INVESTIGATIONS ON THE ORTHOGONAL CUTTING BEHAVIOR OF TI6AL4V WITH MICRO-TEXTURED TOOL GEOMETRIES USING FINITE ELEMENT METHOD

[1]EREN KAYA, [2]FATIH CAKIR, [3]YALCIN OZDEMIR

[1,3]Anadolu University, Department of Mechanical Engineering
[2]Anadolu University, Vocational School of Transportation
E-mail: [1]erenkaya@anadolu.edu.tr

Abstract- Titanium and its alloys possesses superior properties such as high strength/weight ratio and corrosion resistance, however machinability of these alloys are considered to be poor. In order to overcome this disadvantage, improvements in machining processes, cutting tool materials and geometries have been carried out. The purpose of this study is to investigate the influence of textured cutting tools on machining performance of Ti6Al4V. For this purpose, a Finite Element Method model is developed regarding the conditions defined in literature and it is validated. Two different texture geometries are modelled through this model. Orthogonal cutting simulation is performed for four different rake angle values. Resulting cutting force, chip length and cutting temperature values are compared with untextured tool results. It is found that that textured geometry with 10 µm groove depth resulted in a 31% reduction in cutting force, while the tool with 95 µm groove depth did not yield a significant difference. The results show that using a textured tool geometry is an effective method for improving machining performance;however, texture geometry and machining parameters should be selected carefully.

Keywords- Titanium Alloy, Textured Tool, Grooved Tool, Machining Simulation

I. INTRODUCTION

Titanium alloys possesses excellent strength, good fracture and corrosionresistance characteristics. However, machining of Ti6Al4V has been known to be very challenging, due to its strength at elevated temperatures, low thermal conductivity, high ductility and chemical affinity with cutting tool materials. Accelerated tool wear is often reported in machining of these alloys [1].

Surface texture on cutting tools has been widely employed in order to yield more favorable tribological conditions.In fabrication process of textured geometry, mostly applied methods are fiber laser machining[1], wire cut electrical discharge machining, femtosecond laser machining[2], and micro grinding[3]. Kawasegi et al. [2] investigated effects of nanoscale and microscale textures on cutting behaviors of Al alloy. They reported decreased cutting forces and friction behavior in machining with textured carbide tools. Su et al.[1]studied effects of micro-grooved PCD tools in dry cutting of Ti6Al4V. They concluded that friction behaviors can be significantly improved and lower cutting forces can be achieved with textured PCD tools, probably due to reduced tool-chip contact length. Qi et al. [4] investigated orthogonal machining of Ti6Al4V with micro-textured carbide tools under minimum quantity lubrication, cryogenic and dry cutting conditions. It was reported that, cutting forces, friction, surface temperature and tool wear was significantly improved with textured tools. The cutting performance was better when the grooves were perpendicular to chip flow direction.

Finite Element Method (FEM) has been widely employed in simulation of machining process due to high prediction accuracy and savings on experimental cost. Chen et al. [5] conducted a FEM simulation study towards understanding effects of tool-texture rate in orthogonal cutting of Ti6Al4V and concluded that increased texture rate resulted in decreased cutting force and temperature under all conditions. Ma et al. [6] investigated effects of microgroove geometry in dry machining of Ti6Al4V using 3D FEM study. In another study, Ma et al. [7] conducted a 3D FEM study on influence of microhole textured cutting tools on performance in dry machining of Ti6Al4V.

In this study, effects of rake angle in orthogonal machining of Ti6Al4V on cutting force, feed forces and tool-chip contact lengthare investigated, using two different textured tools. To best of our knowledge there is no previous study investigating the effects of rake angleon machinability with micro-textured tools. The authors aim to contribute to research, design and application of the textured cutting tools.

II. FEM SIMULATION PROCEDURE

Fem model of the orthogonal process was developed using Deform 2D© FEM software, where plane strain assumption together with thermo-mechanical analysiswas performed[8]. Constant shear model was implemented with a constant friction factor of μ=0.7.Fig. 1 shows, initial mesh structure of the tool and workpiece at a rake angle of 5 degree. Each simulation is carried out until a cutting time of 1 ms is completed, which is equal to a cutting length of 2 mm. The validation of the FEM model is ensured with an experimentally validated simulation study and explained in Section 3 in detail.

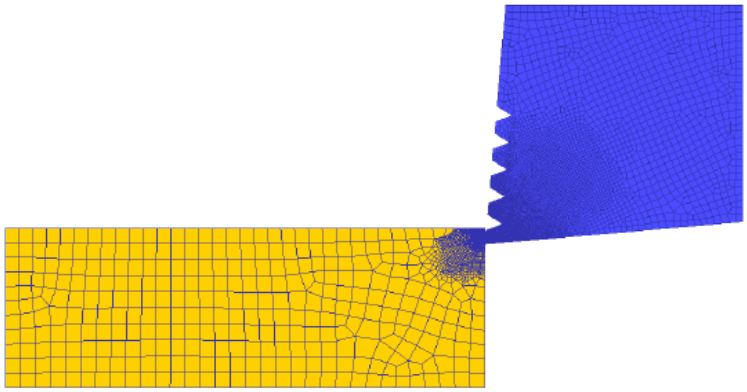


Fig. 1 Initial mesh structure of the workpiece and grooved tool

2.1 Workpiece

The workpiece material is Ti6Al4V and the mechanical and thermal properties of the workpieceemployed 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 ν=0.31, and thermal expansion coefficient of α=9.1 10^{-6}[8].Machining process involves larger strains, very high strain rates and high temperatures. To simulate the therme-visco plastic behavior of the material under these variables, the Johnson-Cook constitutive material model is used, which can be expresses as follows[9]:

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

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, $\dot{\varepsilon}_0$(1 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 [10].The workpieceis meshed with 8000 isoparametric quadrilateral elements. The mesh density at cutting region (upper and left part) was very fine to obtain accurate results. The workpiece dimensions are 3 mm in length and 1 mm in height.

2.2. Cutting Tool

The cutting tool material is WC cemented carbide. Mechanical and physical properties of the cutting tool are given in Table 1. The cutting tool, modelled as a rigid geometry, ismeshed with 7500 quadrilateral elements to obtain accurate groove geometries. The mesh density of the tool tip (cutting region) is kept finer to ensure a more accurate simulation.

Notation	Property	Value
E	*Young's modulus*	650GPa
ρ	*Density*	15,700 kg m^{-3}
ν	*Poisson's ratio*	0.25
α	*Thermal expansion coefficient*	9.1 10^{-6}
c	*Heat capacity*	15 J/ C
K	*Thermal conductivity*	59 W m^{-1} C^{-1}

Table 1Mechanical and physical properties of WC tool[8]

The microgrooves re designed on the rake face of the cutting tool perpendicular to chip flow. This kind of texture direction was reported to be more effective in terms of tool wear and cutting force[2]. Two different groove geometries are designed; namely, T1 with smaller grooves, and T2 with larger grooves. Side view of the grooved tools are show in Fig. 2.

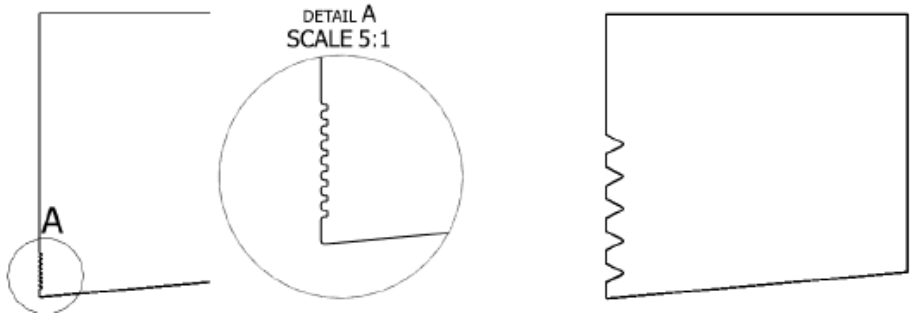


Fig.2 Side view of the grooved tools: a) T1 with small groove size b) T2 large groove size

The simulations are conducted using three different cutting tools; untextured tool, T1, and T2. Various texture patterns and dimension values were investigatedby studies[1-3, 6]. The texture geometries of the cutting tools are designedconsideringthose studies.Thedetermined geometrical parameters of the grooved tools are given in Table 2. It should be noted that all the sharp edges are rounded of using circular curves with radii value of 5 µm.

Microgroove parameter	T1	T2
Edgedistance of the first groove(μm)	45	85
Groove upper width (μm)	10	100
Groove lower width (μm)	10	0 *(Triangular groove)*
Groove depth (μm)	10	95
Groove pitch (μm)	25	170
Edge radius	5	5

Table 2Design parameters of the microgrooves for T1 and T2

III. VALIDATION AND SIMULATION

Ozel et al. [11]conducted experiments and simulations on longitudinal turning of Ti6Al4V with cemented carbide inserts under orthogonal machining conditions . They have validated the simulation design using same cutting parameters with experimentaltests (*Vc*=120 m/min, f=0.1 mm/rev, γ=0^0, 5^o), according to cutting forces and chip thickness results. In presentstudy, FEM simulation design parameters using untextured insert are validated with the reference experimental study with prediction error values for cutting force and chip thickness of %7 and %8, respectively.

Simulation process completed with investigation of four different rake angle values (γ=0°,-5°, 5º, 15°) for each insert geometry (T1, T2, untextured), which makes a total of 12 simulations. The clearance angle is kept constant at 5°. Employed cutting speed and feed rate values are *Vc*=120 m/min and *f*=0.1 mm/rev, respectively.

IV. RESULTS AND DISCUSSION

Fig. 3 shows the main cutting force (F_x) results of T1, T2 and untextured tool at rake angle of 0º, throughout full cutting length. Compared to untextured tool, both T1 and T2 curves display more irregular trend with one distinct maximum and minimum points. However, after some cutting time, they display a steady trend. There is a decrease of required cutting force of T1 and T2 after 0.2 and 0.25 ms of the cutting time, respectively. This behavior is attributed to first arrival of the cut chip to the grooves.After chip flow reaches the last groove on its path, the cutting curve follows a steady path.

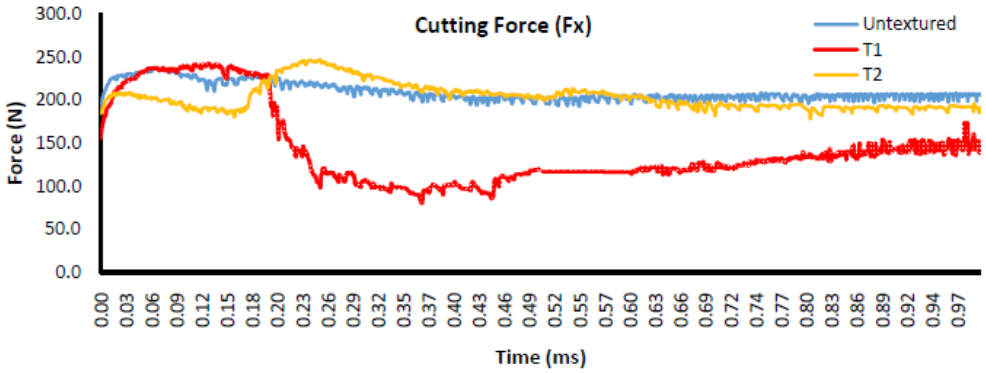


Fig. 3Main cutting force curve behavior of the micro-textured and untextured tools at rake angle of 0°

Time domain averaged cutting forces (Fx) and feed forces (Fy) of all investigated tools under all rake angles are shown in Fig. 4 and Fig. 5, respectively. It is evident from Fig. 4 that, textured tools required less cutting force under all investigated conditions. Cutting with T1 yielded least cutting force under all conditions. The cutting force difference between untextured tool and T1 was maximum at rake angle of 0° (31%) and minimum at 10º (5%). It should also be noted that cutting force of the T1 at a rake angle of 10° is, surprisingly, larger than that of at a rake angle of 5º. The difference between T2 and untextured tool did not significantly affected from rake angle and varied between 2-3%.

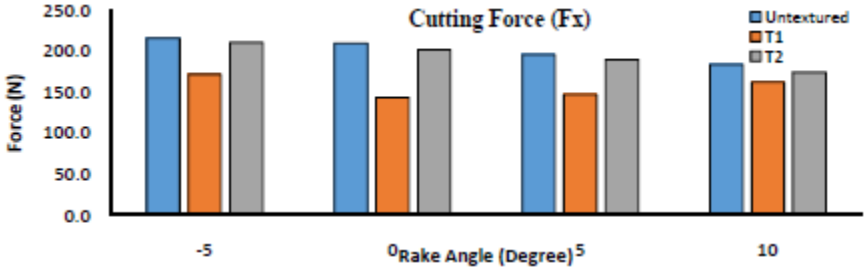


Fig. 4Influence of tool micro texture on main cutting forces under different rake angles

According to Fig 5, feed forces of the textured tools are not always less than untextured tool. The feed force requirement of the T1 was least at rake angle of 5º, with 57% reduction compared to untextured tool. While, at rake angle of 10°, it was larger than untextured tool and T2. Except the case of rake angle

of 10º, T2 yielded largest feed forces compared to both T1 and untextured tool. It can be concluded that, larger groove size leads to unfavorable results regarding feed force results.

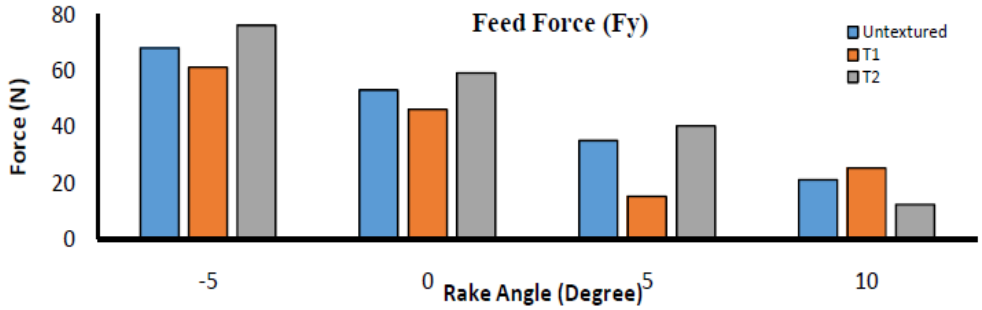


Fig5Influence of tool micro texture on feed forces under different rake angles

Fig. 6 shows the effective chip contact length at the rake face under all simulated conditions.Evidently, contact length is less than untextured for both textured tools. As a result, a reduction of sliding friction at the tool-chip interface is expected, which in turn reduces required cutting forces and, most probably, tool wear rate. No significant difference is observed between T1 and T2 regarding contact length.

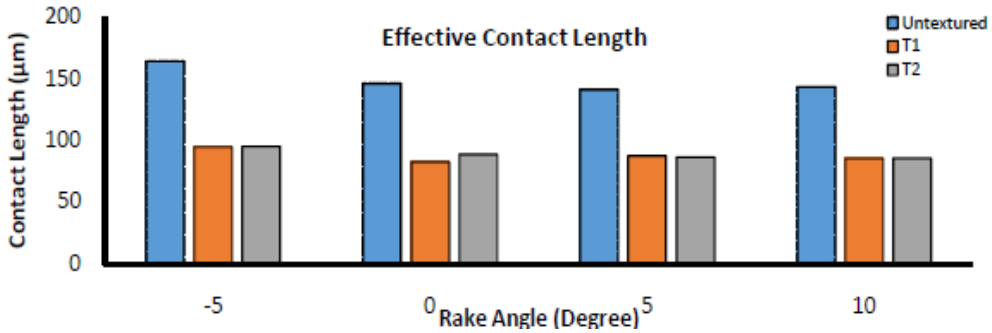


Fig.6Influence of tool micro texture on effective contact length under different rake angles

As shown in Fig. 7 a slight decrease in maximum cutting temperature, due to reduced friction, is observed in T1 compared to untextured tool. While, this behavior is not observed in T2. It can be interpreted that high temperatures are mainly concentrated around groove edges in textured tools, and temperature gradients are also denser at these regions. It should also be noted that there is a considerable difference in shear angle values among the investigated tools, as seen in Fig. 7. Shear angle of untextured tool, T2, and T1 is 30º, 38°, and 43º, respectively; which are in a good agreement with cutting force results.

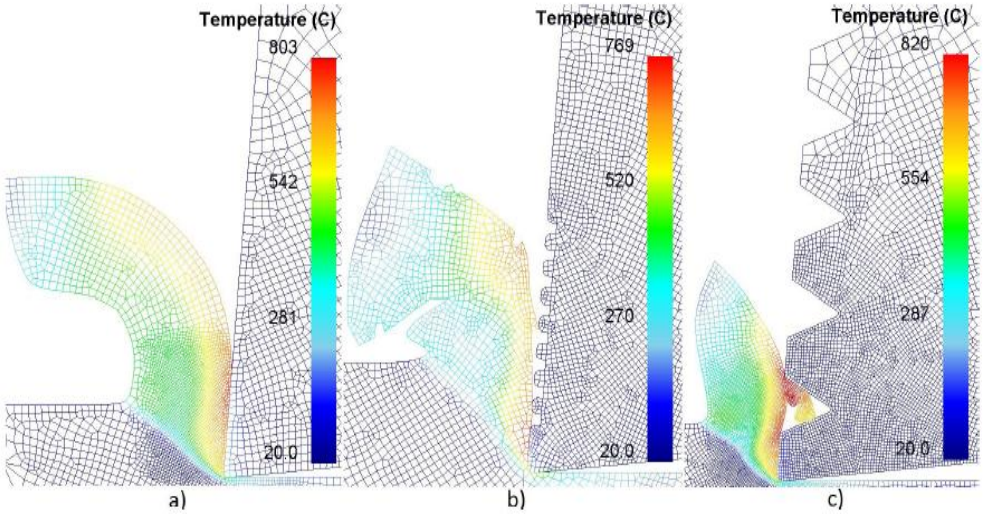


Fig. 7Temperature distribution at tool-chip interface for a) untextured tool b)T1 and c)T2

CONCLUSIONS

Influence of micro-textured geometry at the rake face of the WC cutting tools on cutting force behaviors in orthogonal cutting of Ti6Al4V are investigated in this study. Some conclusions are summarized below:

1. Textured tools displayed decreased cutting forces compared to untextured tools. While, feed forces are not reduced under all cases. The largest force reduction is yielded by 10µmdepth grooved tool at rake angle of 0°. While, 95µmdepth grooved tool displayed its best performance at rake angle of 10º.
2. Effective contact length between cut chip and rake face of the tool is reduced under all conditions. This, probably,resulted in decreased friction, which in turn reduces cutting forces.
3. Maximum cutting temperature is lower with small grooved tool. Besides, the shear angle values are larger in machining with grooved tools. These are also favorable factors for improved machinability.
4. 4.These results are considered promising considering the poor machinability of titanium alloys. Further and detailed investigations are planned to be carried out towards an in depth understanding of textured tool behaviors and implications.

ACKNOWLEDGEMENTS

The authors would like to thank SFTC, and FIGES Engineering A.Sfor their support with Deform 2D.

REFERENCES

[1] Su, Y., et al., Cutting performance of micro-textured polycrystalline diamond tool in dry cutting. Journal of Manufacturing Processes, 2017. 27: p. 1-7.
[2] Kawasegi, N., et al., Development of cutting tools with microscale and nanoscale textures to improve frictional behavior. Precision Engineering, 2009. 33(3): p. 248-254.
[3] Xie, J., et al., Micro-grinding of micro-groove array on tool rake surface for dry cutting of titanium alloy. International Journal of Precision Engineering and Manufacturing, 2012. 13(10): p. 1845-1852.
[4] QI, B.-y., et al., Experimental study on orthogonal cutting of Ti6Al4V with micro-textured tool. Tribology, 2011. 31(4): p. 346-351.
[5] Chen, Z.M., et al. A simulation study on the effect of micro-textured tools during orthogonal cutting of titanium alloy Ti-6Al-4V. in Applied Mechanics and Materials. 2013. Trans Tech Publ.
[6] Ma, J., N.H. Duong, and S. Lei, 3D numerical investigation of the performance of microgroove textured cutting tool in dry machining of Ti-6Al-4V. The international journal of advanced manufacturing technology, 2015. 79(5-8): p. 1313-1323.
[7] Ma, J., et al., FEM assessment of performance of microhole textured cutting tool in dry machining of Ti-6Al-4V. The International Journal of Advanced Manufacturing Technology, 2016. 84(9-12): p. 2609-2621.
[8] Deform-2D, Version 11 User Manual. STFC, Columbus, Ohio State, USA, 2014.
[9] Johnson, G.R. and W.H. Cook. A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures. in Proceedings of the 7th International Symposium on Ballistics. 1983. The Netherlands.
[10] Lee, W.-S. and C.-F. Lin, High-temperature deformation behaviour of Ti6Al4V alloy evaluated by high strain-rate compression tests. Journal of Materials Processing Technology, 1998. 75(1): p. 127-136.
[11] Özel, T., et al., Investigations on the effects of multi-layered coated inserts in machining Ti–6Al–4V alloy with experiments and finite element simulations. CIRP Annals, 2010. 59(1): p. 77-82.

★★★