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Research Article

Efficiency investigations of textured cutting tools in orthogonal cutting of Ti6Al4V alloy: a numerical approach

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Abstract

This paper investigates efficiency of micro-textured cutting tools in dry orthogonal turning of Ti6Al4V alloy using 2D numerical analysis. For this purpose, micro-grooves at different sizes were generated on rake face of cutting tools. Then, orthogonal cutting simulations were conducted using different tool rake angle values. Contact length at tool-chip interface, cutting force and force ratio results were evaluated focusing on performance of micro grooves. The aim was to improve process efficiency and minimize negative environmental impacts by contributing knowledge in development of textured cutting tools. The simulation results revealed that decreased forces, force ratio and contact length is possible with use of textured cutting tools. However, improper selection of texture parameters may cause adverse effects such as increased friction. Accordingly, efficiency of micro-grooves relies on both, groove size and rake angle.

Keywords: Orthogonal machining; Ti6Al4V; textured tool; machinability; FEM.

1. Introduction

Titanium and its alloys are extensively employed in various components of aerospace engine and body parts owing to their fracture and corrosion resistance and high strength to weight ratio. Considering aerospace applications, Ti6Al4V alloy is the most widely used and studied one among the titanium alloys [1]. Despite its attractive benefits, poor machinability of this alloy have been a leading problem in manufacturing process [2]. Inherent properties of this material lead to high cutting loads, high cutting temperatures, severe adhesion, and premature tool failure. These properties are low thermal conductivity, high specific heat and high ductility [3]. In the last century, application of high amounts of cutting coolants and frequent change of cutting tools were the commonly applied methods to improve machinability rate. Unfortunately, neither of these methods are environmentally friendly. This has driven researchers to introduce new methods such as dry or MQL cutting in the last two decades.

Surface texturing of cutting tools has positive influences on reducing cutting temperatures, cutting loads and tool wear. Su et al. [4] investigated machinability performance of micro-textured PCD cutting tools in dry machining of Ti6Al4V alloy. They reported that, compared to non-textured tool, micro-grooved cutting tools led to lower cutting forces, friction coefficient and contact length at tool-chip interface. As they conducted turning experiments in dry cutting conditions, the authors attributed the improvements to decreased actual tool-chip contact length. Arilkirubakaran et al. [5] studied effects of surface texturing generated on the rake face of carbide cutting tools when turning Ti6Al4V alloy. Their results showed that numerical simulation of the study accurately predicted investigated parameters. They also reported that improvements in cutting force, contact area and chip shape is possible with use of textured tools. Obikawa et al. [6] fabricated four different texture patterns (perpendicular, parallel, pit and dot) on rake face of the carbide cutting tools. They found that parallel and dot type micro-textures were more effective in reducing friction force and coefficient of friction when orthogonally machining aluminum alloy Al6061-T6. Xing et al. [7] reported that, it is possible to achieve improved frictional behavior and machinability characteristics with textured Al_2O_3 ceramic cutting tools when turning AISI 1045 hardened steel. Ma et al. [8] conducted a numerical study to investigate performance of micro-hole textured cutting tools in dry machining of Ti6Al4V alloy. According to their results, micro-holes were effective in reducing cutting force components. Geometric parameters of micro-holes have a direct influence on machinability responses. These results show that, surface texturing of cutting tools offers improvements in key aspects of sustainable manufacturing concerns of Ti6Al4V alloy.

The aim of present study is to investigate effects of texture size and tool rake angle variation on machinability performance during orthogonal turning of Ti6Al4V alloy using surface textured cutting tools. Simulations were conducted using commercial FE software. Previous work on surface texturing of cutting tools has only focused on size, position and orientation of texture geometries. To best of authors' knowledge, effects of cutting tool's geometry on performance of surface texturing have not been investigated.

2. Simulation procedure

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FE model of the orthogonal cutting process was developed using Deform 2D© software [9], where thermo-mechanical analysis was performed with plane strain assumption. The simulations included an elasto-viscoplastic workpiece and a rigid cutting tool. Constant shear model was implemented with a friction factor of μ = 0.6. Heat conduction coefficient (h) of 50 kW m^{-2} K^{-1} was used. Finer mesh size in regions close to cutting interface was ensured in order to yield more accurate simulation results. Each simulation was carried out until a cutting length of 5 mm was completed.

2.1. Workpiece and cutting tool

The workpiece material was Ti6Al4V alloy and the mechanical and thermal properties of the workpiece employed in FE simulation are given as follows: density of ρ = 4430 kg m^{-3}, Young's modulus of E = 117 GPa (at 21 ºC), Poisson's ratio of v = 0.31, and thermal expansion coefficient of α = 9.1 10^{-6} [9]. In order to simulate thermo-visco-plastic behavior of the material, Johnson-Cook constitutive material model [10] is used which can be expresses as follows:

$$\sigma = [A + B\mathcal{E}^n] + \left[1 + Cln\frac{\dot{\mathcal{E}}}{\dot{\mathcal{E}}_0}\right][1 - (\frac{T - T_0}{T_{melt} - T_0})^m] \quad (1)$$

where the σ is the equivalent flow stress, A (782.7 MPa) is the initial yield stress, B (498.4 MPa) is the hardening modulus, C (0.028) is the strain rate dependency coefficient, $\dot{\mathcal{E}}_0$ (10^{-5} s^{-1}) is the reference strain rate, n (0.28) is the work hardening exponent, T_0 (20 °C) is the ambient temperature, T_{melt} (1600 °C) is the melting temperature, and m (1) is the thermal softening coefficient [11]. The dimensions of the workpiece was 8 mm in length and 1 mm in height. The resulting mesh was built from 10000 elements and 10202 nodes.

Cutting tool material was uncoated carbide. Mechanical and thermal properties of the cutting tool were taken from software library [9]. It was modelled as a rigid geometry and meshed with 7500 elements and 7729 nodes.

The microgrooves were generated on the rake face of the cutting tool perpendicular to chip flow. This kind of texture orientation was reported to be more effective when machining titatinum alloys [12]. The micro grooves were square shape. Three different textured tools were modelled at groove size values of 10, 50 and 100 µm (see Fig. 1). Groove spacing distances of all tools are equal to groove size of the related tool. It should be noted that all the sharp edges were rounded with radii value of 5 µm in order to achieve more accurate numerical analysis.

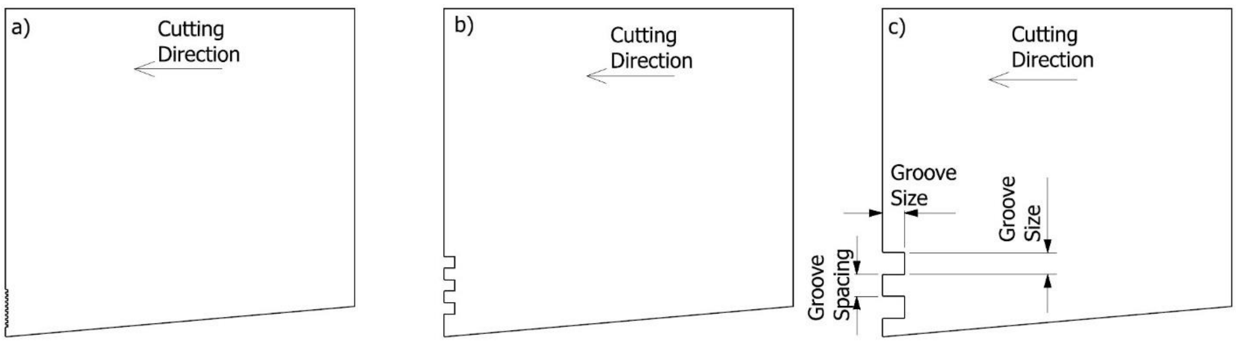

Figure 1. Investigated textured tools at groove size values of a) 10 µm b) 50 µm c) 100 µm

2.2. Simulation and validation

The simulations were run at constant cutting parameters (cutting speed of 120 m/min and feedrate of 1 mm/rev) and various rake angle values (γ = -5°, 0°, 5°, 10°) for each investigated tool (three textured tools and one regular tool). The cutting speed is ensured by keeping the cutting tool steady and moving the workpiece towards the cutting tool.

Özel et al. [13] conducted experiments and simulations for longitudinal turning of Ti6Al4V alloy with cemented carbide inserts under same cutting parameters of the present study at rake angle of 0°. Validation of the present model was ensured by comparing results of present model and experimental results reported by Özel et al. [13]. The comparison revealed that FE model can predict main cutting force (F_v) and feed force (F_f) within 7% and 8% error rates, respectively.

3. Results and discussion

The results are discussed in terms of main cutting force , feed force, force ratio and contact length. Performance of textured cutting tools were evaluated with comparison to that of regular tool under investigated condition. F_v and F_f were calculated as mean force value of the related simulation.

3.1. Cutting forces

Comparisons of cutting force components against groove size are showed in Fig. 2, separately for each investigated rake angle value. In order to assess effects of both force components clearly, F_f columns were presented as a secondary axis. According to these results, main cutting force of all investigated groove sized tools are lower than that of regular tool. Compared to regular tool, maximum decrease of 7% in main cutting force was achieved when groove size of 10 μm at rake angle of $\gamma = 0°$ or groove size of 50 μm at rake angle of $\gamma = 5°$ was applied. Regarding main cutting force, the results also suggest that, groove size of 50 μm was more effective in zero and positive rake angle values compared to negative rake angle. Same condition is valid for groove size of 100 μm. Small grove size performed in a more efficient way at zero rake angle.

Groove size of 10 and 50 μm led to decreased feed force under all rake angle values. Maximum F_f decrease of 50% was achieved when 10 μm groove size and rake angle of $\gamma = 10°$ was applied. Similarly, maximum F_f improvements of groove sizes of 50 and 100 μm were observed when the rake angle is 10°.

Overall, combination of smaller groove size and zero rake angle was the most effective combination for decreasing main cutting force. We are of the opinion that formation of less chip residue led to more reduction in cutting force. Because chip residue formation, which was more prominent at larger grove sizes, results in increased resistance to chip flow with increased friction. Larger groove sizes were more effective at large rake angle values for decreasing feed forces. These results are in a good agreement with the numerical studies conducted by Kaya et al. [14] and Chen et al. [15].

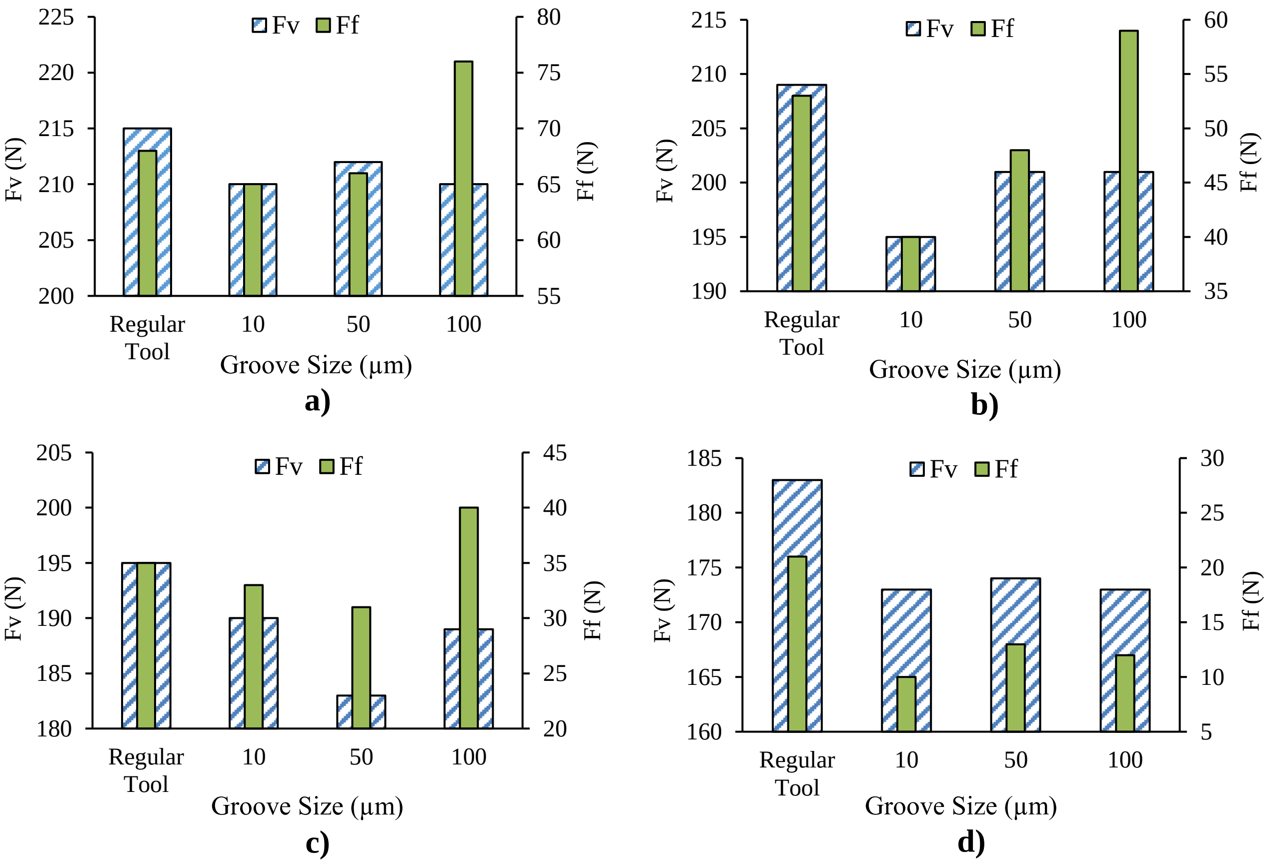

Figure 2. Cutting force results against investigated groove size values for various rake angle values: a) γ=-5° b) γ=0° c) γ=5° d) γ=10°

3.3. Force ratio

Force ratio is calculated as F_f divided by F_v. It was employed for predicting tool wear and yielded a good agreement with experimental results [16]. Determination of optimum cutting parameters and insert coating when cutting Inconel 718 was successfully conducted taking the cutting ratio into consideration by [17]. Decrease of force ratio is favored for lower friction. For instance, at the rake angle of 0°, force ratio corresponds to mean friction coefficient at the tool chip interface according to analytical modelling of chip removal mechanics of metal cutting [18].

Force ratio results at investigated simulation parameters are presented in Fig. 3. According to these results, it is possible to achieve lower force ratio values compared to regular tool in all investigated textured tool conditions except for groove size 100 μm. At the rake angle of 0°, where force ratio is theoretically equal to mean friction coefficient, minimum force ratio was obtained at groove size of 10 μm. Furthermore, at that rake angle, increase of groove size led to increased force ratio. These results suggest that it is possible to achieve improved frictional behaviors with use of textured cutting tools.

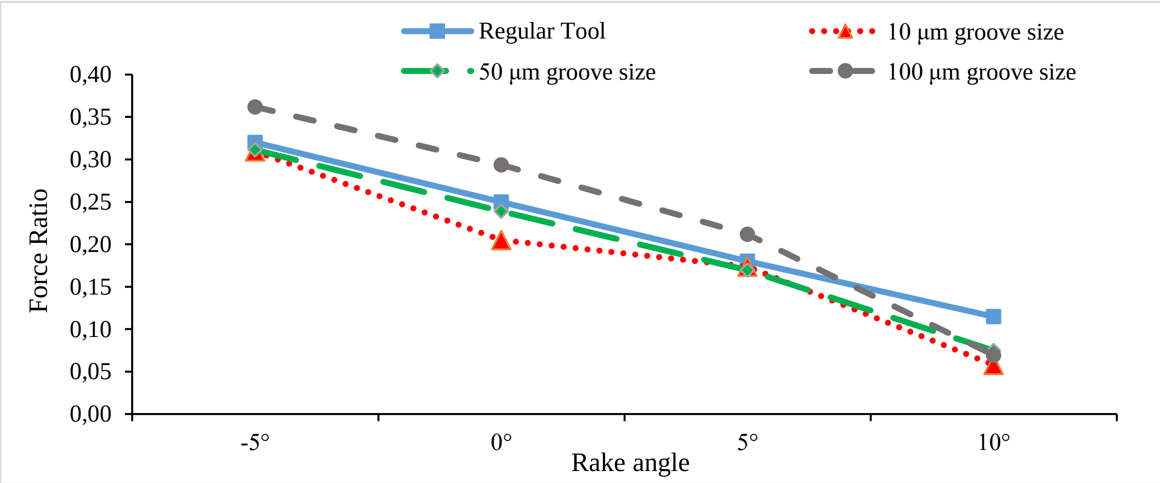

Figure 3. Variations of force ratio with rake angle for various groove size values

3.4. Contact length

The variations of contact length with rake angle for all investigated tools are shown in Fig. 4. The actual contact length measurements were conducted by measuring the contact distance along the rake face. In this method, not all the groove width within of the contact interface were subtracted from total contact length. Instead, only the part of the groove width in which there is no chip residue formation present was subtracted from contact length. Because, chip residue penetrated inside of the grooves causes a contact interface with walls and floors of the grooves.

Compared to regular tool, decreased actual contact length was observed under all investigated cases. Maximum reduction of 20% was observed when 100 µm groove size was applied at rake angle of 5°. Similar to cutting forces, contact length responses of larger groove sizes and small grove size were different at same rake angle values.

Groove size of 10 µm yielded better results at smaller rake angle values, whereas larger groove sizes resulted in less contact length at positive rake angle value of 5°. It is proposed that this phenomenon was originated from the interaction between softened cut chip and groove geometry under high cutting pressures. The bending moment on cut chip increases with increased groove width. This makes penetration of cut chip into grooves easier. When positive rake angle is employed, less normal stress component is applied on rake face. This results in less chip residue formation inside of the grooves, and in turn lower contact length. Conversely, when negative rake angle is employed, normal pressure on rake face increases and cut chip becomes more prone to penetrate into grooves, especially around the region close to cutting edge. Accordingly, there is a strong correlation (r = 0.97) between groove size and contact length when rake angle is -5°. The results suggest that application of smaller groove sizes might be a good solution in this case. In another numerical study, formation of chip residues was reported by Ma et al. [19]. The scholars attributed the different tribological behaviors of textured cutting tools to variation of groove size.

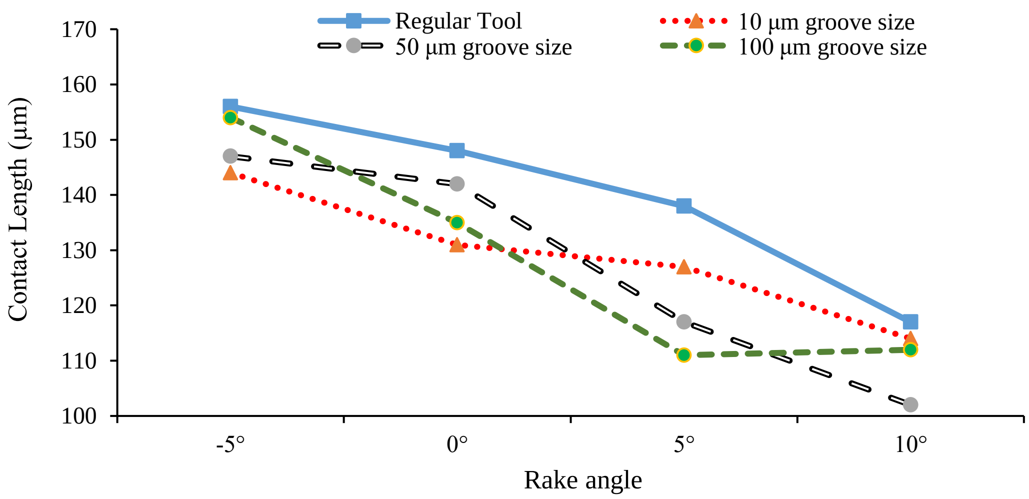

Figure 4. Variations of contact length with rake angle for various groove size values

4. Conclusions

This paper presented effects of groove size and rake angle of textured cutting tools, in dry orthogonal turning of Ti6Al4V alloy in numerical analysis environment. Development of numerical model and machining simulations were carried out using 2D FE software. Cutting force components, force ratio and contact length of textured tools were evaluated and compared with those of non-textured tool.

The results support the idea that improvements in cutting forces, frictional behavior and contact length are possible with application of surface texturing on cutting tools. Groove size had a direct influence on machinability performance. Furthermore, in order to achieve upmost efficiency, tool geometry, more specifically rake angle, should also be taken into account when determining groove size. The evidence from this study suggests that, through application of textured cutting tools in machining of Ti6Al4V alloy, ensuring better tribological conditions is possible. Accordingly, improvements in cutting energy and tool life look very likely. To further this research, the authors plan to conduct experimental machining studies using similar parameters of this simulation.

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