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Performance Evaluation of Novel Micro-textured Tools in Improving the Machinability of Aluminum Alloy (Al 6063)

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Abstract

Ordered array of dots or grooves induces special functionality to the surface. Two types of textures viz. linear (perpendicular to the chip flow direction) and square were developed on plain WC inserts using focused ion beam machining. The inserts were coated with MoS_2 solid lubricants using pulsed DC magnetron sputtering. Dry turning tests were carried out on aluminum alloy (Al 6063) work material. Textured tools are found to be more effective in reducing the cutting forces and sticking behaviour of the work material as compared to the non-textured tools. The novel square textured tools performed better than the linear textured tools in terms of reduced cutting forces and improved surface finish. A reduction of about 30% in cutting forces was observed with square textured tools and that with the linear textured tools was about 20% as compared to the non-textured tools. The reduction in cutting forces and the associated change in sticking behaviour are attributed to the reduction in tool-chip contact area and reduced friction at the tool-chip interface owing to the improved lubrication provided by the interlayer of solid lubricant. Textures are functioning as reservoirs of the solid lubricant which in turn reduces the friction at the chip-tool interface.

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Keywords:

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1. Introduction

In spite of the benefits of using cutting fluids during machining such as reduction of friction at the chip-tool interface, washing away of the wear debris, cooling the chip-tool interface, chip, tool and work piece, the awareness about the environmental pollution (especially of water) and human health, industries worldwide are looking for solutions to use minimum quantity of cutting fluids or altogether to avoid them. Cutting fluids are also difficult to be disposed off. The management, maintenance and disposal of cutting fluids have become more difficult and expensive owing to the strict environmental regulations in almost all countries [1, 2]. The use of cutting fluids can be avoided by using solid lubricants like MoS_2, graphite, CaF_2, WS_2, [1].

One more promising way to reduce the use of cutting fluids is to modify the design of the cutting tools that will reduce friction between chip and tool i.e. to develop micro/nano textures and as a result, reduce the cutting forces and heat generation at the chip-tool interface and improve the tool life. To enhance the effectiveness of the micro/nano textured cutting tool, solid lubricants can further be applied at the chip-tool interface. The advantage with the use of solid lubricants is that hardly any cutting fluid enters the cutting area (chip-tool interface) where it is inevitably required; the solid lubricant can be easily applied at the zone beforehand.

Various types of textures have been developed by different researchers e.g. linear grooves parallel and perpendicular to the chip flow direction, square pits, square dots[3, 4], elliptical [5], micro-holes [6] etc. Different types of lubrication methods e.g. minimum quantity lubrication [4], solid lubricants like MoS_2 [7], WS_2 [8], CaF_2 [9], have been employed. Different methods,

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such as photolithography [3], femtosecond laser [4, 10], laser machining [5], micro-EDM [6], micro-grinding [11], and EDM [12] were used to create the textures. Every process has its own advantages and limitations.

Although aluminum is a relatively soft and easy to machine material, the difficulties associated with its machining are the stickiness of the material and tendency to form a built up edge. This reflects in deterioration of the surface finish. The problems become more severe at high temperature especially in dry machining. Textured tool with solid lubricant coating minimizes such problems. Various research attempts have been made to improve the machinability of aluminum alloy with textured tools.

The present research work is aimed at improving the machinability of Al 6063 alloy using novel textured tools developed by focused ion beam (FIB) machining. Turning of Al 6063 using micro-textured tools developed with help of focused ion beam machining is being reported for the first time. Some of the advantages of micro/nano patterning using focused ion beam machining are listed here. It has the direct writing capability with minimal substrate preparation. It leads to accurate and precise machining on metal, silicon, glass, carbon and diamond. Very accurate positioning of the patterns within tens of nanometres with no heat affected zones is possible with FIB. Complex shapes can be very easily machined.

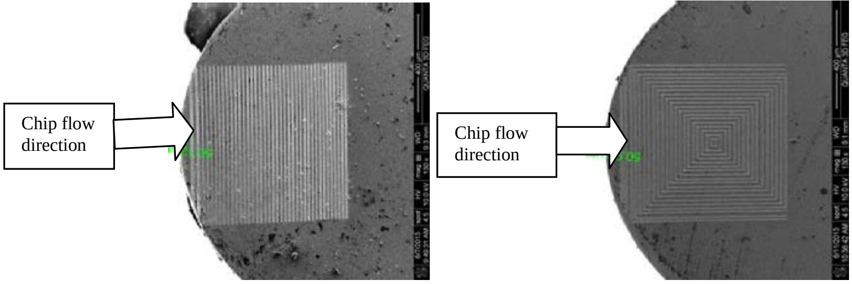
2. Experimental Procedure

2.1. Micro textured array development on WC-Co tools by Focused Ion Beam (FIB) machining

The tool used for machining aluminum alloy was Widia CNMA 120408 plain WC insert. The tool holder used was PCLNL2020K12 (ISO code). The cutting tool geometry was: orthogonal rake angle -6^0, inclination angle -6^0, approach angle 95^0, side clearance angle 5^0. The insert was polished manually in a polishing machine to Ra about 0.05 µm (initial roughness being around 0.16 µm). Polishing the insert improves the bonding strength of the coating. Also, polishing removes the deformed and smeared subsurface of ground WC-based carbides and at the same time almost completely removes the residual stresses caused because of grinding. After polishing, the inserts were cleaned using ultrasonic cleaning in acetone for one hour.

The micro-textures at the chip-tool interface in this research, were produced at the rake surface of the tool by way of utilizing the direct writing capability of the focused ion beam machining. The process parameters such as beam current (42nA), beam voltage (16kV) and beam overlap (50%) were optimized to ensure that the grooves are produced with optimum accuracy and surface finish. The width (1 to 5µm), pitch (5 to 25µm) and depth (1 to 5µm) of grooves are varied to evaluate their effects on the cutting forces, wear characteristics of cutting tools and the surface finish of the workpiece. The textures were made 50µm away from the cutting edge in order to retain strength of the tool at the apex.

It was reported that the micro/nano grooves perpendicular to the direction of chip flow are the most effective in reducing friction [3]. So, the following two types of grooves were produced on the rake surface. The linear grooves, perpendicular to the chip flow direction (Fig. 1a) and the square grooves having the combination of parallel and perpendicular textures (Fig. 1b) were fabricated. Parallel and perpendicular to the sliding direction are two extreme cases of groove orientation. It has been reported that the effect of grooves in other directions are expected to lie between these two extreme cases [13, 14]. The width of the pattern is about 700µm and length along the chip flow direction is also 700µm.



(a) Linear texture (b) Square texture

Fig.1. Typical textures fabricated on WC tool by FIB

Before creating the textures on the inserts, the chip flow direction (CFD) was ascertained so that chip flows along the textures only. The CFD depends on the tool geometry and the machining conditions. The chip flow angle calculated using the approach given in [15] was $41.3105\,^0$. The actual chip flow angle (Ω) measured from the wear tracks of the chip on the rake face of the tool is found to be 41.23^0 as shown in Fig. 3.

Fig. 2 shows the actual cutting condition, drawn to scale, showing that the cutting takes place at the nose radius only. Figure 3 shows the actual chip flow angle measured.

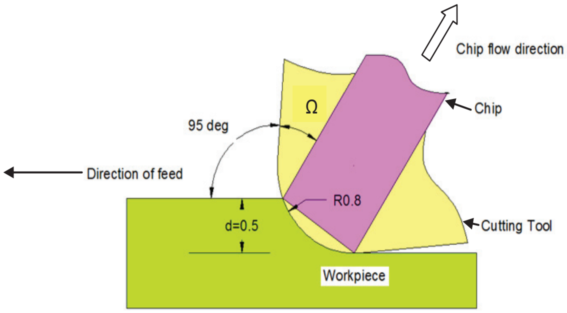


Fig.2. Actual cutting condition (dimensions are in mm)

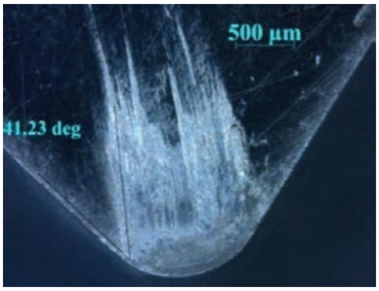


Fig.3. The actual chip flow angle measured on an insert

The composition of the work material Al 6063 is presented in Table 1.

Table 1 Component Wt. (Max) %

Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Other, total
98.41	0.0067	0.0348	0.3495	0.5067	0.078	0.477	0.0236	0.1	0.0137

After fabricating the textures, the inserts were coated with molybdenum disulfide (MoS_2) using pulsed DC magnetron sputtering.

Using the textured and subsequently coated inserts, aluminum round bar of Al 6063 was turned on a Leadwell CNC turning center. The cutting forces were measured using Kistler® piezoelectric dynamometer (model 9257B) mounted on a specially designed fixture. Kistler® tool holder (model: 9129AA) was used for holding the 20mm×20mm shank size cutting tool. The charge generated at the dynamometer was amplified using three-charge amplifiers (Kistler®, Model: 5070A).There was no coolant used. The cutting parameters were; feed rate=0.1 mm/rev, depth of cut=0.5 mm and cutting speed is varied from 100 m/min to 500 m/min. The machining set up is shown in Fig. 4.

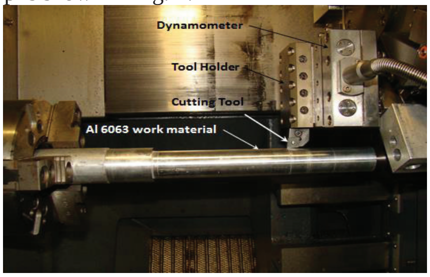


Fig.4. Photographic view of the Experimental Setup

This research work attempts to study the influence of cutting speed and surface texture parameters (Depth, Width and Pitch of grooves) on the machining performance (turning) of Al 6063 aluminum alloy with MoS_2 coated cemented carbide inserts. The performance measuring responses are the cutting forces and surface roughness.

2.2. Design of Experiments

The design of experiments has a major effect on the number of experiments needed. Therefore, it is essential to have a proper design of experiments. Experiments were conducted using central composite design. In the present investigation, the independent variables are cutting speed and depth, width and pitch of the surface texture. The responses measured are the components of cutting force and surface finish. As per the full factorial design, a total of 625 (5^4) experiments need to be performed, but to save machining cost and time, it has been decided to use the central composite design (CCD) technique to reduce the number of experiments. CCD technique can help in interpreting the influence of the process parameters on the responses at intermediary levels also. It has reduced the number of experiments from 625 to 30. It is also useful to see the repeatability of the experimental results. Table 2 presents the parameters and their levels chosen for this study

Table 2 Process parameters and their levels

Factors	-2	-1	0	+1	+2
Cutting speed in m/min	100	200	300	400	500
Depth of grooves in µm	1	2	3	4	5
Width of grooves in µm	1	2	3	4	5
Pitch of grooves in µm	5	10	15	20	25

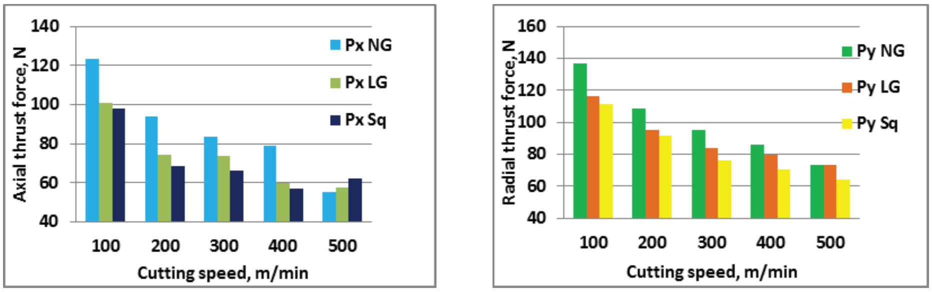
3.0. Results and discussion

3.1. Comparison of non-textured tools with textured tools

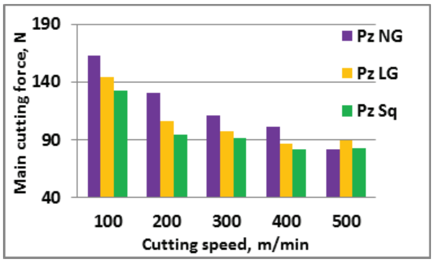
The friction and wear behaviour of boundary lubricated sliding surfaces are influenced by the surface texture. By introducing controlled depressions and undulations in an otherwise flat surface, the tribological properties can be improved. Lubricant can then be supplied even inside the contact by the small reservoirs, resulting in a reduced friction and a prolonged lifetime of the tribological contact [16].

The friction, normal forces and apparent coefficient of friction are calculated based on the formula given in the reference [17].

It can be seen from Fig. 5 that as the cutting speed increases from 100 m/min to 400 m/min, cutting forces reduce steadily. It is also very clear that square grooved tools perform better than the non-grooved and linear grooved cutting tools. It is seen that the grooved tools are more effective over the range of cutting speeds from 100 to 400 m/min. The main cutting force, P_z, axial thrust force, P_x and radial thrust force, P_y are less than that of the non-grooved tools at almost all speeds for both the types of textures. Same is the case for the friction force and normal force, as shown in Fig. 6. It can also be seen that square grooves are more effective in reducing the cutting forces than linear grooves. The largest reduction can be seen in the radial thrust force and little less in axial thrust force which are highly correlated with friction force.



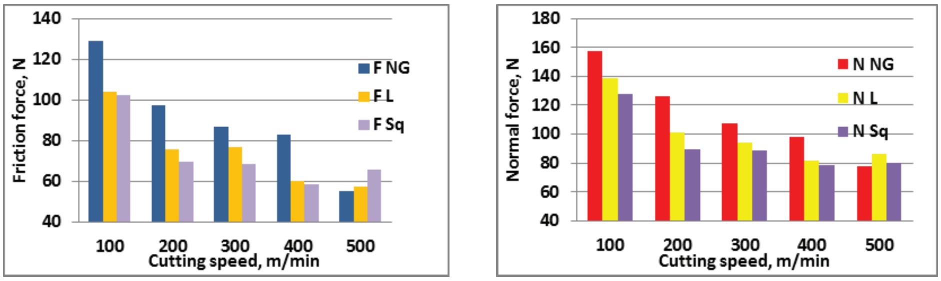
(a) Cutting speed v/s Axial thrust force (b) Cutting speed v/s Radial thrust force



(c) Cutting speed v/s main cutting force

Fig. 5. Comparison of cutting forces for grooved and non-grooved tools

NG=Non-grooved coated tool, LG=Linear grooved tool, SG=Square grooved tool



(a) Cutting speed v/s friction force (b) Cutting speed v/s normal force

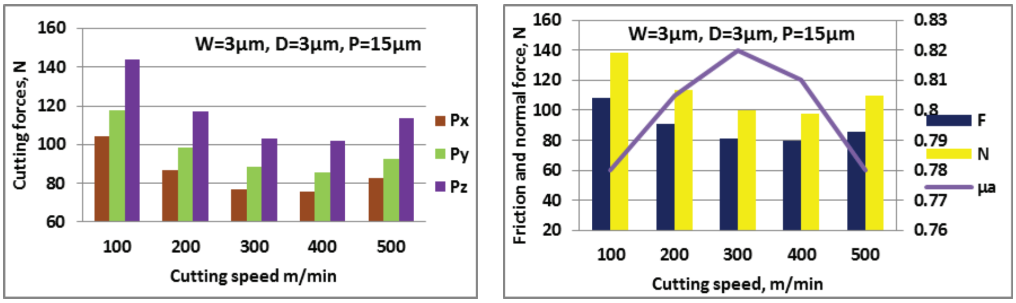
Fig. 6. Cutting speed versus friction force F and normal force N for grooved and non-grooved tools
NG=Non-grooved coated tool, LG=Linear grooved tool, SG=Square grooved tool

There is about 20% reduction in cutting forces for textured tools as compared to the non-textured tools up to 300 m/min. The percentage reduction in cutting forces declines with increase in speed beyond 300 m/min cutting speed. The maximum reduction in cutting forces is about 30 % for square grooved tools and 20 % for linear grooved tools at 200 m/min cutting speed. Further studies are carried out on square textured tools since they have exhibited better performance than the linear textures.

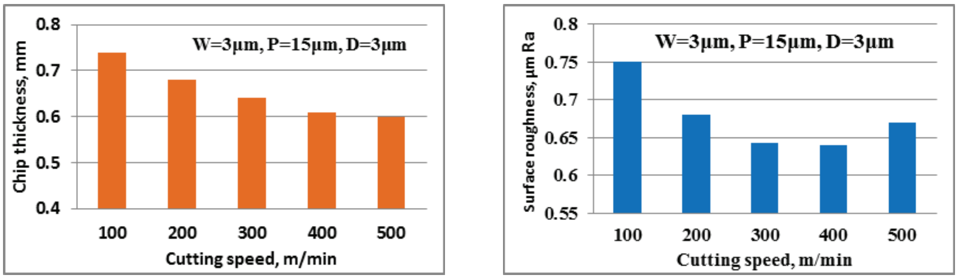
3.2. Analysis of the square grooved tools

3.2.1. Effect of Cutting speed

It is very clear from Fig. 7 (a) that all the cutting force components P_x, P_y and P_z reduce as the cutting speed increases. Same is the case with friction and normal forces and the coefficient of friction as shown in Fig. 7 (b). The increase in speed also has a favourable effect on the chip thickness (Fig. 7 (c)). As chip thickness reduces, shear angle increases. Surface roughness also decreases with increase in speed up to 400 m/min (Fig. 7 (d)).



(a) Cutting speed v/s cutting forces (b) Cutting speed v/s friction and normal forces

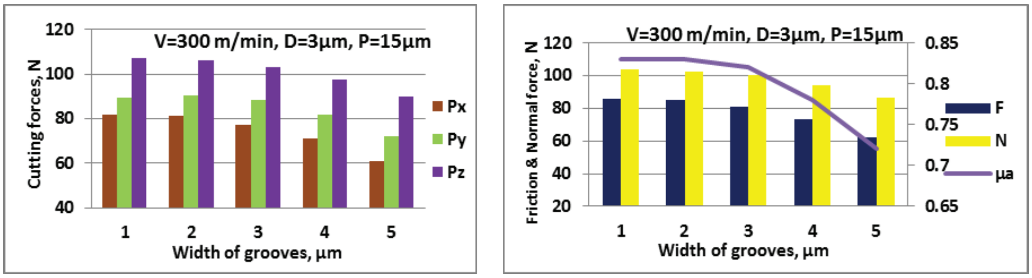


(c) Cutting speed v/s chip thickness (d) Cutting speed v/s surface roughness

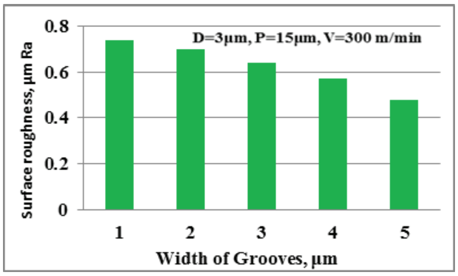
Fig. 7. Effect of cutting speed on various parameters

3.2.2. Effect of Width of Grooves

As shown in Fig. 8, cutting force components P_x, P_y and P_z decrease with the increase in width of grooves in the texture. Friction force and the coefficient of friction follow similar trend as P_x and P_y and normal force follows similar trend as the main cutting force P_z. Surface roughness decreases with increase in width of grooves. The reason is increase in the width of the grooves in the texture increases the capacity of the texture to store solid lubricants better, reducing the friction between the chip and tool.



(a) Width of grooves v/s cutting forces (b) Width of grooves v/s friction & normal forces

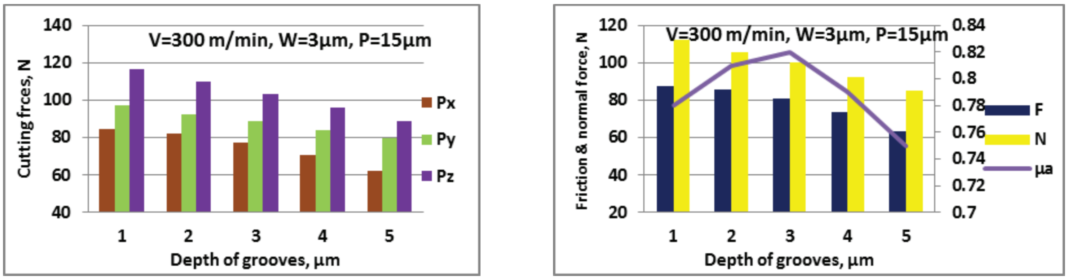


(c) Width of grooves v/s surface roughness

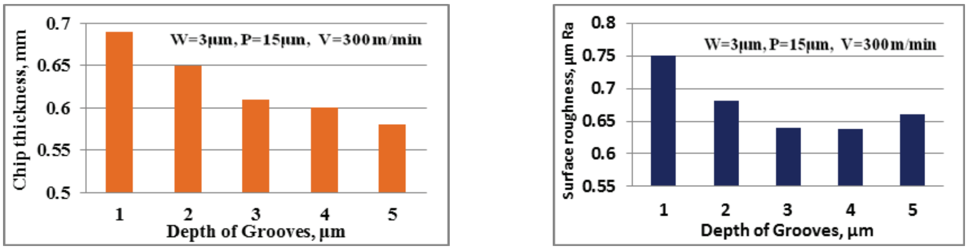
Fig. 8. Effect of width of grooves on various parameters

3.2.3. Effect of Depth of Grooves

Fig. 9 (a) shows that, P_x and P_z decrease steadily with the increase in the depth of grooves. Friction and normal forces also decrease with increase in depth of grooves (Fig. 9 (b)). Fig. 10 (c) shows that, as the depth of grooves increases, chip thickness reduces, which is a favourable machining condition. Surface roughness also decreases with the increase in depth of grooves (Fig. 9 (d)). Deeper grooves store more solid lubricant, MoS_2, and help more in reducing friction and thereby reducing the chip thickness.



(a) Depth of grooves v/s cutting forces (b) Depth of grooves v/s friction & normal forces

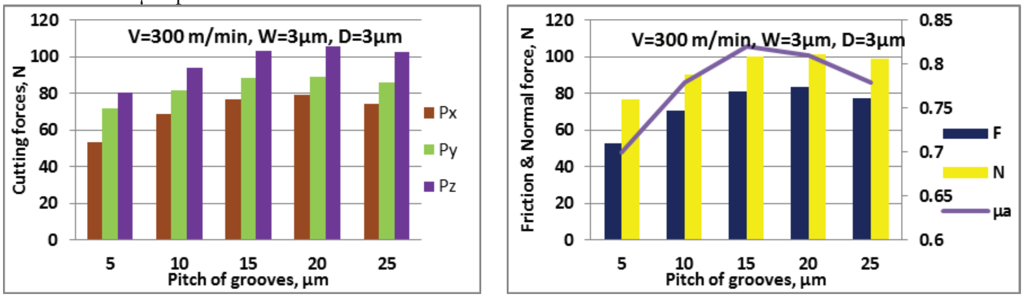


(c) Depth of grooves v/s chip thickness (d) Depth of grooves v/s surface roughness

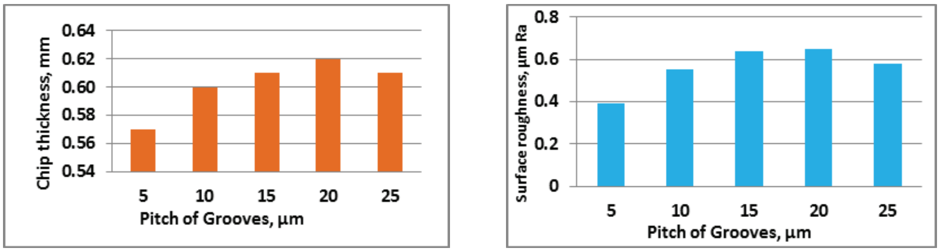
Fig. 9. Effect of depth of grooves on various parameters

3.2.4. Effect of Pitch of Grooves

As the pitch of the grooves increases, cutting forces, friction and normal forces steadily increase Fig. 10 (a) and (b). Surface roughness and chip thickness increase as the pitch of the grooves increases (Fig. 10 (c) and (d)). Smaller pitch is better. Least forces are obtained at 5µm pitch.



(a) Pitch of grooves v/s cutting forces (b) Pitch of grooves v/s friction & normal forces



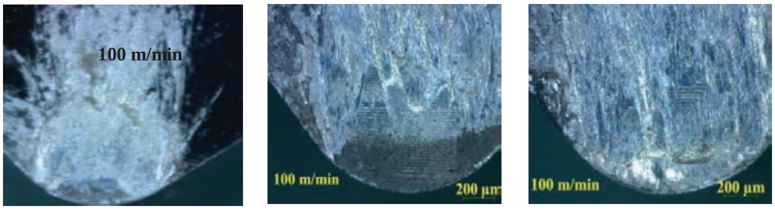
(c) Pitch of grooves v/s chip thickness (d) Pitch of grooves v/s surface roughness

Fig. 10. Effect of pitch of grooves on various parameters

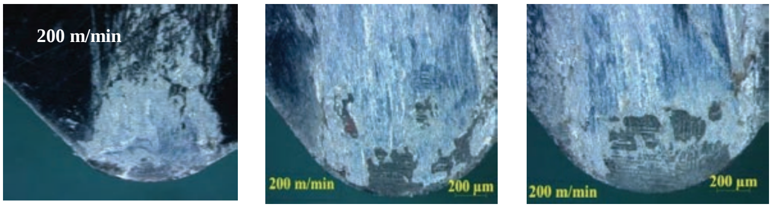
Analysis of the effect of pitch, width and depth of grooves on cutting forces, chip thickness, and surface roughness shows that finer textures (larger width, smaller pitch and larger depth) are more beneficial.

3.2.5. Comparison of cutting tools at different speeds

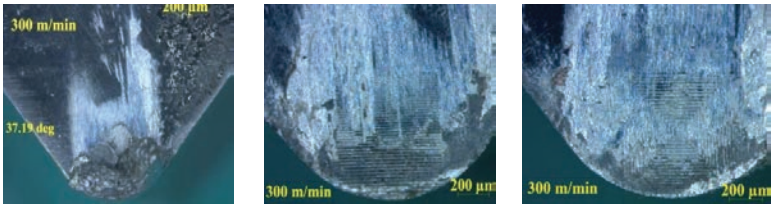
At all cutting speeds, from 100 to 500 m/min, it can be very clearly seen that there is far less sticking of the workpiece material on the rake surfaces of textured tools, especially at cutting speeds from 200 to 400 m/min (Fig. 11). Less sticking of the chip is seen for the square textured tools. The reduction in sticking of chip on the rake surface is the reason for the decrease in cutting force. This again results in improved surface finish and it reduces the built up edge formation. For the same speed, finer grooved (more width and depth and less pitch) tools reduced material sticking more effectively.



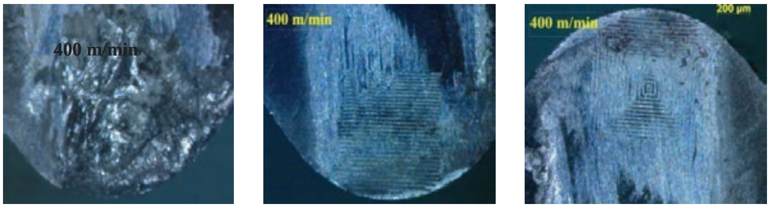
Non-textured (a-1) Linear textured (a-2) Square textured (a-3)



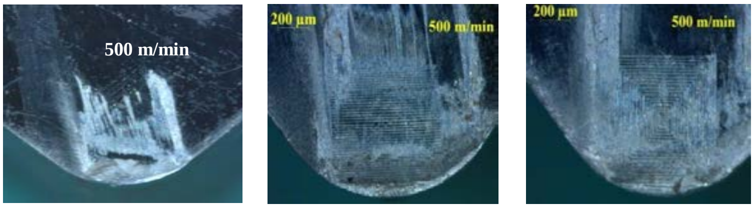
Non-textured (b-1) Linear textured (b-2) Square textured (b-3)



Non-textured (c-1) Linear textured (c-2) Square textured (c-3)



Non-textured (d-1) Linear textured (d-2) Square textured (d-3)



Non-textured (e-1) Linear textured (e-2) Square textured (e-3)

Fig. 11. Comparison of wear tracks of textured and non-textured tools at different cutting speeds

It can also be seen that the sticking area is a little away from the apex. In the sticking zone, high intensity peak of aluminum is observed, which confirms the sticking of aluminum at the rake face of the tool in that zone.

4. Conclusions

Surface textures of two types viz. linear and square were fabricated at the rake face of the WC inserts using focused ion beam machining and were subsequently coated with MoS_2 solid lubricants using pulsed DC magnetron sputtering process. Dry turning tests were carried out on aluminum alloy Al 6063 using these coated textured tools. The following conclusions are arrived at
Textured tools performed better than the non-textured tools in terms of reduced cutting forces and the sticking tendency of the work material to the rake face of the tools. Out of the two types of textured tools produced, square textured tools performed better in terms of reduction of force and sticking of material as compared to the linear textured tools. A reduction of about 30% in cutting forces was observed with square textured tools and that with the linear textured tools was about 20% as compared to the non-textured tools. Chip thickness and surface roughness decrease with the increase in cutting speed, texture depth and width and decrease in texture pitch. There is a clear evidence of reduction in the sticking behaviour of the aluminum alloy while using the textured tools and square textured tools are found to be better.

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