Evaluating the effectiveness of the novel surface textured tools in enhancing the machinability of titanium alloy (Ti6Al4V)

Pankaj RATHOD*, Sivanandam ARAVINDAN* and Venkateswara Rao PARUCHURI*

* Department of Mechanical Engineering, IIT Delhi, Hauz Khas, New Delhi:110016, India
E-mail: aravindan@mech.iitd.ac.in

Received 10 June 2015

Abstract
The effectiveness of the novel micro textured tools developed as an attempt to improve the machinability of Ti6Al4V material is studied. Different types of textures were developed on the rake face of the tools and subsequently coated with a solid lubricant (tungsten disulfide). Square and circular textures are developed for the first time. The textured and coated tools were used for machining Ti6Al4V. Adhesion of the material to the rake face of the tools is observed to be decreased considerably although not eliminated completely. Maximum reduction in the main cutting force was 60% for the square textured tools. Friction at the rake face of the tool is reduced considerably which results in the improvement of tool life. The change in adhesion behaviour and the observed reduction in cutting forces are attributed to the reduction in chip-tool contact area owing to the surface texture on the tool inserts. Further, these textures are acting as reservoirs of solid lubricant. Chip morphology is also found to be favourably altered through the reduction in the segmentation frequency (about 40% for square textured tools and 27% for linear textured tools).

Key words: Dry machining, Tungsten disulfide, Textured tools, Focused ion beam machining

1. Introduction

High strength, low density, and excellent corrosion resistance are the main properties that make titanium alloys favoured for a variety of applications. Examples include aircraft (high strength in combination with low density), aero-engines (high strength, low density, and good creep resistance up to about 550 °C), biomedical devices (corrosion resistance and high strength), and components in chemical processing equipment (corrosion resistance). Ti6Al4V is known as the “workhorse” of the titanium industry because it is by far the most common Ti alloy, accounting for more than 50% of the titanium usage. It is an alpha + beta alloy that is heat treatable to achieve moderate increase in strength.

In spite of its fascinating characteristics, it is considered to be difficult to machine material because of its low thermal conductivity (resulting in high heat generation at the chip-tool interface), high chemical reactivity—especially at high cutting temperature (leading to an accelerated adhesive tool wear) and low modulus of elasticity (causing harmful deflections in the workpieces). (Komanduri and Hou 2002)

Siekmann (1955) pointed out that ‘machining of titanium and its alloys would always be a problem, no matter what techniques are employed to transform this metal into chips’ and, Komanduri and Reed Jr (1983) have commented that ‘this is still true in so far as cutting tool materials are concerned’ (Machado and Wallbank 1990).

Cutting fluids are used to cool the workpiece, cutting tool and chip, lubricate the cutting zone, and carry away the wear debris. But the harmful effects of cutting fluids like fumes, skin irritation and environmental pollution and strict governmental regulations have forced the manufacturers to restrict their use or to totally avoid them i.e. employ dry machining. Dry machining has the advantages of being environmentally benign and human friendly. The wave of using environment friendly production techniques across the globe has forced the producers to do away with cutting fluids and use dry machining as far as possible. During dry cutting, machining performance can be improved by applying a suitable solid lubricant.

High compressive stresses, highly strained work material surface, high chemical reactivity and intimate contact between the tool and chip at high speeds, restricts the entry of any cutting fluid in the cutting area. These conditions lead to unavoidable chemical bonding and interlocking between the work material, chip and tool (Trent 1988).

Tungsten disulfide (WS2) is an excellent lamellar solid lubricant. WS2, as a dry solid lubricant, has a lower coefficient of friction (COF) than molybdenum disulfide (MoS2) and graphite. It has higher resistance to oxidation as compared to MoS2.
and graphite. MoS$_2$ oxidizes at about 400 °C and WS$_2$ oxidizes at about 800 °C. WS$_2$ can also be used in high temperature and high pressure applications. WS$_2$ can be used either by mixing the powder with a wet lubricant like oil, grease or synthetic lubricant and applied at the area of interest, or it can be coated by spraying, burnishing or sputter coating. WS$_2$ gives better performance than MoS$_2$ and graphite, at temperatures higher than 500 °C. WS$_2$ has the benefits of having low COF (0.03 dynamic), anti-galling properties, ability to be used with other lubricants, ability to reduce noise and inert, non-toxic and environmentally friendly. Fluid lubricants have difficulty in reaching the cutting area while solid lubricants can be applied beforehand exactly at the cutting zone. The shear strength of the tungsten disulfide (WS$_2$) is about 20 MPa, while the shear strength of the carbide tool material is in the range of 700–800 MPa (Sugihara and Enomoto 2009).

Recently researchers are interested in producing micro/nano structures on cutting tool inserts in order to reduce the friction at the chip-tool interface using different micro-machining processes; photolithography (Obikawa et al. 2011), femto-second laser (Kawasegi et al. 2009; Lei et al. 2009; Sugihara and Enomoto 2009; Lian et al. 2013), laser machining (Enomoto et al. 2012; Jianxin et al. 2012; Ze et al. 2012) micro-EDM (Jianxin et al. 2009; Koshy and Tovey 2011; Wenlond et al. 2011), micro-grinding (Xie et al. 2012). Only a limited number of studies are available on machining of Ti alloys using textured tools. (Xie et al. 2012; Ze et al. 2012; Xie et al. 2013; Sun et al. 2014) In terms of shape (micro-dimples, linear, square dots, square pits, pyramidal, etc.), size (from few nanometers to about 150 microns) and orientation of textures (linear parallel or perpendicular to the chip flow direction, elliptical, pits, dots, pyramid, etc.), variations are found. In this study, we have manufactured novel surface textured tools and coated them with WS$_2$ solid lubricant. It has been proved beyond doubt that the textures on the rake face of the cutting tools reduce friction, cutting forces, heat generation, and improve tool life in presence of solid or liquid lubricants and without lubricants as well. The present study attempts to prove that the newly developed textures namely, square and circular, produced using Focused Ion Beam (FIB) machining are probably better than the previously attempted textures in improving the machinability of titanium alloy Ti6Al4V.

2. Experimental Procedure

The tool used for machining titanium alloy Ti6Al4V is PCLNL2020K12 plain WC insert. The important dimensions of the tool are inclination angle ($\lambda_s$) = -6°, orthogonal rake angle ($\gamma_o$)= -6°, nose radius (Re) = 0.8mm.

The Micro/Nano textures at the chip-tool contact interface in this research are produced at the rake surface of the tool by using direct writing capability of the focused ion beam machining. FIB has the capability to produce very intricate structures with utmost accuracy and precision on almost all conducting materials with negligible surface or sub-surface damage to the components. The process parameters such as beam current (42nA), beam voltage (16kV) and beam overlap (50%) are optimized to ensure that the grooves are produced with optimum accuracy and surface finish.

The following three types of textures are produced on the rake surface; (a) the textures with linear grooves (Fig.1 a) are produced perpendicular to the chip flow direction (CFD), (b) the textures with square grooves (Fig.1 b) being a combination of parallel and perpendicular (to the CFD) grooves, and (c) textures with circular grooves (Fig.1 c). The width of the pattern is about 700μm and length along the chip flow direction is also 700μm. Fig.1 (d) shows the WS$_2$ coated tool and Fig.1 (e) shows the SEM image of the same tool without coating. The textures are produced 50μm away from the cutting edge in order to retain the strength of the tool at the apex. The square and circular textures are produced for the first time as far as textured tools are concerned.
The width (1 to 5μm), pitch (5 to 25μm) and depth (1 to 5μm) of grooves are varied to study their effect on the cutting forces, wear characteristics and the surface finish of the workpiece.

To improve the adhesion strength of WS$_2$, it was common to incorporate an interlayer between the coating and the substrate material (Lian et al. 2013). Zirconium interlayer was deposited using pulsed DC magnetron sputtering with the following parameters: base pressure=1.0x10$^{-5}$ mTorr, working pressure=5x10$^{-3}$ mTorr, power to target=30 W, gas flow rate=40 SCCM (Standard Cubic Centimeter per Minute), deposition time=10 min. Sputtered coating provides a very smooth and uniform layer of the solid lubricant on the insert and it has a longer life than the burnished layer. The structured inserts were then coated by WS$_2$ with pulsed DC magnetron sputtering. The sputtering parameters are; base pressure=1.0x10$^{-5}$ mTorr, working pressure=5x10$^{-3}$ mTorr, power to target=80 W, gas flow rate=40 SCCM, deposition time=60 min. Thickness of the coating is around 600 nm as shown in Fig. 2.

The experimental setup is shown in Fig. 3. Ti6Al4V alloy round bar of diameter 50 mm was turned with the textured, WS$_2$/Zr coated inserts 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). The dynamometer is attached to the turret with the help of a machine adapter and the tool holder is fixed on the dynamometer. The cutting parameters were; feed rate=0.1 mm/rev, depth of cut=0.5 mm and cutting speed was varied from 60 m/min to 140 m/min. Feed rate and depth of cut were kept constant throughout the experiments. Experimentation was carried out using various textured tools at different cutting speeds. No cutting fluid was used. For, each experiment, a new tool was used. The length of cut in each experiment was 50mm. Experiments were designed using central composite design. Hence, with four variables and five levels, 30 experiments were conducted with textured tool to evaluate the effect of all the parameters (depth, width and pitch of the grooves in the textures and cutting velocity) on cutting forces and surface finish during Ti6Al4V machining. Table 1 shows the chemical composition of work material.

| Table 1 Titanium Alloy Ti6Al4V |
|-------------------------------|
| Element | Content Wt % | Element | Content Wt % |
| Carbon   | -            | Titanium | 89.97       |
| Aluminum | 6.05         | Vanadium | 3.82        |
| Si       | 0.1          | Iron     | 0.05        |
| Oxygen   | -            | Hydrogen | -           |
| Other Total | 0.01       | Other Total | 0.01       |

Fig. 1 Types of surface textures developed at the rake face of cutting tools

Fig. 2 Coating of WS$_2$ on the substrate

Fig. 3 Photographic view of the Experimental Setup

[DOI: 10.1299/jamdsm.2015jamdsm0035] © 2015 The Japan Society of Mechanical Engineers
The responses measured were the cutting force components (main cutting force, axial thrust force and radial thrust force) and surface roughness. For force measurement, a dynamometer (Kistler 9129AA) with charge amplifier (multichannel charge amplifier type 5070A) was employed. The forces reported were measured when the process was in the steady stable state. Surface roughness of the machined surface was measured by Form Talysurf surface roughness tester.

3. Results and Discussion

3.1. Comparison of textured tools with non-textured tools

To assess the effectiveness of the various textured tools, the cutting forces obtained were compared with those obtained with non-textured tools. The non-textured tools were also coated with WS$_2$/Zr. All the textures had the dimensions $3\mu m$ width, $3\mu m$ depth and $15\mu m$ pitch. The results obtained are shown in Fig. 4.

![Fig. 4 Effect of speed on cutting forces on different types of textures](image)

(Note: For the entire discussion, NT=Non-textured tool, Li=Linear textured tool, Sq=Square textured tool, Cr=Circular textured tool, $P_x$=axial thrust force, $P_y$=radial thrust force, $P_z$=main cutting force, $\mu_a$=apparent coefficient of friction)

It can be seen from Fig. 4 (a), (b) and (c) that the textured tools exhibit less forces when compared to the non-textured tools over the entire range of speeds from 60 to 140 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 all speeds. Same is the case for the friction force and normal
force, as shown in Fig. 4 (d) and (e). The friction force \( F \) and normal force \( N \) and coefficient of friction \( \mu_a \) have been calculated from the formulae (Bhattacharyya 1984)

The largest reduction can be seen in the axial thrust force and little less in radial thrust force, which are highly correlated with friction force. It can be seen that square grooved textures are more effective in reducing the cutting forces than linear grooves and circular grooves. Circular grooves are a little less efficient than square grooves but, the time taken to produce these grooves is half that of square and linear grooves using FIB.

The least forces achieved with square textured tool with texture dimensions width=3μm, Depth=3 μm and pitch=5 μm at 100 m/min cutting speed are \( P_x=30.29 \) N, \( P_y=53.09 \) N and \( P_z=88.53 \) N. While the least forces achieved with non-textured tools at 80 m/min cutting speed are; \( P_x=67.25 \) N, \( P_y=85.13 \) N and \( P_z=146.87 \) N. There is a reduction of 60.28 % in the main cutting force \( P_z \) in the case of square textured tools which confirms the potentiality of textured tools.

3.2. Chip formation

Machinability of a material can be evaluated from surface quality, tool wear and life, and power consumption (cutting forces). It has been observed that these criteria are directly related to the mechanism of chip formation and separation.

The low thermal diffusivity of Ti alloys gives rise to very high temperatures at the tool–chip interface, which increases the rate of tool wear and cutting forces. Low thermal conductivity gives rise to heat accumulation in the primary shear zone, which contributes to shear localization and chip segmentation, which in turn can cause harmful tool/workpiece vibrations. (Liu et al. 2013) Shear localized chips are formed during machining of Ti6Al4V alloy at very low cutting speed (about 9 m/min). Komanduri and Hou (2002) have propounded that the thermoplastic instability (strain hardening v/s thermal softening) as well as the generation of micro-cracks in the shear band can cause the reduction in shear strength of the material in the shear band. Other mechanisms proposed for this shear instability include structural transformation, as in the reversion of martensite to austenite in some steels. The first mechanism of shear instability (namely, thermal softening v/s strain hardening) appears to be operational at the higher cutting speeds, while the second mechanism appears to be operational at the lower cutting speeds, where adiabatic conditions are unlikely to be the case.

In the periodic segmented chip region, the segmentation frequency can be calculated through dividing cutting speed by the length of undeformed surface. (Sun et al. 2009)

Fig. 5 shows the cross-section of a typical segmented chip in machining of Ti6Al4V alloy. The slipping angle \( \theta \) is defined as the angle between the shear band and the tangent of the machined surface at the end of the shear band. \( L \) is the undeformed surface length. The segmentation frequency (average distance between the two consecutive shear bands) is given by

\[
f_c = \frac{V}{L} \tag{1}
\]

Where \( f_c = \)chip segmentation frequency, kHz, \( V= \)cutting speed, m/sec and \( L= \)undeformed surface length, m

Fig. 5 Cross-section of a typical segmented chip in machining of Ti6Al4V alloy. (Sun et al. 2009)

Fig. 6 shows the side images of chips at different cutting speeds with tools having different texture dimensions (width, depth and pitch). The side images of the chips at different speeds and with different texture dimensions show that the segmentation frequency and the slipping angle depend not only on the cutting speed but also vary with the dimensions of the
texture. The first digit in each figure represents cutting speed in m/min, second digit width in microns, third digit depth in microns and fourth digit pitch of the grooves in microns. All the figures are for square grooved tools, unless otherwise specified. It can be seen that for every speed and with the changes in the texture dimensions or type of texture (no texture, circular, linear or square texture), the segmentation frequency and slipping angle are different. It should also be noted that increase in depth and width of the texture decreased the segmentation frequency. Increase in pitch, increases the segmentation frequency.

(1) 60-3-3-15  
(2) 60-3-3-15 linear  
(3) 60 No grooves  
(4) 80-4-2-20  
(5) 80-4-2-10  
(6) 80-4-4-20  
(7) 80-3-3-15  
(8) 80-2-2-10  
(9) 80-2-2-20  
(10) 80-3-3-15 circular  
(11) 80 No grooves  
(12) 100-3-3-25  
(13) 100-3-1-15  
(14) 100-3-3-15  
(15) 80-3-3-15 linear
As can be seen from Fig. 7(a) that with the increasing cutting speed, the segmentation frequency also increases. Segmentation frequency for the textured tools is less than that for the non-textured tools. Square grooved tools perform better in terms of segmentation frequency and this can also be correlated with the reduction in cutting forces and improvement in surface finish. Fig. 7(b) illustrates the reduction in segmentation frequency using textured tools in comparison with the non-textured tools. Chip segmentation frequency is reduced by 40% for the square textured tools and 27% for the linear textured tools as compared to the non-textured tools at 80 m/min cutting speed (Fig. 7b). The reduction in segmentation frequency is
instrumental in reduction of the cutting forces. Reduction in segmentation frequency leads to reduced vibrations in the workpiece during machining ultimately leading to improved surface finish.

![Graph showing effect of cutting speed on segmentation frequency](image)

Fig. 7 Effect of cutting speed on segmentation frequency (NT=Non-textured, L=linear texture, Sq= Square texture)

The tool–chip contact length is an important parameter because it represents the length of seizure and the frictional interface that generates heat along the secondary deformation zone of the chip, in addition to being the contact interface that transfers the heat generated at the primary shear zone into the tool. It is reasonable to expect that a shorter tool–chip contact length will result in greater coolant penetration, greater cooling efficiency and longer tool life (Bermingham et al. 2012). Chip contact length for Ti6Al4V is given by (Iqbal et al. 2009)

\[
L_c = 1.15 \times t_2 + 0.70 \times t_1
\]

(2)

For example, measured chip thickness, \(t_2=0.135\) mm at cutting speed 80 m/min for non-textured tool

Where \(t_1=\) undeformed chip thickness= \(f \times \sin\Phi = 0.1 \times \sin95=0.1\) mm

\(L_c=0.225\) mm

Where \(f =\) feed mm/rev, and \(\Phi =\) tool approach angle.

But on measurement, the tool-chip contact lengths at 80 m/min for different textured tools are 0.179mm (Fig. 16 b), 0.157mm(Fig. 16 d), 0.201mm (Fig. 16 h) and 0.207mm (Fig. 16 g), which is the effect of the texture. For the non-textured tool, it is 0.223mm (Fig. 17 b). Thus, textured tools give considerably smaller chip-tool contact length, and as a consequence, improve tool life. This is possibly converted to reduced heat generation and reduced heat transfer to the tool. The results obtained by Bermingham et al. also support the above argument on the increased tool life with reduced chip-tool contact length (Bermingham et al. 2011).

Fig. 8 shows the EDX at the underside (side in contact with the rake face of the tool) of the chip. The sulfur and tungsten at the underside of the chip has come from the WS\(_2\) coating which is responsible for the reduction in friction between the chip and tool.
3.3. Analysis of the cutting performance of square textured tools

Since square textures were found to be the best among the three types of textures under consideration, experiments were conducted with square textured inserts. Fig. 4 illustrates the variation in cutting forces with the variation in cutting speed from 60 m/min to 140 m/min.

3.3.1 Effect of cutting speed

It can be seen from the Fig. 9 (a) and (b) that as the cutting speed is increased from 60 m/min to 140 m/min, cutting forces, friction and normal forces, and coefficient of friction increased. The cutting forces are minimum at 80 m/min speed. In the machining of Ti6Al4V, there is a significant increase in the thrust force (axial and radial) with an increase in cutting speed which could be due to the increase in deflection of the workpiece because of the low modulus of elasticity of Ti6Al4V material. It is also clear that the coefficient of friction for the textured tools is less than that for the non-textured (NT) tools.

The relationship between thrust force and cutting speed in machining Ti6Al4V is governed by the interfacial conditions on the tool rake face; namely, welding between the chip and the tool (Barry et al. 2001).

Chip thickness increases and shear angle reduces [Fig. 9 (c) and (d)] as the cutting speed is increased, which is consistent with the above observation. Surface roughness [Fig. 9 (e)] is observed to be increased with the increase in cutting speed from 60 m/min to 140 m/min. The reason could be the increase in deflection of the workpiece with speed due to low elastic modulus of the Ti6Al4V titanium alloy. Increase in chip segmentation frequency with increase in cutting speed also is responsible for the increase in surface roughness.
3.3.2. Effect of Width of grooves

Fig. 10 shows the influence of the variation in the width of the grooves on the various parameters viz. cutting forces, friction and normal forces, chip thickness and surface roughness. It can be seen from Fig. 10 (a) and (b) that as the width of the grooves is increased from 1μm to 5μm, cutting forces, friction and normal forces and the coefficient of friction are observed to be decreased. In the selected range of width of the grooves, highest width i.e. 5μm, gives the least forces. Chip thickness reduces with the increase in the width of the grooves in the selected range (Fig. 10c). Surface roughness also reduces with the increase in the width of the grooves (Fig. 10d), which is consistent with the above observations. The reason is, as the width of the grooves increases, the capacity of the grooves to retain the solid lubricant increases and there is a better supply of solid lubricant between the underside of the chip and rake face of the tool insert.

3.3.3. Effect of Depth of grooves

Fig. 11 shows the influence of the variation in the depth of the grooves on the various parameters viz. cutting forces, friction and normal forces, chip thickness and surface roughness.
As the depth of the grooves is increased from 1μm to 5μm [Fig. 11 (a) to (c)], cutting forces, friction and normal forces and the coefficient of friction decrease steadily. In the selected range of depth of the grooves, highest depth i.e. 5μm, gives the least forces. Chip thickness [Fig. 11 (d)] reduces with the increase in the depth of the grooves in the selected range. Surface roughness also reduces with the increase in the depth of the grooves, which is consistent with the above observations. Same as the effect of width of the grooves, with the increase in the depth of grooves, the capacity of the grooves to store the solid lubricant increases and there is a better supply of solid lubricant between the underside of the chip and rake face of the tool insert.

Fig. 11 Effect of depth of grooves on various parameters

3.3.4. Effect of Pitch of grooves

Fig. 12 illustrates the influence of the variation in the pitch of the grooves on the various parameters viz. cutting forces, friction and normal forces, chip thickness and surface roughness.

As the pitch of the grooves (distance between the consecutive grooves) increases from 5μm to 25μm, the cutting forces increase steadily till 15μm and then decrease [Fig. 12 (a) and (b)]. Same is the trend with the chip thickness and surface roughness [Fig. 12 (c) and (d)]. Best performance is obtained at 5μm pitch.
In summary, with the increase in the width (Fig. 10 c) and depth (Fig. 11 d) of the grooves chip thickness is reducing due to the reduction in friction force as a result of better lubrication at the chip-tool interface caused by increased capacity of the texture to retain solid lubricant. Same is the case with the increase in pitch (Fig. 12 c) causing increase in chip thickness due to increased friction at the chip-tool interface.

Since, \[ \tan \beta_0 = \frac{\cos \gamma_0}{\xi \sin \gamma_0}, \]

Where \( \beta_0 \) is shear angle, \( \gamma_0 \) is orthogonal rake angle, and \( \xi \) is chip reduction coefficient=\( t_2/t_1 \), \( t_1 \) is undeformed chip thickness and \( t_2 \) is actual chip thickness. The corollary is as chip thickness decreases, shear angle increases.

From the above discussion, it is very clear that there is a definite relationship among the dimensions of the texture (width, depth and pitch) and the performance of the cutting tools. The speed 80 m/min and dimensions of the texture, width=5μm, depth=5μm and pitch= 5μm gave the best results.

### 3.4 Analysis of Tools

#### 3.4.1. Discussion on tool wear

Consideration of tool wear is very important from the point of view of cost control and cost optimization during machining of Titanium alloys. During machining of titanium alloys, because of the very low thermal conductivity (about 1/6th of steel) of the alloy, most of the heat is concentrated at the apex of the tool insert. The tip is subjected to very high thermal stresses. The heat buildup at the tip of the tool causes faster plastic deformation, chipping and adhesive and diffusive wear of the tool tip, and eventually leads to catastrophic failure. The very high chemical affinity of titanium alloys with almost all tool materials aggravates the problems of diffusion wear. These typically limit the cutting speeds and feeds and eventually the productivity. (Kuttolamadom et al. 2012)

Fig. 13 shows the difference in the wear characteristics of tools while machining steel and titanium alloys. Komanduri and Reed Jr (1983) have stated that the two modes of wear in the machining of titanium alloys are; partial cratering at the apex of the tool and flank wear on the clearance face. In the conventional form of crater wear, which occurs mostly in the machining of steels, the crater begins a slight distance away from the tool edge and progresses gradually to an increasing depth. The shape of the crater is somewhat like an ellipsoid. By contrast, in the machining of titanium alloys, the maximum crater depth occurs at the apex and only half the crater is formed.
At cutting speeds from 61 m/min to 122 m/min, crater wear limits the tool life in machining Ti6Al4V titanium alloy. Flank wear is stable and does not contribute to tool failure until crater wear weakens the edge and plastic deformation of the cutting edge causes acceleration of the wear at the flank. (Hartung et al. 1982) Therefore, it is more beneficial to create the textures on the rake face than the flank face of the tool insert.

As stated in section 2, for each experiment, a new tool was developed and the length of cut in each experiment was 50mm.

![Characteristic wear behaviour of WC tool when machining Ti6Al4V](image)

As can be seen from Fig. 14, the sticking of titanium material takes place at the apex of the cutting tool insert. The thickness of the sticking layer is about 1μm. In Fig. 14 and 15, (a) is the sticking zone, (b) is the zone within the groove and (c) is the zone outside the groove. The thickness of the sticking layer is measured at the area ‘A’ in the sticking zone. The EDX images are for the tool at 100 m/min cutting speed and groove dimensions depth=3μm, width=3 µm and pitch=15 µm.

![EDX showing elements in the sticking zone](image)
From Fig. 15 (a) in the sticking zone, it is very clear that titanium, aluminum and vanadium have come from the chip. There is more sulfur inside the groove. Grooves behave like reservoirs for the solid lubricant. Even after the coating has been removed from the surface (Fig. 15 c), solid lubricant stored in the grooves is being continuously fed between the chip and the rake face of the tool (Fig. 15 b), which is the cause of reduction in friction between the chip and tool.

The adherent deposits of chip material i.e. Ti, Al and V found on the rake surface in the sticking zone, is an indication of intimate adhesion between the chip and the tool rake surface.

3.4.2. Wear characteristics of different tools
Fig. 16 Wear tracks and sticking behaviour for square textured tool inserts.
Fig. 16 presents the wear tracks and sticking behaviour for square textured tool inserts. Figure with suffix 1 indicates the condition of the tool prior to machining and suffix 2 indicates condition of the tool after machining. The first digit in each figure represents cutting speed in m/min, second digit width in microns, third digit depth in microns and fourth digit pitch of the grooves in microns. As it can be seen from the tool images in Fig. 16, whatever the dimensions of the texture, sticking of material at the apex of the insert increases with the increase in speed. Although the textured tools cannot prevent the sticking of the material altogether, they reduce the tendency of sticking considerably. All the textures are prepared 50μm away from the edge of the inserts considering strength of the insert at the apex.

![Fig. 16](image1)

(a) 60 m/min                              (b) 80 m/min           (c) 100 m/min  
(d) 120 m/min                        (e) 140 m/min

Fig. 17 Sticking behaviour at the non-grooved tool inserts

Fig. 17 shows the sticking behaviour at the non-grooved tool inserts at different speeds. It can be seen that as the cutting speed increases, the tool-chip contact length also increases except at 140 m/min where it decreases a little.

An attempt was made to start the texture right from the edge of the insert to see whether it makes any difference in the sticking behaviour of the material (Fig. 18). The dimensions of the texture were 3W-3D-15P and machined at 100 m/min. Only the square grooves proved to be a little more effective in reducing the sticking of the material.

![Fig. 18](image2)

(100-3-3-15) (a)                     (b)              (c)

Fig. 18 Tool inserts having textures without any gap between the texture and the cutting edge.
It can also be seen that as compared to the non-textured tools there is a lot less sticking of the material on textured tools, except at 140 m/min cutting speed where the sticking is more in case of textured tools.

4 Conclusions

Three different types of textures were created at the rake face of the cemented carbide inserts. The textured tools were subsequently coated with Zr/WS$_2$ solid lubricants using pulsed DC magnetron sputtering. Turning tests were carried out on Ti6Al4V alloy using these textured and coated tools. The following conclusions were arrived at:

1. The square textures were observed to be more efficient in reducing cutting forces and friction at the chip-tool interface as compared to the linear and circular textures.

2. The observed reduction in friction force can be attributed to:
   - Reduction in chip contact area.
   - Influence of the WS$_2$ solid lubricant.
   - The grooves of the pattern act as a reservoir of WS$_2$.
   - There is better heat conduction and less heating of the tool tip owing to larger surface area resulted due to the patterns.

3. Chip thickness reduces with the increase in depth and width of the texture and increases with the increase in pitch of the texture. Consequently, shear angle increases with increasing groove depth and width and decreases with increase in pitch of the grooves.

4. Cutting forces decrease with increase in depth and width of the texture and increase with increase in pitch of the texture. The highest reduction in the main cutting force observed is 60.28%. The lowest cutting forces observed are at 80 m/min cutting speed, 5μm width, 5μm pitch and 5μm depth from among the selected range of variables.

5. The surface textures effectively reduce the adhesion of work material to the rake face of the cutting tool and in a way, reduce the heat generation and cutting forces and improve tool life.

6. Chip segmentation frequency reduced by 40% for the square textured tools and 27% for the linear textured tools as compared to the non-textured tools at 80 m/min cutting speed. The reduction in segmentation frequency is instrumental in reduction of the cutting forces.

7. Reduction in friction reduces the cutting heat and plastic deformation of the work/tool material and as a result, it improves the machinability of the work material. The texture reduces friction between the tool rake face and chip surface by controlling the mechanical and tribological properties at the rake surface.

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