# Experimental Comparative Study of Conventional andMicro-Textured Tools during Machining of AISI 1040 Alloy Steel

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## Abstract

In the field of dry machining, recent researchindicates that surface texture has potential to influence tribological conditions. However, very little attention has been given to controlled surface texturing of cutting tools. An experimental study of the performance of the micro-texture high speed steel (HSS) grade M2 cutting tool in machining of AISI 1040 steel samples is carried out. Surface textures were made using Rockwell hardness tester on rake face of the HSS M2 tool. Structural analyses are done on cutting tool using ANSYS workbench to evaluate the effect of micro-texture on the stresses and strains generationat cutting edge of the cutting tool in cutting operations. It is found that the effect of micro-texture on stress generation is very small which can be neglected. Dry cutting tests were carried out on AISI 1040 steel sample using lathe machine with micro-textured tools and conventional cutting tool for a varying range of feed and cutting speed. The machining performance was analyzed in terms of feed force, cutting force and coefficient of friction. The results demonstrate that the surface texture on the rake face of cutting tools significantly reduces cutting forces and coefficient of friction when compared with that of the conventional tool.

*Keywords*: Surface texture, Cutting tools, Dry cutting

## 1. Introduction

Severe friction exists as the chip flows over the rake face and the tool flank of the cutting tool in dry machining. Relative motion between the tool and chip surfaces produces frictional heating to the cutting tool, resulting in high temperature at the tool–chip interface. As a result, crater and flank wear develops quickly on the tool rake face and flank face under the high pressure, high temperature and sliding speed at the interface. According to Shaw (1984), wear processes involve both chemical and mechanical interaction between contacting surfaces and are very complex in nature, which are mostly governed by the cutting speeds, the cutting forces and the chemical composition of workpiece and tool materials. As expressed by Kramer (1991): “Metal machining have a unique tribological situation in which clean surfaces are cleaved from the interior of the workpiece and maintained in a condition of nearly 100% real area of contact with the tool surface during sliding.”Therefore, decreasing the contact area between the tool-workpiece interface and tool-chip interface is of particular interest in mechanical micromachining. The friction and adhesion between tool and chip is tend to be higher in dry cutting operation, which causes high wear rates, high temperature generation, which ultimately results in shorter tool life. This motivates researchers like Deng et al. (2009) and Renevier and Hamphire (2001) to develop new cutting tool with self-lubricating properties to reduce cutting temperature by reducing coefficient of friction between contact surfaces. Few self-lubricationapproaches have been attempted, out of those methods; Deng et al. (2006) used a ceramic tool with burnishing of $CaF_2$ solid lubricants over rake face of cutting tools. By experimentation, they observed that the friction coefficient between the tool-chip interfacesis decreased in dry cutting with ceramic tool burnished with $CaF_2$ solid lubricant as compared with that of tool without solid lubricants. Liu et al. (1999) have found that coating of $MoS_2$ or $MoS_2$/Ti over tool surfaces can enhance the tribological properties.

Enomoto and Sugihara (2010) attempted surface texturing of tool to improve tribological properties of lubricated surface, and the presence of artificially created micro-dimples on frictional surface results in substantial reduction in friction and wear as compared with non-textured surfaces.Surface texturing as a means for enhancing tribological properties of mechanical components has received a great deal of attention and has already been put to practical use in some fieldssuch as a piston/cylinder system by Etsion (2004).Various different processes are used for texturing from conventional machining to focused energy-beam processes, due to which improvement is attributed to several physical mechanism such as local supply of lubricant increases by creation of lubricant reservoir, wear debris entrapment and also increase of load carrying capacity by a hydrodynamic effect as mentioned by Basnyat (2008). For example, Jayal et al. (2008) employed uncoated cemented tungsten carbide tools with rake surfaces ground to different tolerance levels during production and observed that several surface texture parameters for the tool’s rake surfaces had significant effects on measured cutting forces and estimated tool-chip interface temperatures during dry continuous orthogonal machining of AISI 1020 steel. Sugihara and Enomoto (2009) developed a cutting tool with nano/micro textured surface utilizing femto-second laser technology to improve anti-adhesive effects by considering the texture patterns. Deng et al. (2011) made micro holes on the rake or the flank face of cemented carbide (WC/Co) tools using micro-EDM, MoS$_2$ solid lubricants were filled into the micro holes. Results shows that these kinds of self-lubricating tools reduces cutting friction at the tool-chip interface and cutting forces as compare to the conventional cutting tool.

In the present study, surface textures were fabricated over high speed steel M2 cutting tool using Rockwell hardness tester. Turning of AISI 1040 steel cylindrical bar having hardness of 13HRC is carried out using HMT lathe. Cutting forces were measured by KISTLER piezoelectric dynamometer.Size of indent over the textured surface was measured using optical microscope and 3-D surface profilometer. Structural analyses are done on cutting tool using ANSYS workbench to evaluate the effect of micro-scale texture on the stress generationat the cutting edge in cutting operations and scanning electron microscope (SEM) was used to show wear debris entrapment phenomena.

## 2. Experimental procedures

### 2.1 Preparation of cutting tools with micro-scale textures over rake face

Surface textures were created using Rockwell hardness tester on rake face of the cutting tool. Fig. 1 shows the conical dimple micro-textured cutting tool, microscopic image of the conical dimple, 3-D surface profile of conical dimple.Diameterand depth of indents are measured from the optical microscope and 3-D surface profilometer. Conical dimples have average diameterand depth of 150.45 μm and 52 μm respectively were created.

### 2.2 Cutting experiments procedure

Cutting experiments are done on lathe machine using conventional cutting tools and micro-textured cutting tools. Cutting forces are measured using KISTLER dynamometer as shown in Fig. 2.High speed steel grade M2 cuttingtools were used for cutting operation having $0^0$ rake angle, 75° cutting edge angle, 6° clearance angle, 0° inclination angle and 0.8mm nose radius with input condition for cutting operations as given: feed 0.04-0.92 mm/rev, cutting speed 7.8-37.5 m/min, and depth of cut0.5 mm is kept constant. The workpiece material used for cutting operations is AISI 1040 steel. Experiments were performed with conventional tools (CT) and micro-texture cutting tools (TT).

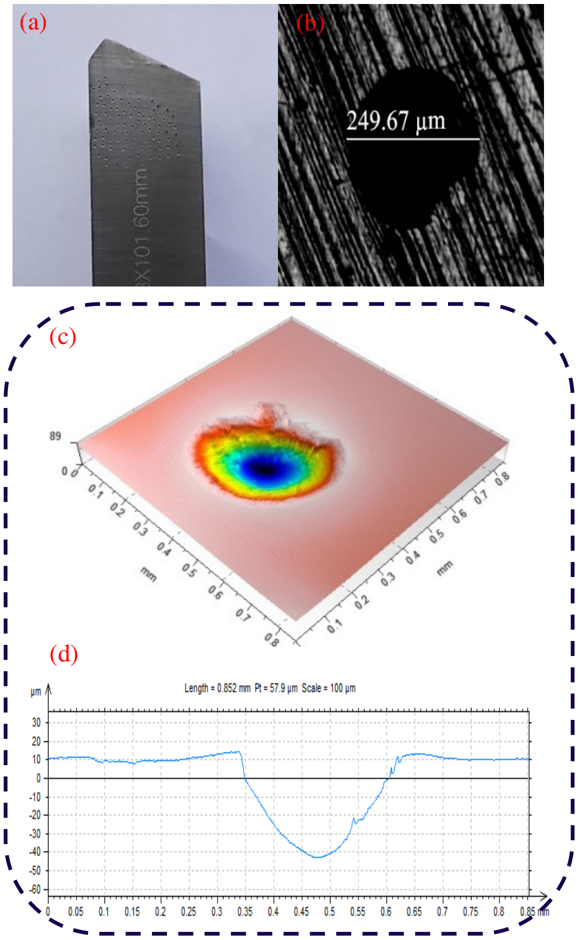

**Figure 1 Micro-textured cutting tool: a) textured tool image, b) microscopic image, c)3-d profile ofmicro-texture, and d) 2-d surface profile of micro-texture**

## 3 Results and discussion

### 3.1 Structural analysis of cutting tool

To evaluate the effect of micro-texture on the mechanical properties like stress generation of the tool under cutting forces Finite Element Analysis (FEA) is done. Structuralanalyses are done using ANSYS workbench. Cutting tools are modeled in Pro-E software and then imported to the ANSYS workbenchfor analyses. Structural analyses are done on the conventional tool (CT) and dimple micro-texturedcutting tool (DT). Cutting forces are applied on the cutting edge of tool in cutting and feed directions are taken from literature Deng Jianxin et al. (2011).The mechanical properties for the high speed steel cutting tool are selected as density ρ= 8.169g/cm3, Young's modulus of elasticity E=210GPa and Poisson's ratio υ=0.3. The maximum Von Mises stresses and strains in cutting tools due application of loads is show in the Fig. 3 (a) – 3 (d).It is quite clear from the simulation results that there is not much difference in von Mises stress and strain along the main cutting edge from the tools with and without rake face texturing. However, it can be observed from the figure 3(a)-(d) that the von Mises stress and strains near the cutting tip are very less for both conventional and textured tools. Therefore it can be concluded from the analysis that the rake surface texturing of the cutting tool do not affect that much on the mechanical strength of the tools. This conclusion is supported by actual machining experiments because no catastrophic failure occurred for the tools with textured rake face. The main reason is that the rake face texturing is relatively away from the cutting edge where the load is most severe during machining (Jianxin et al. 2012).

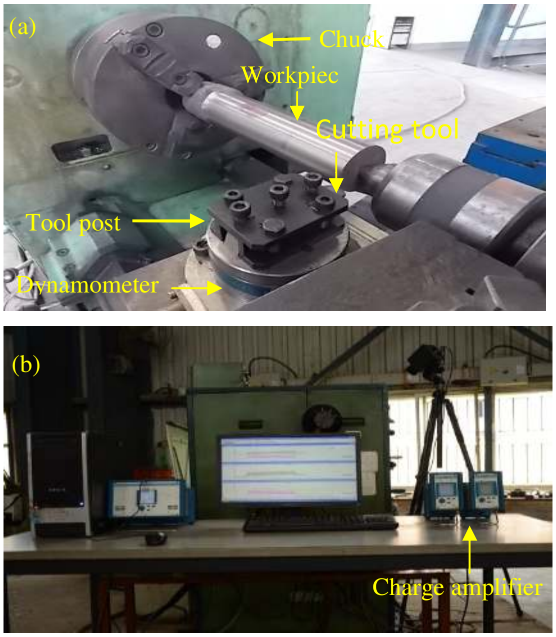

**Figure 2 Experimental setup for orthogonal cutting: a) lathe and b) data acquisition system**

### 3.2 Cutting forces

The cutting and feed forces are measured by usingKISTLER piezoelectric dynamometer. All experiments were done for 3 times and theaverage values of the cutting forces are takenfrom the forces obtained by dynamometer.The cutting forces obtained in the micro-textured tool are less compared to normal conventional tool. This is due to the reduction in real contact area between the tool and chip interface due to the presence of number of micro-dimpleswhile using micro-textured tool as compare to the normal conventional cutting tool.

### 3.3 Force analysis

Cutting experiments are carried out using input conditions as shown in the table 3 for conventional tool (CT) and micro-texturedcutting tool (TT). Depth of cut is kept constant as 0.5 mm. The cutting force and feed force are measured while cutting operation on lathe. Variations of forces for different feed and

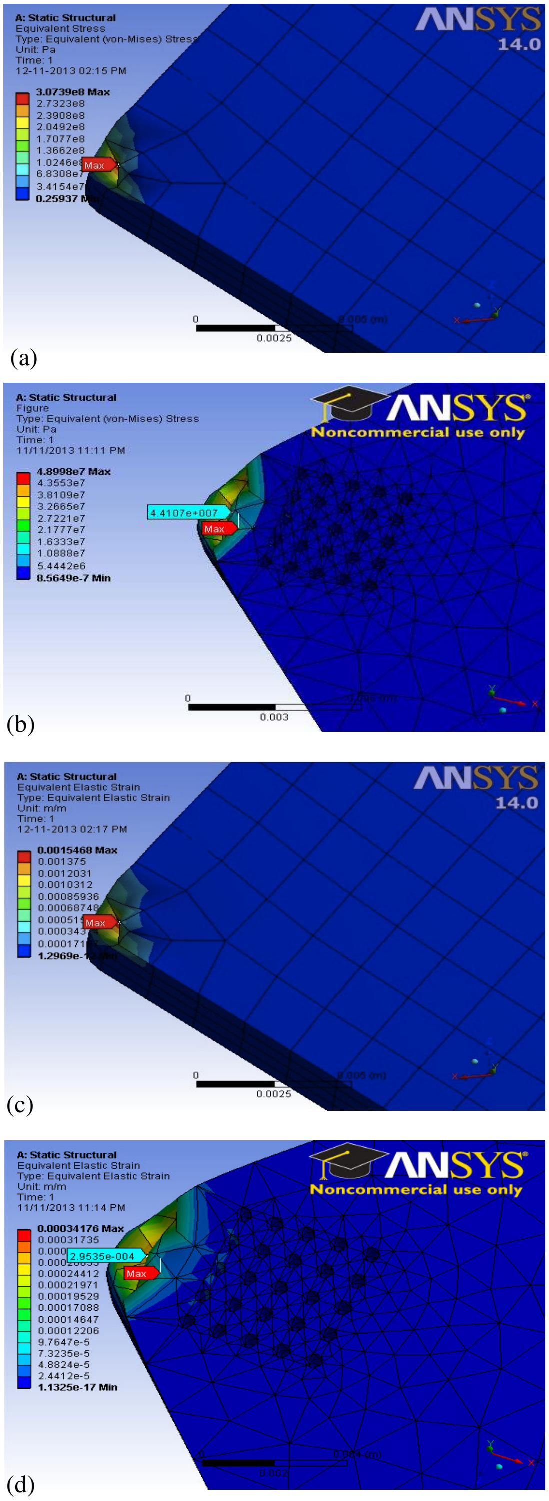

**Figure 3 Structural analyses: a) stress field in conventional cutting tool, b) stress field in micro-textured cutting tool, c) strain field in conventional cutting tool, and d) stain field in micro-textured cutting tool**

cutting speed are shown in the Fig. 4 (a) – 4 (d).From the force analysis of conventional cutting tool and textured tool it can be observed that forces in the textured tool are less compared to the conventional tool. Set of experiments with varying cutting speeds and feed on micro-scale conical dimple textured highspeed steel M2 cutting tool (TT), and conventional high speed steel cutting tool (CT) were performed.

Analysis of variance (ANOVA) was used to check the accuracy. Table 3 shows the plan of cutting having two different input conditions keeping depth of cut constant at 0.5mm. To optimize number of experiments central composite rotatable design (CCRD) technique is used. As per CCRD technique, number of experiments = $2^k$ + rotatable + central runs, since in the present work number of variables k has been taken as 2 (cutting speed and feed rate), therefore the number of experiments required to be performed for single tool as per CCRD technique is (4+4+5), i.e., 13.

**Table 3 Plan of Experiments**

| Experiment No. | Feed (mm/rev) | Cutting speed (rpm) |
|---|---|---|
| 1 | 0.52 | 88 |
| 2 | 0.80 | 52 |
| 3 | 0.92 | 88 |
| 4 | 0.52 | 88 |
| 5 | 0.52 | 88 |
| 6 | 0.80 | 148 |
| 7 | 0.04 | 88 |
| 8 | 0.52 | 88 |
| 9 | 0.16 | 148 |
| 10 | 0.52 | 192 |
| 11 | 0.16 | 52 |
| 12 | 0.52 | 40 |
| 13 | 0.52 | 88 |

As it can be observed from the experiments results, the cutting forces and feed forces reduced for micro- textured tools comparatively conventional HSS M2 tools. Might be two reasons are possible for reduction of cutting forces and feed forces by this mechanism. The first reason is due to reduction of real contact area between tool-chip interfaces of rake face of micro-textured cutting tools due to presence of number of micro-pools over rake face of textured cutting tool. Reduction in cutting tool rake face and chip direct contact area leads to less friction force which results in decreasing of cutting forces. The other one is because of micro-wear debris entrapment inside these texture which were created by welding and rupture phenomena while dry cutting operations. But after some time of machining at high speed, it is observed that these micro-textures are fully filled with wear debris and at that point very small change is noticed in cutting force and feed force with respect to cutting speed as shown in Fig. 4(b) and 4(d). Trapped wear debris particle are shown by scanning electron microscopic (SEM) images in Fig. 5(a)-(c).

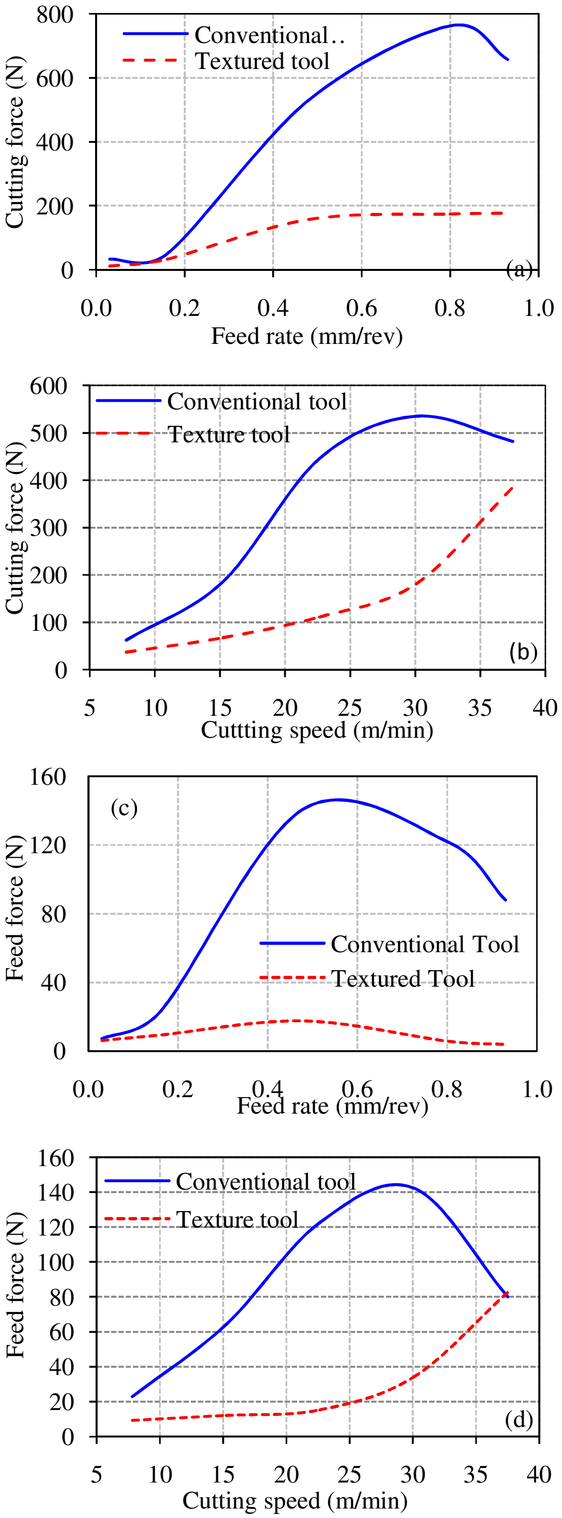

**Figure 4 Variation of:(a) cutting force with feed rate, (b) cutting forces with cutting speed, (c) feed forces with feed rate, and (d)feed forces with cuttingspeed**

### 3.4 Friction Coefficient Analysis

Friction angle can be related to feed force and cutting force by Merchant's circle diagram. The average COF can be evaluated using the following formula (Ze et al., 2012):

$$\mu = \tan(\beta) = \tan(\alpha + \arctan(F_t / F_c)) \qquad (1)$$

Where β is the friction angle, α is the rake angle. In the present work for making texturing, flat type cutting tool is used (α = 0). $F_t$ is feed force and $F_c$ is cutting force. A decrease in tool face friction leads to a decrease in the energy required for chip formation, thus improving the efficiency of the process. Hence, the formula reduces to the following:

$$\mu = \tan(\beta) = F_t / F_c \qquad (2)$$

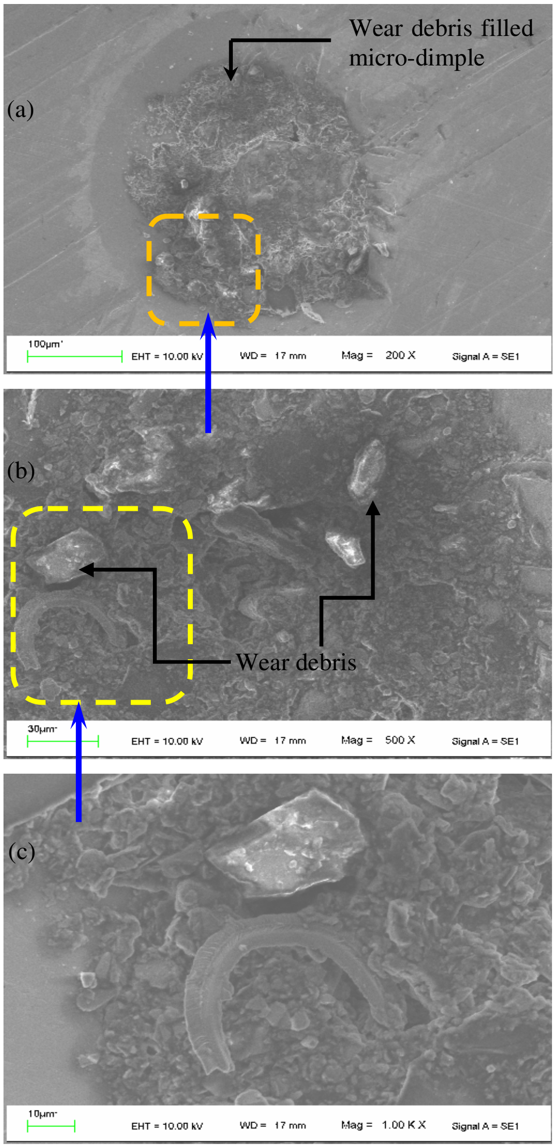

**Figure 5SEM images of micro-dimples filled with wear debris**

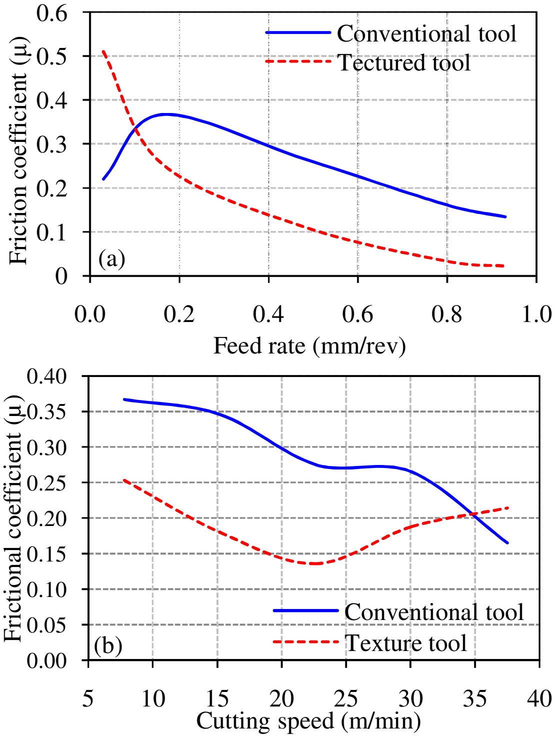

**Figure 6 Variation of friction force with: (a)feedrate, and (b)cutting speed**

In the present scenario as shown in Fig. 6(a), initially friction coefficient of micro-textured cutting tool is more but as feed increases up to a certain point it start decreasing because surface roughness of textured cutting tool is higher as compare to conventional tool, so initially friction coefficient is more than conventional tool but contact area between tool-chip interface is less for textured cutting tools so friction coefficient reduces after certain point. Fig. 6(b) shows relationship between friction coefficient and speed. As shown in Fig. 6(b), at higher speed friction coefficient of textured tool is more because micro-texture were filled with wear debris at higher speed which were produced because of welding and rupture after some time of machining. So friction coefficient is more at higher speed.

## 5 Conclusion

Study was performed to investigate the effect of surface texturing over tool rake surface on cutting forces and friction coefficient under solid lubricating conditions. The following conclusions were obtained:

1)Effect of micro-texture on the stresses and strains generationat cutting edge of the cutting tool in cutting operations isvery small which can be neglected.

2) Surface texturing effectively reduces the cutting force and feed forces after texturing of cutting tools.

3) Friction coefficient decreases with textured tools as

compare to conventional tool for large range of feed and speed.

4) Two reasons are possible for reduction of cutting forces and feed forces by micro-texturing of tool rake face. The first reason is due to reduction of contact area between tool-chip interfaces of rake face of micro-textured tools due to presence of number of micro-dimples. Reduction in tool rake face and chip direct contact area leads to less friction force which results in decreasing of cutting forces. The other one is because of micro-wear debris entrapment inside these texture which were created by welding and rupture phenomena while dry cutting operations.

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