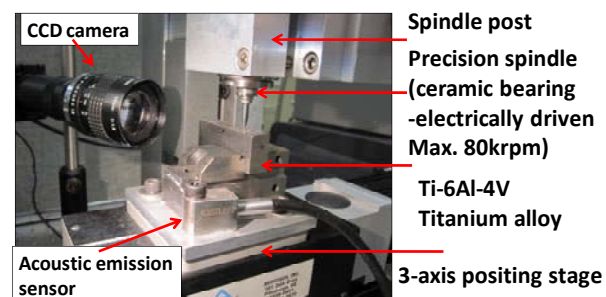


Figure 4. The experimental set-up for micro-milling.

In order to observe the quality of the channels machined and performance of the coatings, micro-milling tests were run at the cutting speeds (v_c) of $25, 42, 50, 62, 75$ and 82 m/min , nominal axial depth of cut (a_p) of $40, 70$ and $100\mu\text{m}$, and feed per tooth (f_t) of $0.5, 2.5,$ and $4.5\mu\text{m/tooth}$. An orthogonal array of L18 experimental design was utilized for statistical analysis. A total number of 18 channels were machined with each fresh/unused micro-tool. In general, long and continuous chips that are usually wrapped around the micro end mill are observed after completing most passes on the machined channels as shown in Fig. 5.

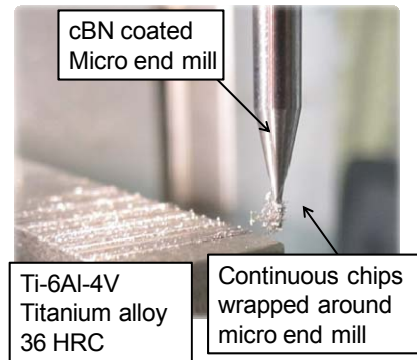


Figure 5. The image of bulk chip shapes in micro-milling.

The burr width was measured using digital optical microscopy and surface roughness is measured along the bottom of the channels using Mitutoyo SJ-400 digital surface analyzer. The burr images on the machined channels were inspected for burr width measurements as shown in Fig. 6. The burrs at entry and the exit locations of the channels were also characterized. The burrs are larger in size at the exit location of the micro end mill along the machined channels.

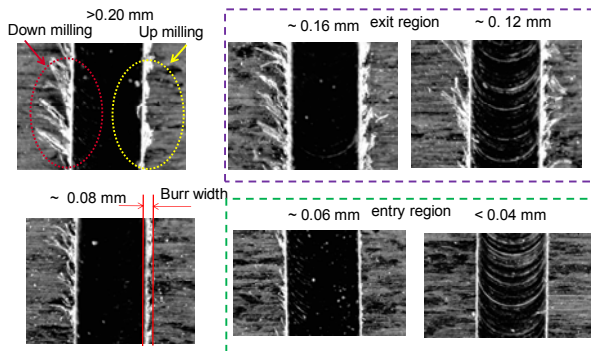


Figure 6. Examples of the measured burr widths and the burrs at entry and exit locations.

In addition, uncoated and coated micro end mills were tested for tool life. Each experimental test set (L18) was repeated until the micro-tools in $\phi 508 \mu\text{m}$ diameter are worn. Tool diameter and tool edge roundness are measured after each test set and the images with measurements are given in Figure 7 and Figure 8 respectively. It can be seen that cBN coated micro-tool ($\phi 508 \mu\text{m}$) has outperformed uncoated WC/Co micro-tool in terms of tool wear.

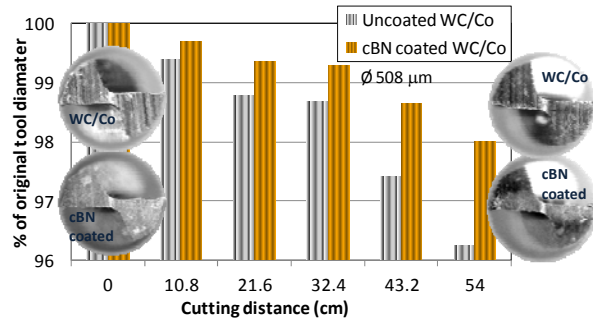


Figure 7. Measured change in the tool diameter due to the tool wear.

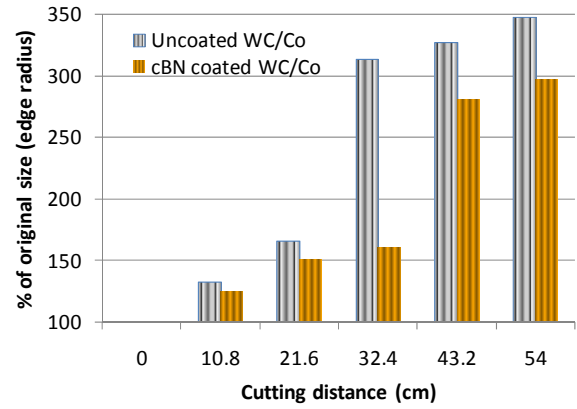


Figure 8. Increase in tool edge roundness after micro-milling (original micro-tool diameter is around $\phi 508 \mu\text{m}$).

Test results showing the effects of cutting speed, feed, and axial depth of cut are summarized in the following sections. In these figures, each cutting condition tested has been represented with a marker and the trend lines are fitted to these test conditions for each micro-tool (WC/Co- $\phi 381 \mu\text{m}$, cBNcoated- $\phi 381 \mu\text{m}$, WC/Co- $\phi 508 \mu\text{m}$, cBNcoated- $\phi 508 \mu\text{m}$ and WC/Co- $\phi 635 \mu\text{m}$).

3. INFLUENCE OF CUTTING SPEED ON SURFACE ROUGHNESS AND BURR WIDTH

Increasing the cutting speed reduced surface roughness for micro-tools in diameter of 635 and 508 μm , where as micro-tools in $\phi 381 \mu\text{m}$ showed opposite trend as shown in Figure 9. This is seen as an interesting observation and it is perhaps related to decreasing process performance as the micro-tool diameter gets smaller.

Increased cutting speed also increased burr formation. Burr formation is seen as a result of increasing tool wear and ploughing dominated cutting action. However, better average surface roughness values and lower burr width values were obtained with cBN coated micro-tools in all micro-tool sizes tested as shown in Figure 10. This is perhaps due to improved tool-chip contact friction conditions with the coatings. The authors have also conducted Finite Element modeling and simulations in order to reveal the effects of cBN coatings in forces, temperatures, and tool wear rates in micro-milling. However, these FE modelling studies are not included in the investigations presented in this paper.

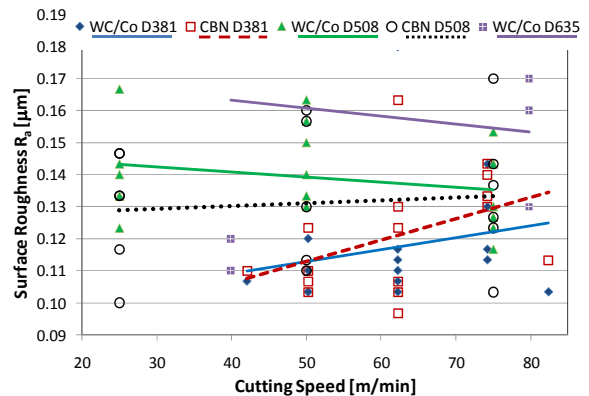


Figure 9. Effect of cutting speed on surface roughness.

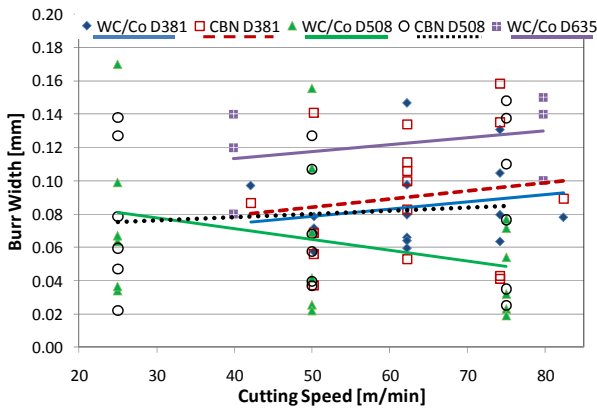


Figure 10. Effect of cutting speed on burr width.

4. INFLUENCE OF FEED RATE ON SURFACE ROUGHNESS AND BURR WIDTH

It is found that the effect of feed is significant on the burr formation but less on the average surface roughness as shown in Figure 11. It is generally accepted that due to size effect and ploughing dominated cutting, very low feed rates result in poor surface roughness values in contrast to conventional scale milling processes. In addition, it is also seen that increased feed reduces burr width as shown in Figure 12.

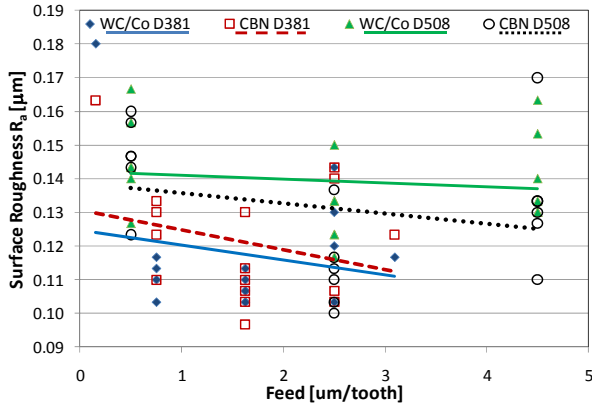


Figure 11. Effect of feed rate on surface roughness.

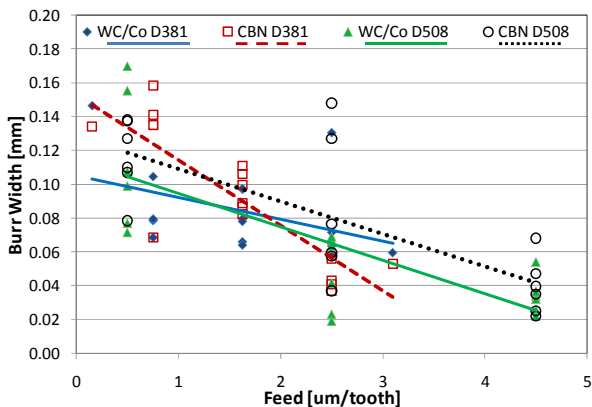


Figure 12. Effect of feed rate on burr width.

On the other hand, there is a limit in increasing the feed rate associated with the limited fracture strength and toughness of the tungsten carbide micro-tool. Increasing chip load on

the micro-tool more likely would cause an undetectable tool breakage and unrecoverable damage on the micro-machined geometrical feature.

5. INFLUENCE OF AXIAL DEPTH OF CUT ON SURFACE ROUGHNESS AND BURR WIDTH

The tests have also revealed that the effects of depth of cut on surface roughness and burr width would indicate that a medium level of depth of cut is more favourable as shown in Figure 13.

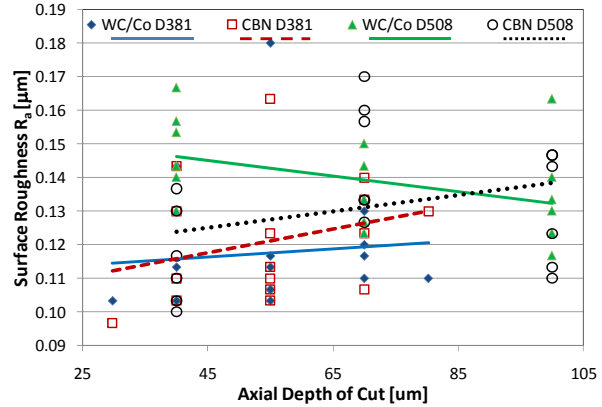


Figure 13. Effect of depth of cut on surface roughness.

With one exception all test results concurred that the increasing axial depth of cut would slightly increase surface roughness but not affect burr formation and burr width as shown in Figure 14.

It should be noted that the micro-milling tests have been replicated 2 or 3 times and the measured surface roughness and burr with values are the averages of multiple readings along a single channel and combined averages of these averages for replicated cutting conditions. Therefore, measurement inaccuracies and uncertainties are well normalized and minimized by including a large set of test data for almost all of the micro-milling tests presented in this work.

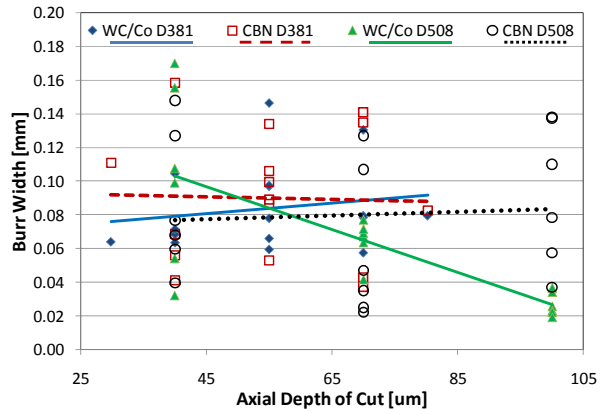


Figure 14. Effect of depth of cut on burr width.

6. PROCESS OPTIMIZATION

In order to improve the surface quality, both surface roughness and burr formation should be considered simultaneously. Since both are process parameter-dependent, optimality of one may result in an unacceptable

outcome of another. Therefore, another objective of this work is to optimize the process parameters in order to improve the surface quality in terms of surface roughness and burr formation.

Genetic and evolutionary multi-objective optimization has been applied to materials processing field successfully. Particularly, particle swarm optimization can be used for real world multi-objective optimization problems, since it provides fast convergence as depicted in single objective optimization problems [12]. Therefore, similar to the previous work in [13,14] optimization of micro-milling parameters using regression models and particle swarm optimization is also conducted in this paper. The details of the multi-objective PSO method are given in [12-14].

At first, a second order regression model is used to establish input-output relationship between response and controllable variables efficiently that takes the generic form.

$$y = \beta_0 + \sum_{i=1}^3 \beta_i x_i + \sum_{i=1}^2 \beta_{ij} x_i x_j + \sum_{i=1}^3 \beta_{ii} x_i^2 + \varepsilon \quad (1)$$

Where y = surface roughness, R_a [μm] or burr width [mm], $x_1 = v_c$ [m/min], $x_2 = f_t$ [$\mu\text{m}/\text{tooth}$], and $x_3 = a_p$ [μm].

In addition, the optimization problem with two objective functions can be formulated as following:

$$\begin{aligned} & \text{minimize } \{f(x), g(x)\} & (2) \\ & \text{s.t. } f(x) \leq b_1 \text{ and } g(x) \leq b_2 \\ & \text{where } x \in X. \end{aligned}$$

In this formulation, micro-milling process parameters are represented with the vector of $x = [x_1, x_2, \dots, x_n]$ ($x_1 = v_c$, $x_2 = f_t$, $x_3 = a_p$). X represents the solution space with all feasible values for the micro-milling process parameters.

The regression models are utilized in formulating objective functions. The function $f(x)$ represents the objective function for surface roughness and the function $g(x)$ represents the objective function for burr width.

In the case of micro-milling process, the optimization problem is defined for micro-milling process parameters with multiple objectives. Decision variables such as cutting speed, axial depth of cut per pass, and feed per tooth are constrained within the ranges of the experimental conditions.

The simulations are run by using a particle swarm population of 200 and a maximum number of 300 iterations with varying learning rates. After obtaining the best particle values in each iteration of the simulation, the particles are plotted in a two-dimensional objective space for viewing. This procedure is repeated until a clear Pareto frontier forms. The simulations usually take less than 20 minutes in a PC with Intel Pentium Dual 2.40 GHz processor. Therefore, the Pareto frontiers of the non-dominated solution sets are obtained by using this multi-objective PSO method.

The Pareto frontier of the non-dominated solutions for two objective functions minimizing surface roughness, $\min(R_a)$, and minimizing burr width, $\min(\text{Burr})$, are presented for micro-tool with diameters of $\varnothing 381 \mu\text{m}$ and $\varnothing 508 \mu\text{m}$ as shown in Figure 15 and Figure 16 respectively.

Micro-milling process parameters that minimize both burr width and surface roughness for uncoated micro-tool with diameter of $\varnothing 381 \mu\text{m}$ are identified along the lowest cutting speed tested (48 m/min) and at the lowest axial depth of cut (40 μm) in the solution (decision variable) space (see Fig. 15b). Whereas, optimum process parameters for the cBN coated micro-tool were able to achieve lower burr width and surface roughness values and mostly identified along the highest feed rate (2.5 $\mu\text{m}/\text{tooth}$)

and the lowest cutting speed (48 m/min) in the solution (decision variable) space.

Optimal micro-milling parameters for the micro-tool with a diameter of $\varnothing 508 \mu\text{m}$ were found at the lowest cutting speed and the highest axial depth of cut (100 μm) for the cBN coated micro-tool and at the highest cutting speed and near the highest axial depth of cut for uncoated micro-tool in the solution (decision variable) space (see Fig. 16b). These differences in the optimal process parameters might be related to the higher stiffness of the micro-end mill at larger diameters favouring higher axial depth of cuts. However, overall improvements in the achieved burr width and surface roughness values with the use of cBN coated micro-tools remain as the prime outcome of these investigations.

7. CONCLUSIONS

In this research, micro-tools with cBN coatings are experimented on tungsten carbide for possible improvements in micromachining of Ti-6Al-4V alloy. The performance of the process using uncoated and cBN coated micro-tools is compared in terms of surface finish, burr formation and tool wear. The results reveal improved process performance when using cBN coated micro-end mills in micromachining of Ti-6Al-4V. Therefore, it can be concluded that the cBN coatings on micro-end mills improve the micro-milling process performance.

8. ACKNOWLEDGEMENTS

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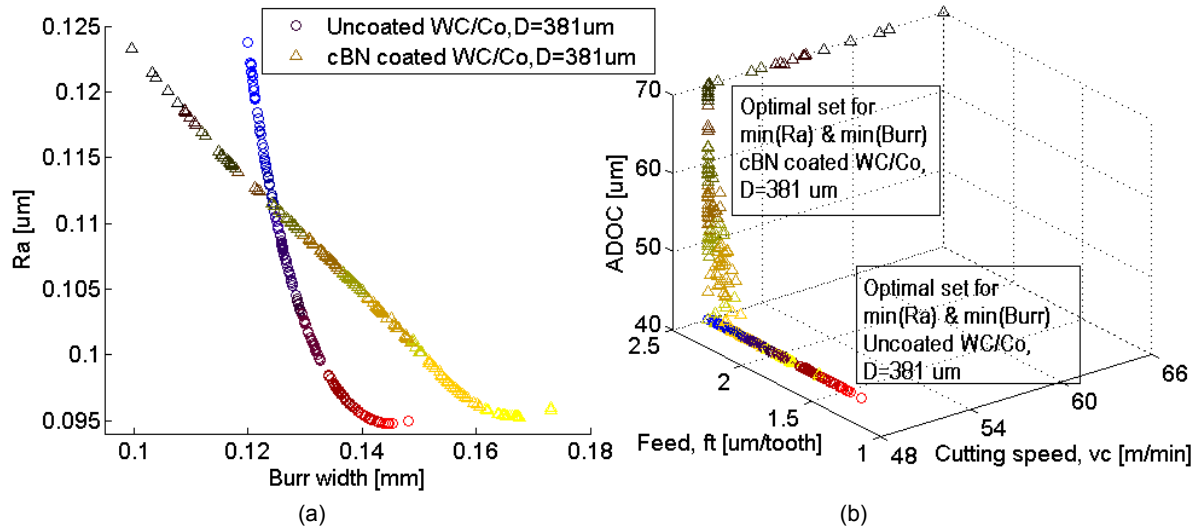


Figure 15. Optimal micro-milling parameters for micro-tool with $\varnothing 381 \mu\text{m}$ represented in (a) objective function space and (b) solution (decision variable) space.

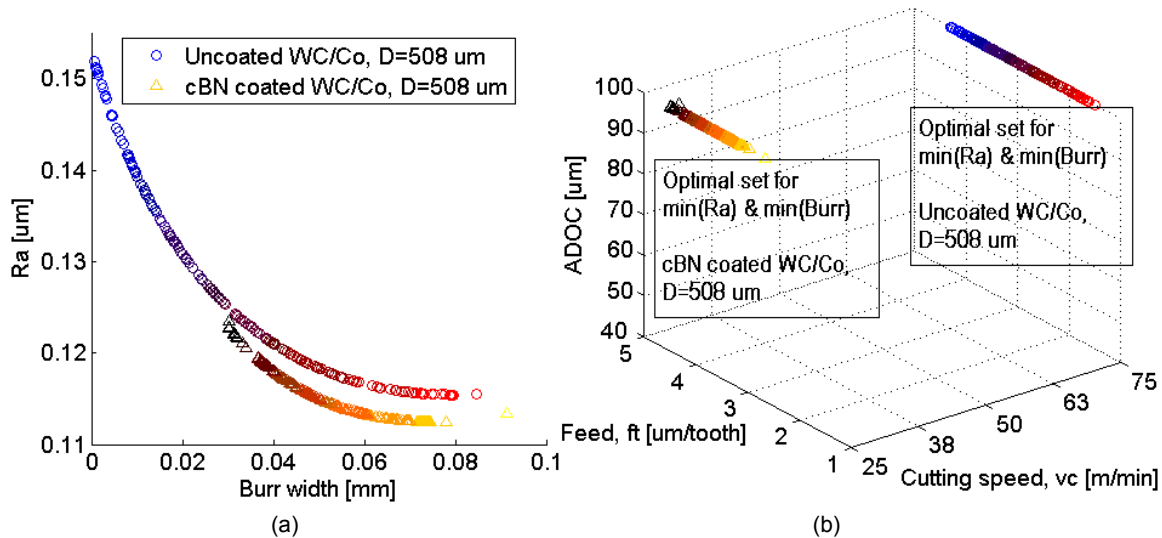


Figure 16. Optimal micro-milling parameters for micro-tool with $\varnothing 508 \mu\text{m}$ represented in (a) objective function space and (b) solution (decision variable) space.