Silicon (2018) 10:1949–1959
https://doi.org/10.1007/s12633-017-9707-x

ORIGINAL PAPER

Investigation of FEM Simulation of Machining of Titanium Alloy Using Microgroove Cutting Insert

Kalipada Maity[1] · Swastik Pradhan[1]

Received: 8 June 2017 / Accepted: 30 November 2017 / Published online: 17 April 2018

Abstract

In this paper, FEM simulation of machining of titanium alloy using microgroove cutting insert has been carried out using DEFORM-3D software. The cutting insert with microgroove has been made with Solidworks software. The 3D machining simulations of all the different types of microgroove patterns in cutting inserts were done at constant cutting variable, i.e. cutting speed of 125.6 m/min, feed of 0.23 mm/rev and depth of cut of 2 mm respectively. The simulation results were partially validated with experiments. There was good agreement between experiment and simulation. The cutting temperature, effective stress, tool wear rate and temperature at the chip/tool interface has been determined. There was an improvement in the machinability criteria using cutting tool with microgroove pattern.

Keywords Titanium alloy · Chip tool interface temperature · Tool wear rate · Effective stress and cutting temperature

1 Introduction

Ti-6Al-4V grade 5 titanium alloy has remarkable advantages toward mechanical properties such as high strength-to-weight ratio, better corrosion resistance and toughness as compared to other materials. Therefore, titanium alloys were mostly applied in the field of aeronautics, automobile, shipbuilding and manufacturing of medical instrument and dental implant. However, machining of titanium alloys is a challenging task, due to its peculiar process characteristic of high chemical reactivity, low thermal conductivity, high thermal strength and low modulus of elasticity [1–3]. Hence, the cutting tool deteriorates rapidly and the rapid tool wear rate of the cutting tool reduces the life of the cutting tool. To enhance the tool life of the cutting tool the machining has to be conducted in such a way that there will be less rise in temperature. It will improve the wear resistance and simultaneously the life of the cutting tool. In most of the machining process the tool-chip interface can be improved by using cutting fluids [4] and surface coating methods [5, 6]. The contamination of cutting fluid at the time of machining leads to a serious issue toward the disposing and recycling. The cost of the recycle or disposing is high. The process of disposing of the waste material is also bit difficult task [7].

Minimum quantity lubricant (MQL) is another remarkable method that has been widespread and applied in many of the manufacturing industries. MQL is a new lubrication technique used for the cutting of metals. In this method, the lubricating oil and compressed gas are mixed and vaporized. This pressurized microscale droplet is then jetted in the tool-workpiece interface zone to increase the cutting performance of the machining process [8–10]. In a similar way, cryogenic conditions machining is another new technique that improves the machinability of the metals. In this advanced machining technique, the liquid nitrogen (LN_2) is used as a coolant for cutting tools. The operating temperature of the liquid nitrogen is about -196 °C. The main advantages of cryogenic machining are that it is more environment-friendly as compared to other cutting fluid since no harmful chemicals are involved. The major constituent of the LN_2 is nitrogen. When LN_2 gets evaporated,

✉ Kalipada Maity
kpmaity@gmail.com

Swastik Pradhan
swastik.rock002@gmail.com

[1] Mechanical Engineering and Department, National Institute of Technology, Rourkela 769008, Odisha, India

it is mixed with air. A higher material removal rate is possible through cryogenic machining and the life of the cutting tool increases as compared to rest of the cutting process. However, the machining cost of the cryogenic machining is costly and the setup cost for the formation of liquid nitrogen is also very expensive [11–13].

A new trend in machining revealed by a few of the researcher that by creating micro-texture on the top face of the cutting tool reduces the cutting temperature, adhesion and improves the wear resistance at the tool-chip interface. This type of machining process does not involve in any kind of environmental hazard and also the disposal and recycling of the chip are much easier than the other turning process done with cutting fluid as a coolant.

Enomoto and Sugihara [14] modified the cutting tool using femtosecond laser technology. The top surface of the cutting tool is engraved with micro-textured. Results indicate that face-milling experiment has been carried out with micro-texture cutting tool that improves the lubricity and anti-adhesive properties in the tool-chips zone during machining of aluminum alloy. Obikawa et al. [15] performed the machining of aluminum alloy with different shape of micro texture created on the coated tool face of the cutting tool. As a result, it observed that parallel type and square-dot type of micro-texture effectively improved the machinability of the aluminum alloy. Enomoto et al. [16] made various stripes on the rake surface of the Ti-AlN cutting tools. Carbon S53C was used to perform the face milling experiment with cutting speed of 200 m/min, feed rate of 0.2 mm/rev and 2 mm depth of cut. It was observed that, micro-stripe grooves of 5 μm deep, 20 μm wide and 20 μm apart, with TiAlN coating significantly improved the wear resistance and lubricity of the cutting tool surface. Ma et al. [17] had done the FEM performance analysis of the microhole cutting tool with titanium alloy. It was noted that that microhole diameter, microhole depth, edge distance and micro hole position affected the cutting forces, tool-chip contact length and decrease in the energy consumption during machining. Zhang et al. [18] had used two different techniques to create nano-scale surface texture. In first technique, nano-scale surface texturing on the rake face were done nearly close to the main cutting edge of the WC/Co carbide tools. Then, tools were deposited with $Ti_{55}Al_{45}N$ hard-coatings. In the second technique, the cutting tool was first undergone with $Ti_{55}Al_{45}N$ hard-coatings. Then nano-scale surface texturing was made on the coated tool surfaces. The results revealed that a reduction in cutting forces, cutting temperatures, friction coefficient at the tool–chip interface and tool wear rate was observed by using first technique i.e. textured than coated cutting tool. But the results were more effective when compared with the second technique i.e. coated than textured coating tools. Chang et al. [19] made three different types of micro-textures on the cutting tool by using focused ion beam. The three different types of micro-texture were varied to each other according to the direction of cutting, i.e. the cutting of micro-texture was done in the horizontal direction, parallel directions and a sloping of 45° angle. It was observed that out of the three micro-texture pattern the low cutting force and best tool wear was achieved when the machining was carried out using the perpendicular direction micro-texture cutting tool. Kawasegi et al. [20] observed that low cutting forces were achieved when the micro-texture was made perpendicular to the chip flow direction during machining of titanium alloy with minimum quantity lubrication. Xing et al. [21] machined the AISI1045 workpiece with Al_2O_3/TiC ceramic cutting tools having nano-textures with WS_2/Zr coatings. Results revealed that the nano-textured cutting tool with the coating of WS_2/Zr was more effective and provided better results rather than WS_2/Zr coated ceramic cutting tool without nano-textures. Sugihara and Enomoto [22–24] formed nano- texture surface on the rake face of the cutting tool. The cutting fluid retention was improved that led to the achievement of good anti-adhesive effect during machining of aluminum alloy. Sugihara and Enomoto [25] also studied the crater and flank wear of the micro texture cutting tool during machining of carbon steels. It was observed that the crater wear increased due to the formation of micro-reservoir for cutting fluid and formation of micro-trap for wear debris. Some of the micro-strips were also grooved in the flank face of the cutting tool which yielded excellent wear resistance properties. Deng et al [26] observed that with the micro-texture cutting tool the cutting forces, surface roughness and coefficient of friction decreased during machining of the hardnend tool steel as compared to the non-texture cutting tool. Xing et al. [21]

Table 1 Geometrical specification of cutting tool used for modeling and simulation

Insert number	Description	Value
S	Insert shape	Square
N	Insert clearance angle	0 degree
M	Tolerance class	0.06
G	Insert features	Cylindrical hole with both side chip breaker
12	Size	12.70 mm
04	Thickness	4.76 mm
08	Corner radius	0.8 mm

Table 2 Various dimensions of the microgroove of cutting insert [29]

Insert number	Depth of grooves (μm)	Width of grooves (μm)	Spacing of grooves (μm)	Distance of grooves from cutting edge (μm)
Tool 1	Cutting inserts without microgroove			
Tool 2	6	48	67	329
Tool 3	18	58	53	330
Tool 4	29	59	53	250
Tool 5	34	64	58	326

was also seen that the fabrication of texture on cutting tool reduced the vibration for a stable cutting and maintained a uniform surface quality. Obikawa et al. [15] used four different type of micro-textures cutting tool for machining of A6061-T6 aluminum alloy. It was also observed that parallel and dot type micro-textures effectively reduced the friction force and coefficient of friction. Xie et al. [27] used both texture and non-textured cutting tool to study the effect of cutting force and cutting temperature. The minimum wear at the tip of the cutting tool was also observed, when 25 μm depth was engraved in the textured cutting tool. The presence of sharp cutting edges at the tip of the cutting tool significantly reduced the cutting temperature and cutting force during th machining operation. It was also observed that 1322 °C cutting temperature was observed at the cutting tip of the non-textured cutting tool, while it was only 500 °C for microgrooved cutting tool. Lei et al. [28] found that a more environmental friendly machining was performed by forming micro-holes on the surface of the cutting tool with a minimum amount of lubricant. The lubricant used in the micro holes reduced the usages of the large amount of cutting fluid during machining of titanium alloy. Yang et al. [29] studied that, the adhesion and the average coefficient of friction on the rake surface reduced by using microgroove cutting tool combined with cryogenic minimum quantity lubrication during machining of titanium alloy. In this study, FEM simulation of machining of titanium alloy using microgroove pattern cutting insert has been carried out using DEFORM-3D software. The cutting insert with different microgroove has been made with Solidworks software. The 3D machining simulations of all the different types of microgroove pattern cutting inserts were done at constant cutting variable, i.e. cutting speed of 125.6 m/min, feed of 0.23 mm/rev and depth of cut of 2 mm respectively. The simulation results were partially validated with experiments. The cutting temperature, effective stress, tool wear rate and temperature at the chip/tool interface has been determined.

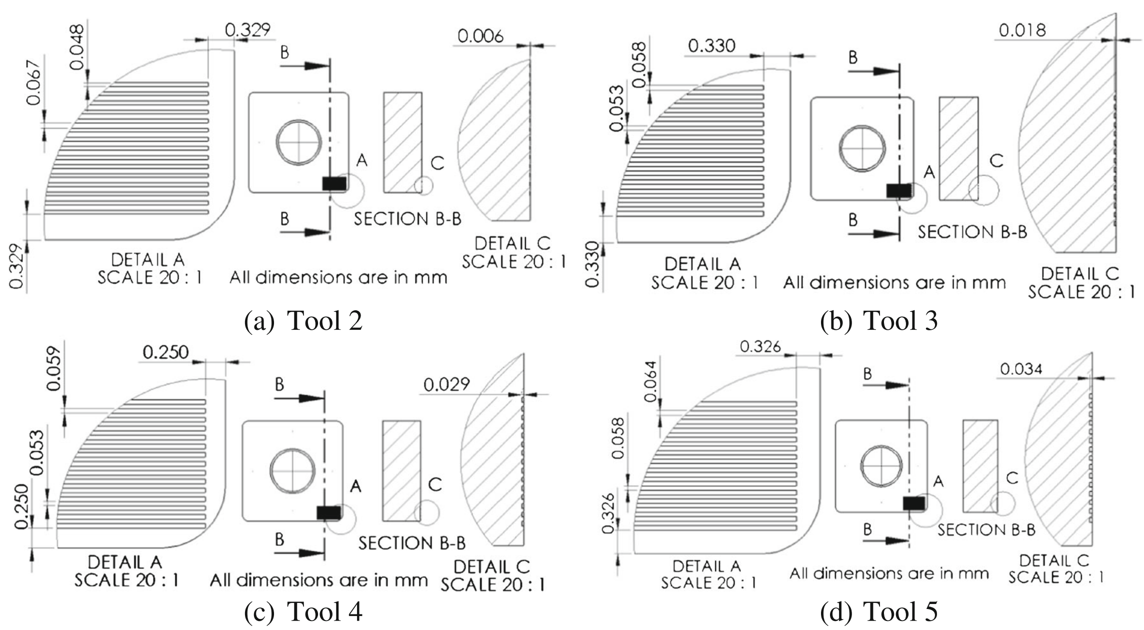


Fig. 1 Drafting view of the microgroove cutting inserts

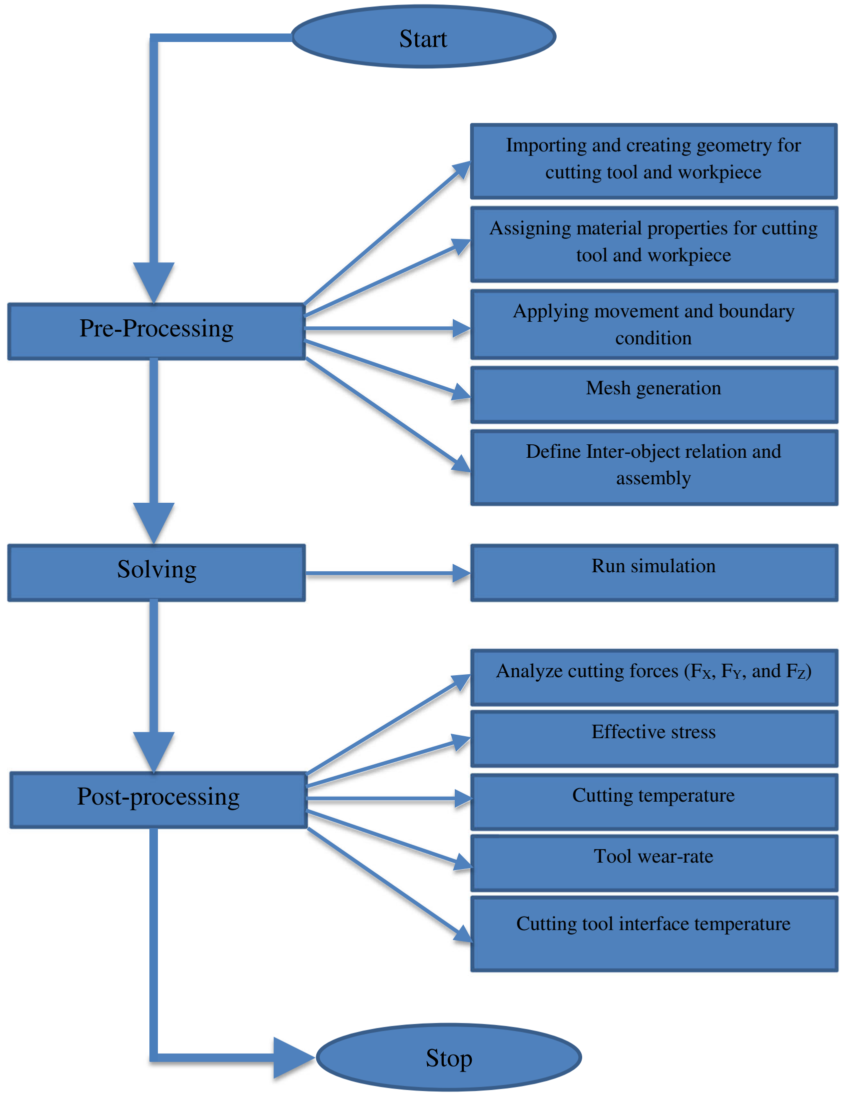


Fig. 2 Flow chart of DEFORM-3D modeling and simulation

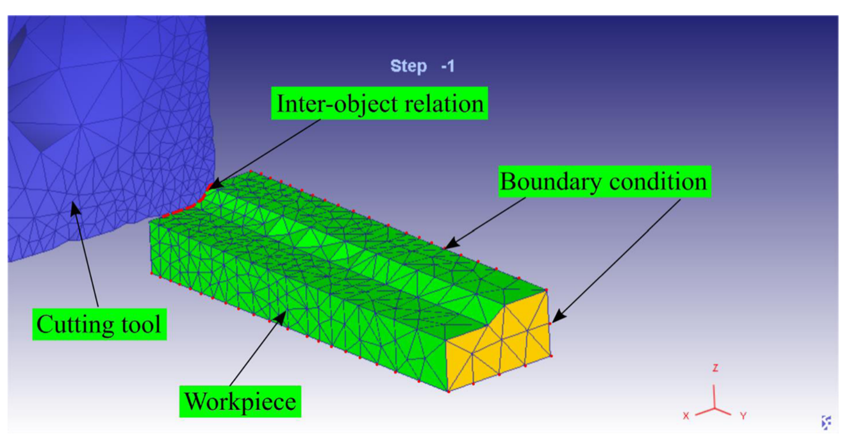
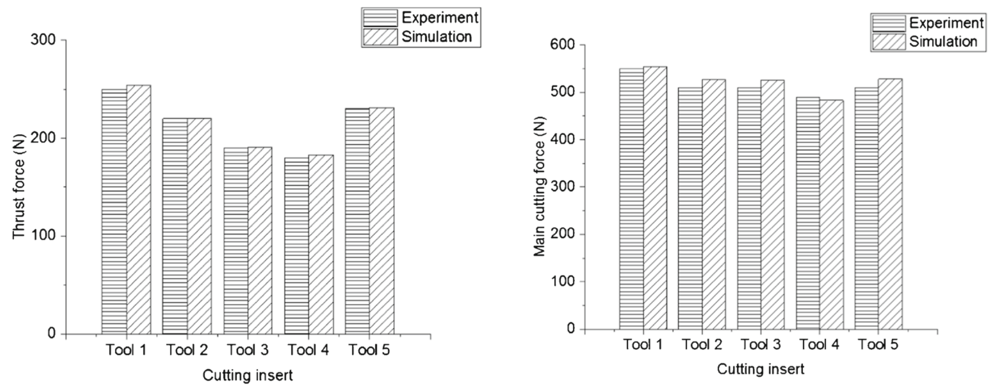
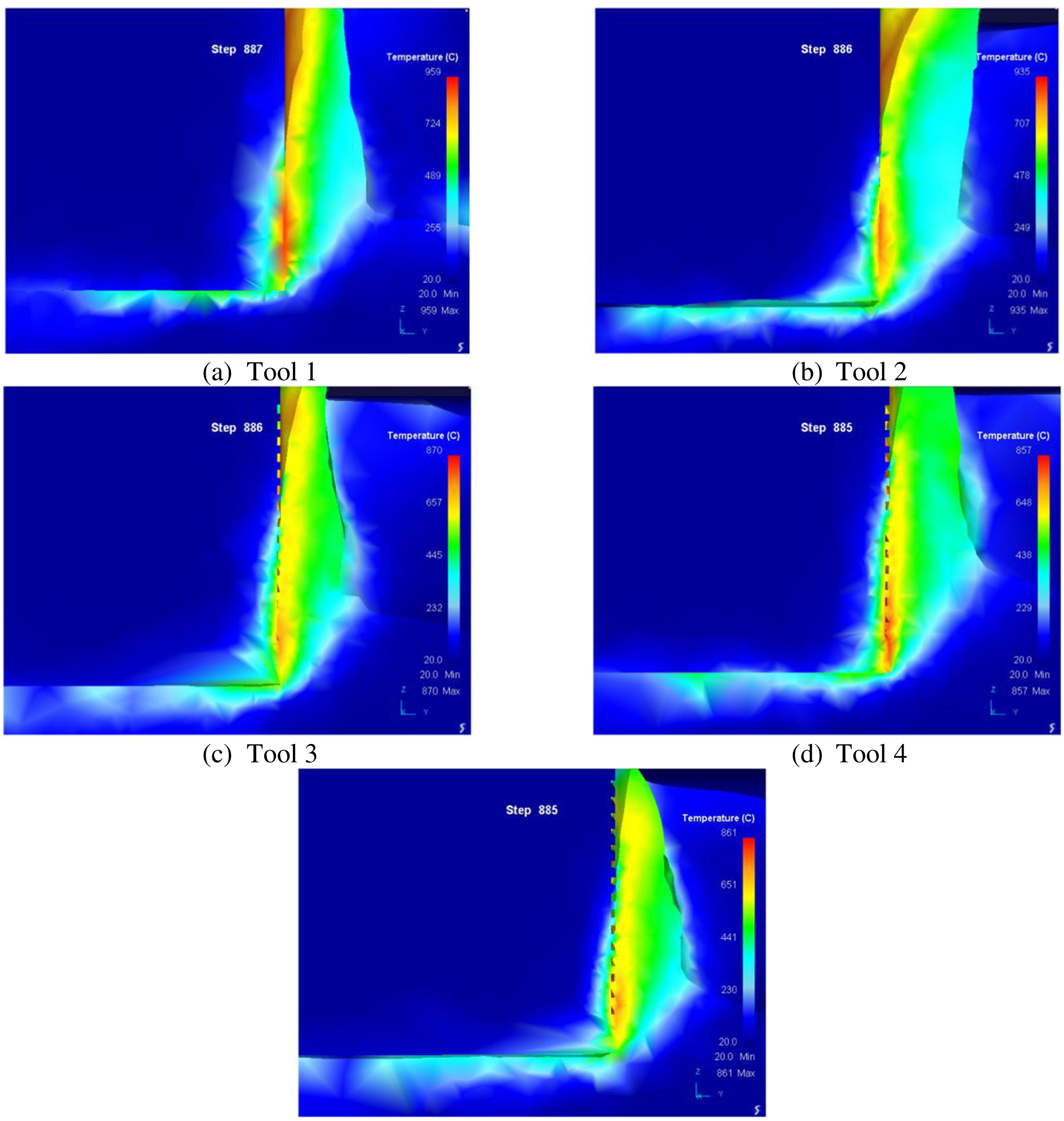


Fig. 3 Boundary conditions of cutting tool and workpiece

Fig. 4 Comparison of simulated force with experiment



(a) Thrust force (b) Tangential cutting force



(a) Tool 1 (b) Tool 2

(c) Tool 3 (d) Tool 4

(e) Tool 5

Fig. 5 Effects of microgroove geometry on cutting temperature FEM simulation

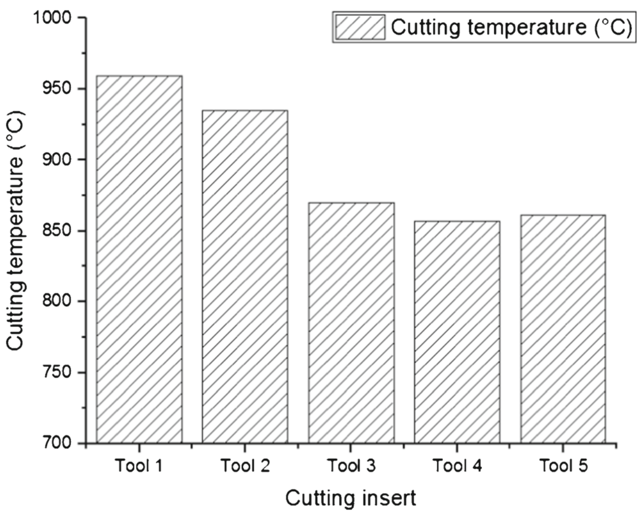


Fig. 6 Effects of various types of microgroove geometry on cutting temperature

2 3D Modeling of Cutting Tool

The 3D geometry of the cutting inserts is designed as per the SNMG120408 specification. The detail description of the SNMG120408 is defined in Table 1.

The micro grooves on the rake surface of the cutting tool are made as per micro groove depth, width, spacing between grooves and distance away from the cutting edges. The different types of dimension used for the creation of the microgroove are shown in Table 2.

The 3D model of the microgroove cutting inserts with its detailed microgroove dimensions in 2D drafting view is shown in Fig. 1.

3 3D Machining Simulation

The 3D machining simulation of the cutting inserts and the workpiece has been carried out using DEFORM-3D software.

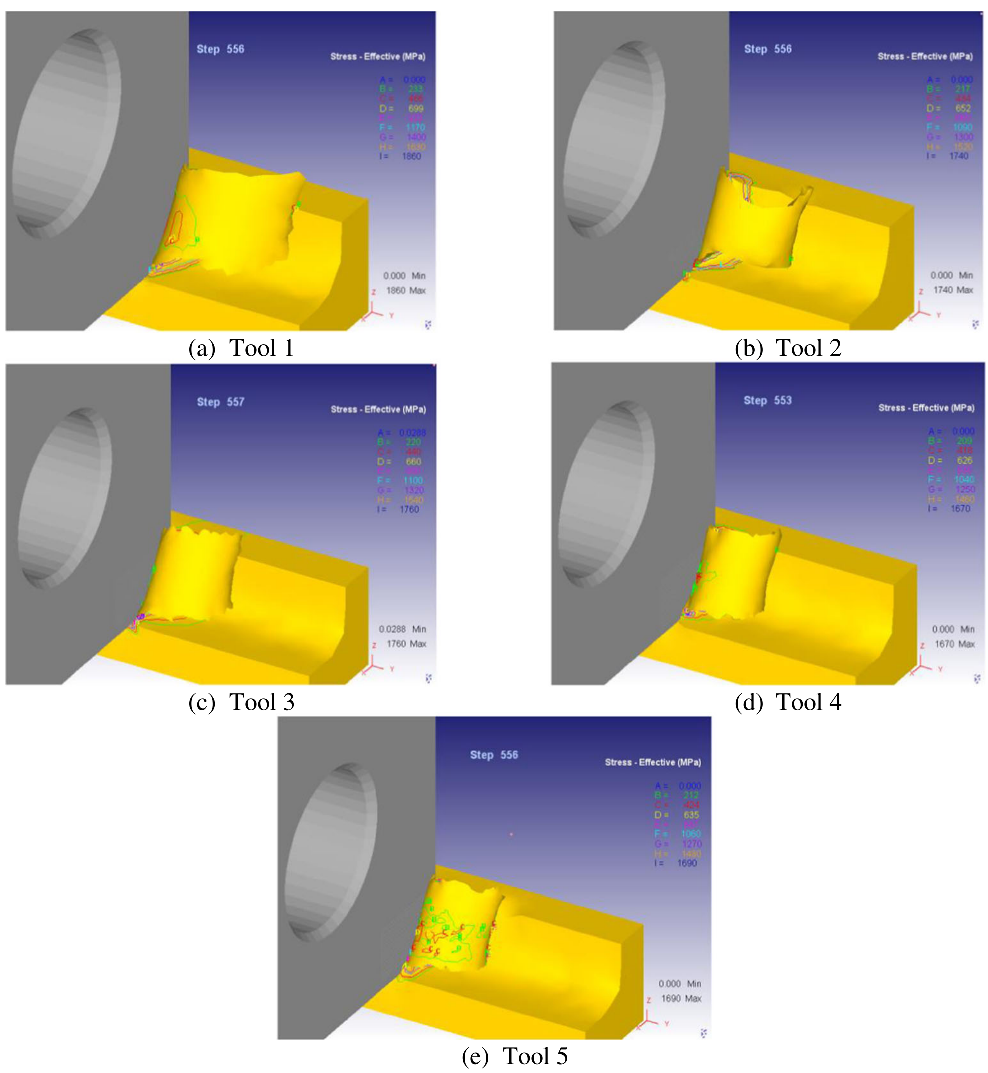


Fig. 7 Effects of microgroove geometry on effective stress FEM simulation

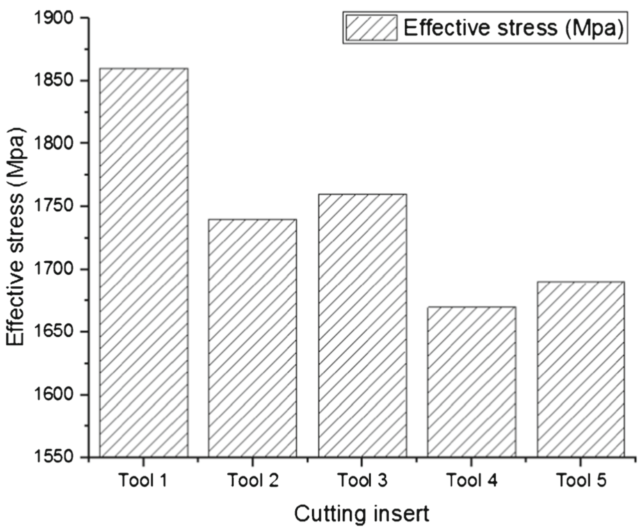


Fig. 8 Effects of various types of microgroove geometry on effective stress

The DEFORM-3D software performed the machining simulation analysis in three different steps, i.e. pre-processor, simulation and post-processor. Detailed descriptions of the work done by all three steps are described in the flow chart as shown in Fig. 2.

The 3D geometry of the cutting inserts with microgroove files modeled in Solidworks 2012 software was saved in sterolithography (STL) file format. This STL file of the cutting inserts was imported into DEFORM-3D software for the simulation. The cutting insert was considered as rigid and the workpiece modeled in the DEFORM-3D workbench was considered as plastic. The material properties of both the cutting insert and workpiece were defined from the material library of the DEFORM-3D software. The material properties applied to the cutting inserts and workpiece were tungsten carbide and titanium alloy (Ti-6Al-4V) respectively.

The boundary condition of each the cutting tool and workpiece were defined separately. The base part of the workpiece are fixed in X, Y and Z direction. The motion of the cutting insert is governed by specifying cutting speed of the cutting tool, whereas movement of the workpiece is restricted. The boundary conditions of the cutting tool and the workpiece is shown in Fig. 3.

The machining simulation of the cutting operation is done as per the cutting variable i.e cutting speed at 125.6 m/min, feed rate of 0.23 mm/rev and depth of cut at 2 mm [29].

4 Results and Discussion

The machining of titanium alloy using cutting inserts with microgroove patterns has been discussed here. The effect of variation of different microgroove patterns on machinability criteria has been investigated. The width and depth of microgroove, spacing between microgrooves and the distance away from the cutting edges are varied to obtain the best machinability criteria. The simulated results of the thrust force and tangential cutting force of the microgroove and without microgroove inserts were obtained. It was observed that, the thrust forces and the main cutting force decreased during FEM simulation using microgroove cutting tool as compared to the non-microgroove cutting tool. Due to the thermal softening effect and the reduction in the coefficient of friction of the microgroove cutting inserts the thrust force and tangential cutting force reduced as compared to the non-microgroove cutting inserts [30, 31].

The experimental investigation carried out [29] at the same machining conditions were compared with this simulated results for both the microgroove and non-microgroove cutting inserts as shown in Fig. 4.

There was a good agreement between simulation and experiment for different cutting inserts. The maximum percentage of errors between both simulation and experimentation was within 4%. Whereas the average error percentage is 1.58%. Based upon the comparisons, it is seen that, the results of the cutting simulation using the finite element model of both microgroove and non-microgroove cutting inserts predicts well with an adequate accuracy.

4.1 Effect of the Microgroove Geometry on the Cutting Temperature

The cutting temperature obtained during the finite element modeling (FEM) simulation of the non-microgroove and all different types of microgroove cutting inserts were shown in Fig. 5. It can be shown from the Fig. 6 that the cutting temperature obtained from the microgroove cutting inserts is less as compared to the regular cutting inserts. Since the tool-chip contact area during microgroove FEM simulation is less, the frictional force is less which reduces the temperature [30]. Microgroove cutting inserts with the grooves specification of 24 μm depth of grooves, 59 μm width of grooves, 53 μm spacing between grooves and 250 μm distances away from the cutting edges predicts a minimum cutting temperature of 857 °C as compared to other microgroove cutting inserts. An average of 11%, cutting temperature is reduced during FEM simulation using the microgrooves cutting inserts as compared to the regular cutting inserts.

4.2 Effect of the Microgroove Geometry on the Effective Stress

Stress is expressed in terms of forces acting in the unit area of material. The stress is again resolved in terms of normal stress and shear stress. Both the normal and shear stress

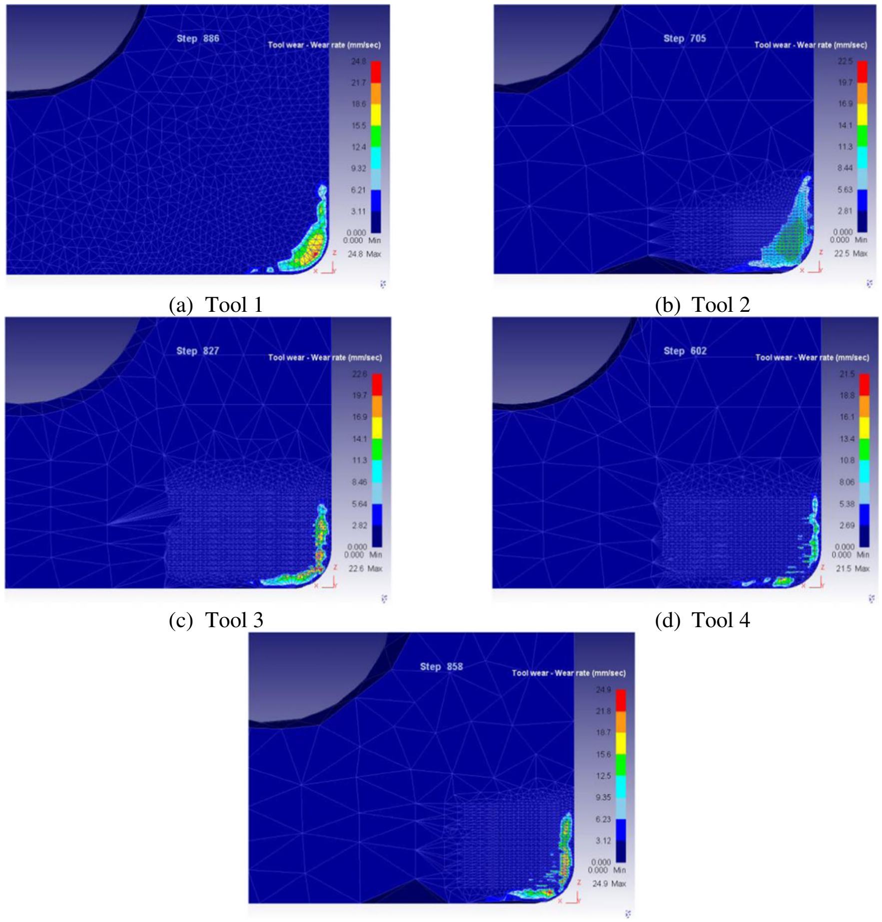

(a) Tool 1 (b) Tool 2 (c) Tool 3 (d) Tool 4 (e) Tool 5

Fig. 9 Effects of microgroove geometry on tool wear rate FEM simulation

again is subdivided into a total of six stress components with three each respectively. When the shear stress acting along a defined axis is zero, then the resultant normal stress acting on the same axis is termed as principal stress [32]. The effects of the effective stress of the regular and microgroove cutting inserts during FEM simulation are analyzed using the DEFORM-3D software. The effective stress developed during the FEM simulation with the different types of cutting inserts has been shown in Fig. 7. It is depicted from the Fig. 8 that, the effective stress developed during non-microgroove FEM simulation is high as compared to the other microgroove cutting inserts. The effective stress developed for the microgroove cutting inserts, tool no 4 and 5 are nearly same. An average of the overall 10%, reduction in the effective stress is observed as compared to the non-microgroove cutting inserts.

Fig. 10 Effects of various types of microgroove geometry on tool wear rate

4.3 Effect of the Microgroove Geometry on the Tool Wear Rate

Figure 9 shows the images of the tool wear rate of the inserts with and without microgroove pattern. The tool wear was caused due to the higher contact area between the cutting insert surface and chip, friction at the tool-chip interface and the cutting temperature at the surrounding

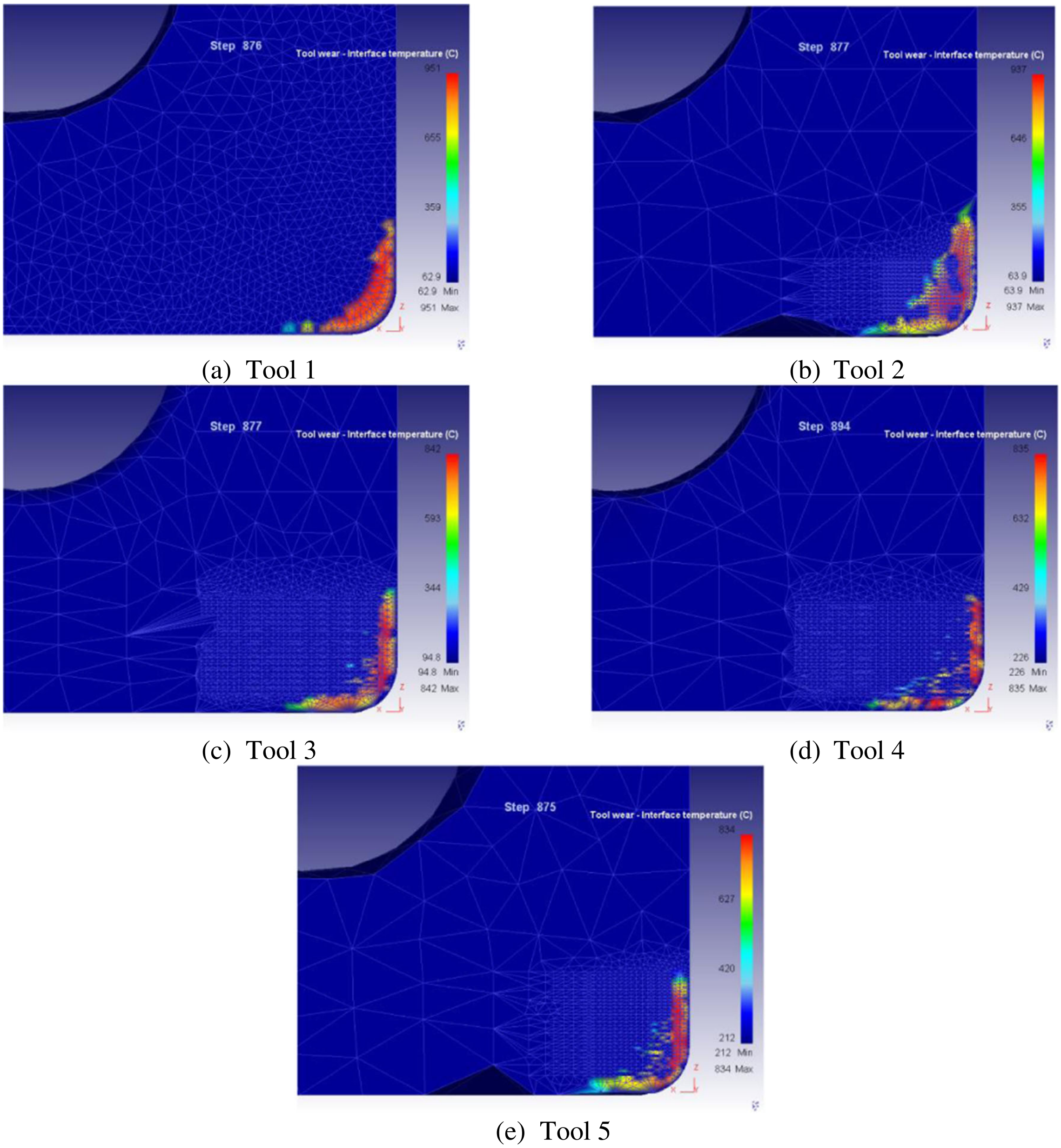


Fig. 11 Effects of microgroove geometry on cutting tool interface temperature FEM simulation

of the tool tip. The tool wear rate on the rake surface of the microgroove and non-microgroove cutting inserts were observed at a cutting speed of 125.6 m/min, feed of 0.23 mm/rev and depth of cut of 2 mm. A higher tool wear rate is observed for non-microgroove cutting insert as compared to the microgroove cutting inserts. It is due to the high contact area between the tool and chip, which results in more friction. Also, due to the higher cutting temperature occurred by the abrasion and adhesion mechanism the tool wear of the non-microgroove cutting temperature is high as compared to the microgroove cutting inserts [30]. Refers to Fig. 10 the tool wear rate of regular cutting inserts was more as compared to the microgroove cutting inserts. An average of 13% tool wear rate reduced using cutting inserts with microgroove pattern. Tool no 5 show the minimum tool wear rate among the other microgroove cutting inserts.

4.4 Effect of the Microgroove Geometry on the Chip Tool Interface Temperature

Figure 11 shows the temperature at the chip tool interface observed during FEM simulation. From Fig. 12, it is shown that the cutting temperature at chip tool interface of the microgroove cutting tool decreases as compared to the non-microgroove cutting tool. Due to the formation of the microgroove on the top surface nearer to the cutting edge

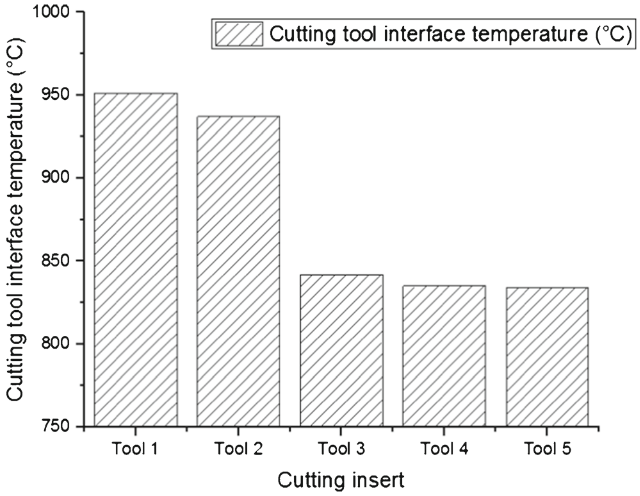


Fig. 12 Effects of various types of microgroove geometry on cutting tool interface temperature

of the cutting insert, the actual contact of the tool-chip will be equal to the nominal contact length minus the width of all the microgrooves [29]. Hence, the reduction in the actual contact length of the tool-chip interface reduces the friction force, which reduces the temperature at the tool interface. An average of 12% reduction in the cutting temperature of tool interface was observed as compared to non-microgroove cutting.

5 Conclusions

In this study, three-dimensional finite element modeling of the non-microgroove and microgroove cutting tool with different depth, width, spacing and distance away of the microgroove form the cutting edge were made using Solidworks software. The FEM simulation of the cutting tool on the workpiece (titanium alloy) was carried out using DEFORM3D software. The simulated data were compared with the available experimental data. The key finding of the research was summarized below:

- Microgroove cutting insert effectively reduces the thrust force and the tangential cutting force. The average reduction percentage in cutting force of microgroove pattern cutting tool to plain cutting tool was 11.88%.
- There was good agreement between experiment and simulation. The average discrepancy was 1.58%.
- The cutting temperature, effective stress and tool wear rate reduced for cutting insert with microgroove pattern due to reduction in the chip tool contact area.
- The microgroove cutting insert with 29 µm depth, 59 µm width, 53µm spacing and 250 µm away from the cutting edge yielded the best cutting performance as compared with the other microgroove cutting inserts.

References

1. Ezugwu EO, Wang ZM (1997) Titanium alloys and their machinability—a review. J Mater Process Technol 68(3):262–274
2. Nabhani F (2001) Machining of aerospace titanium alloys. Robot Comput-Integr Manuf 17(1):99–106
3. Ezugwu EO, Bonney J, Yamane Y (2003) An overview of the machinability of aero engine alloys. J Mater Process Technol 134(2):233–253
4. Adler DP, Hii WWS, Michalek DJ, Sutherland JW (2006) Examining the role of cutting fluids in machining and efforts to address associated environmental/health concerns. Mach Sci Technol 10(1):23–58
5. Derflinger V, Brandle H, Zimmermann H (1999) New hard/lubricant coating for dry machining. Surf Coat Technol 113(3):286–292
6. Hanyu H, Kamiya S, Murakami Y, Saka M (2003) Dry and semi-dry machining using finely crystallized diamond coating cutting tools. Surf Coat Technol 174:992–995
7. Sreejith PS, Ngoi BKA (2000) Dry machining: machining of the future. J Mater Process Technol 101(1):287–291
8. Dhar NR, Islam MW, Islam S, Mithu MAH (2006) The influence of minimum quantity of lubrication (MQL) on cutting temperature, chip and dimensional accuracy in turning AISI-1040 steel. J Mater Process Technol 171(1):93–99
9. Wang ZG, Rahman M, Wong YS, Neo KS, Sun J, Tan CH, Onozuka H (2009) Study on orthogonal turning of titanium alloys with different coolant supply strategies. Int J Adv Manuf Technol 42(7-8):621–632
10. Duchosal A, Leroy R, Vecellio L, Louste C, Ranganathan N (2013) An experimental investigation on oil mist characterization used in MQL milling process. Int J Adv Manuf Technol 66(5–8):1003–1014
11. Hong SY, Ding Y, Jeong W-c (2001) Friction and cutting forces in cryogenic machining of Ti–6Al–4V. Int J Mach Tools Manuf 41(15):2271–2285
12. Hong SY, Markus I, Jeong W-c (2001) New cooling approach and tool life improvement in cryogenic machining of titanium alloy Ti-6Al-4V. Int J Mach Tools Manuf 41(15):2245–2260
13. Bermingham MJ, Kirsch J, Sun S, Palanisamy S, Dargusch MS (2011) New observations on tool life, cutting forces and chip morphology in cryogenic machining Ti-6Al-4V. Int J Mach Tools Manuf 51(6):500–511
14. Enomoto T, Sugihara T (2010) Improving anti-adhesive properties of cutting tool surfaces by nano-/micro-textures. CIRP Ann-Manuf Technol 59(1):597–600
15. Obikawa T, Kamio A, Takaoka H, Osada A (2011) Micro-texture at the coated tool face for high performance cutting. Int J Mach Tools Manuf 51(12):966–972
16. Enomoto T, Sugihara T, Yukinaga S, Hirose K, Satake U (2012) Highly wear-resistant cutting tools with textured surfaces in steel cutting. CIRP Ann-Manuf Technol 61(1):571–574
17. Ma J, Ge X, Qiu C, Lei S (2016) FEM assessment of performance of microhole textured cutting tool in dry machining of Ti-6Al-4V. Int J Adv Manuf Technol 84(9-12):2609–2621
18. Zhang K, Deng J, Meng R, Gao P, Yue H (2015) Effect of nano-scale textures on cutting performance of WC/Co-based Ti 55 Al 45N coated tools in dry cutting. Int J Refract Met Hard Mater 51:35–49
19. Chang W, Sun J, Luo X, Ritchie JM, Mack C (2011) Investigation of microstructured milling tool for deferring tool wear. Wear 271(9):2433–2437
20. Kawasegi N, Sugimori H, Morimoto H, Morita N, Hori I (2009) Development of cutting tools with microscale and nanoscale textures to improve frictional behavior. Precis Eng 33(3):248–254

21. Xing Y, Deng J, Li S, Yue H, Meng R, Gao P (2014) Cutting performance and wear characteristics of Al 2 O 3/TiC ceramic cutting tools with WS 2/Zr soft-coatings and nano-textures in dry cutting. Wear 318(1):12–26
22. Sugihara T, Enomoto T (2009) Development of a cutting tool with a nano/micro-textured surface—Improvement of anti-adhesive effect by considering the texture patterns. Precis Eng 33(4):425–429
23. Sugihara T, Enomoto T (2012) Improving anti-adhesion in aluminum alloy cutting by micro stripe texture. Precis Eng 36(2):229–237
24. Enomoto T, Sugihara T (2011) Improvement of anti-adhesive properties of cutting tool by nano/micro textures and its mechanism. Proced Eng 19:100–105
25. Sugihara T, Enomoto T (2013) Crater and flank wear resistance of cutting tools having micro textured surfaces. Precis Eng 37(4):888–896
26. Zhang K, Deng J, Xing Y, Li S, Gao H (2015) Effect of microscale texture on cutting performance of WC/Co-based TiAlN coated tools under different lubrication conditions. Appl Surf Sci 326:107–118
27. Xie J, Luo MJ, Wu KK, Yang LF, Li DH (2013) Experimental study on cutting temperature and cutting force in dry turning of titanium alloy using a non-coated micro-grooved tool. Int J Mach Tools Manuf 73:25–36
28. Lei S, Devarajan S, Chang Z (2009) A study of micropool lubricated cutting tool in machining of mild steel. J Mater Process Technol 209(3):1612–1620
29. Yang Y, Su Y, Li L, He N, Zhao W (2015) Performance of cemented carbide tools with microgrooves in Ti-6Al-4V titanium alloy cutting. Int J Adv Manuf Technol 76(9-12):1731–1738
30. Arulkirubakaran D, Senthilkumar V, Kumawat V (2016) Effect of micro-textured tools on machining of Ti–6Al–4V alloy: an experimental and numerical approach. Int J Refract Met Hard Mater 54:165–177
31. Koshy P, Tovey J (2011) Performance of electrical discharge textured cutting tools. CIRP Ann-Manuf Technol 60(1):153–156
32. Fluhrer J (2006) Deform 3D user's manual version 6.0. Scientific Forming Technologies Corporation, Columbus