Influence of Cutting Tool Flank Surface Texture in Dry Metal Machining

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Abstract—*Previous research has demonstrated the ability of the surface texture on rake surfaces of cutting tools to influence tribological conditions in metal cutting. However, the effects of texturing on the cutting tool's flank surface, which has major implications for machined surface integrity, have received very little attention. This paper presents the results of a preliminary study in which slabs of AISI 1045 plain carbon steel were subjected to intermittent orthogonal cutting using P30 grade cemented tungsten carbide tools possessing different surface textures on the flank surfaces for a range of cutting speeds and feeds under dry cutting conditions. Machining performance under the various experimental conditions attempted was evaluated through the analysis of measured cutting forces and workpiece surface roughness. The results demonstrate that texturing the flank surfaces of cutting tools significantly influences tribological conditions even under the intense contact conditions encountered in machining, and provide new insights into the nature of frictional contact in metal cutting. Based on these preliminary results some areas for further research in development of next-generation cutting tools are identified.*

Keywords: *Dry, Machining, Tool, Flank, Surface, Texture*

INTRODUCTION

Dry and near-dry machining (NDM), also known as minimal quantity lubrication (MQL) machining, have witnessed significant research over the last two decades [1–2] for the following major reasons: environmental and economic issues related to the profligate use of conventional cutting fluids, and operator safety and legal issues related to the health hazards arising from the use of cutting fluids. The major thrust areas of research in dry and near-dry machining include development of advanced tool materials and tool-coating systems, improved process modeling and process parameter optimization, material design for enhanced self-lubrication, etc. However, one potentially beneficial research area that has received relatively less attention is the use of controlled surface texturing on cutting tool surfaces for enhanced tool-chip friction reduction under dry and near-dry cutting conditions.

Metal cutting involves the generation of extreme tribological conditions at two major locations: The tool-chip interface, and the tool-workpiece interface. Previous research has shown that the presence of oxygen, and/or other gases, in the machining environment has a significant influence on the severity of tool-chip/tool-workpiece interfacial contact, and hence also on general machining performance [3–5]. Rowe and Smart [6] observed that extensive welding of the chip to the cutting tool occurred in machining of iron in a near-vacuum atmosphere, while allowing oxygen into the vacuum chamber immediately allowed the tool-chip contact conditions to approach those existing under dry cutting in regular atmosphere. Further, since there is a very short time available for oxygen transport and reaction at the chip undersurface at higher cutting speeds it was hypothesized that the rate-controlling factor for the reaction was gas adsorption on the tool surface [6]. Wakabayashi *et al.* [7–8] studied the performance of different lubricants during cutting in a controlled-atmosphere chamber and found that the presence of oxygen had a significant influence on the performance of these agents for effective near-dry machining at low cutting speeds. Further, based on the work of Wakabayashi *et al.* [9], they hypothesized that the rate of reaction at the chip surface was the rate-controlling factor.

Thus, appropriate texturing of cutting tools' rake surfaces may potentially be exploited to improve the access of reactants present in the machining environment–typically, oxygen in the case of dry cutting and/or MQL fluid/vapors in the case of near-dry machining–to the chip undersurface, and thus reduce the intensity or extent of tool-chip/tool-workpiece contact for overall machining performance improvement: reduction in cutting forces, decrease in cutting temperatures, consequent improvement in machined surface integrity, etc.

Some preliminary work has demonstrated the potential of surface texturing when applied to the rake surfaces of cutting tools. Jayal *et al.* [10] employed commercially available uncoated P20 grade cemented tungsten carbide tools that were ground on the rake surface to different tolerance levels and observed that the various surface texture parameters for the tools' rake surfaces had significant effects on measured machining forces and estimated tool-chip interface temperatures during dry orthogonal machining (tube turning) of AISI 1020 steel at cutting speeds of 200–300 m/min and feeds of 0.05–0.1 mm/rev.

Lei *et al.* [11] produced microholes on rake surfaces of uncoated cemented tungsten carbide tools using a femtosecond laser and observed that machining using tools with oil and solid lubricant filled micropools produced significantly lower machining forces and tool-chip contact lengths, as well as more coiled chip forms, as compared to dry or flood-cooled cutting with untextured tools during turning of AISI 1045 at a cutting speed of 120 m/min, feed rate of 0.3 mm/rev and depth of cut of 1 mm.

Kawasegi *et al.* [12] induced microscale and nanoscale textures (parallel and cross-hatched groove patterns) on rake surfaces of uncoated cemented tungsten carbide tools using a femtosecond laser and observed a significant beneficial effect of the surface texturing, especially when oriented parallel to the cutting edge, on machining forces during turning of A5052 aluminum alloy under MQL conditions at cutting speeds in the range of 400–600 m/min, feed rate of 0.1 mm/rev and depth of cut of 0.2 mm. Similarly, Enomoto and Sugihara [13] generated micro-and nano-textures (parallel grooves) on rake surfaces of cemented tungsten carbide tools with diamond-like carbon coatings using a femtosecond laser and observed a significant beneficial effect of the micro-/nano-grooves, particularly when oriented parallel to the cutting edge, on rake face adhesion during face milling of A5052 aluminum alloy in the presence of conventional coolant flooding at a cutting speed of 380 m/min, feed rate of 0.12 mm/rev and depth of cut of 3 mm.

Koshy and Tovey [14] produced isotropic (areal) and linear (parallel groove pattern) textures on rake surfaces of high speed steel tools using electrical discharge machining and observed several interesting trends in the measured machining forces during continuous and intermittent orthogonal cutting of annealed AISI 1045 steel and 6061 aluminum under flood cooled conditions at cutting speeds of 2–75 m/min and feed rates of 0.025–0.1 mm/rev. A continuous/areal texture pattern was found to be more beneficial than a linear (series of parallel grooves) pattern while the reduction in force was found to be maximum when the textured region was situated slightly away from the cutting edge, at a distance that related to the feed rate used. Further, maximum benefit from the tool surface texturing was observed at low cutting speeds and interrupted cutting conditions.

The above-mentioned studies highlight the potential for exploiting controlled surface texturing on cutting tools' rake surfaces for overall improvement in machining performance. However, there is a lack of studies investigating how the use of various surface textures on the flank surfaces of cutting tools may influence machining performance, particularly related to workpiece surface integrity since it is the tool's flank surface that is in direct contact with the newly generated machined workpiece surface. This paper presents the results of an initial experimental study to explore whether the application of different surface textures on cutting tools' flank surfaces has a significant effect on the machining process for a widely-used, medium carbon-content, plain carbon steel under modern cutting conditions.

EXPERIMENTAL PLAN

Rectangular pieces of AISI 1045 steel, with a mean hardness of 230 BHN and thickness of 6.8 mm, were subjected to intermittent orthogonal machining via a peripheral milling operation on a CNC vertical machining center (Fig. 1). P30 grade uncoated cemented tungsten carbide cutting inserts with ISO designation TPUN160308 were employed in combination with a Falcon SMS22060 style milling toolholder of 50 mm diameter providing a positive rake angle of 5^0.

All the cutting inserts were purchased from a single manufacturing lot from the same tool manufacturer. One-half of the inserts were left in the as-purchased/received condition while the other half were subjected to a short grinding operation on the flank surface, only sufficient to alter the surface texture without significant material removal, such that the grinding marks were oriented perpendicular to the cutting edge.

The experimental plan considered 3 different variables–cutting speed, feed, and tool flank surface texture–varied at different levels, as shown in Table 1. The depth of cut (radial) was held fixed at 0.3 mm. A randomized factorial experiment design with two replicates was conducted, giving a total of 16 machining experiments.

Fig. 1: Experimental Setup for Intermittent Orthogonal Cutting (Feed Motion of the Tool is along X Direction)

Table 1: Variables Employed in the Experiment and Their Respective Levels

Variable	Levels
Cutting Speed (*V*)	100, 150 m/min
Feed (*f*)	0.157–0.471 mm/rev
Tool Flank Surface Texture	Untextured: As-received (R_a = 0.241 ± 0.018 μm; no lay direction, typical of powder metallurgy components), Textured: Flank surface ground with 6 μm grit grinding wheel (R_a = 0.042 ± 0.004 μm; lay direction perpendicular to cutting edge)

A fresh cutting edge was used for each trial, and machining cuts were restricted to a length of 30 mm in the X direction (Fig. 1) to ensure minimal alteration of contact conditions through wear. Cutting forces were measured using a Kistler® multi-component dynamometer (9257B) interfaced with a Kistler® multi-channel charge amplifier (5070), while surface roughness (R_a) was measured using a Surfcom 130A profilometer at a cut-off value of 0.8 mm.

RESULTS AND DISCUSSION

Table 2 lists the major correlations observed between cutting speed (*V*), feed (*f*), cutting force (F_x), thrust force (F_y), machined workpiece surface roughness and tool flank surface roughness. Both F_x and F_y showed strong positive correlations with *f* and with each other, as expected. Further, F_y showed a significant negative correlation with *V*; however, this cannot be attributed to increased thermal softening of the workpiece material at higher cutting speed since a similarly strong negative correlation with *V* was not observed in the case of F_x. Instead, this apparent correlation is probably an artifact of the experimental plan employed, where the two feed levels (0.157, 0.314 mm/rev) used at the higher cutting speed (150 m/min) were lower than the feed levels (0.236, 0.471 mm/rev) used at the lower cutting speed (100 m/min). Hence, with this experimental plan a general increase in cutting speed implies a general decrease in feed and thus any variable that shows a positive correlation with *f* would tend to display a negative correlation with *V* as well due to this relationship between *V* and *f*.

The other noteworthy trends observed were the significant positive correlations between tool flank surface roughness and thrust force (F_y) and between tool flank surface roughness and machined workpiece surface roughness (Table 2). Thus, under certain conditions the surface texture present on flank surfaces of cutting tools can have significant effects even under the intense contact situations and relatively aggressive cutting parameters encountered under typical modern industrial conditions. Moreover, these observed correlations have major implications for workpiece surface integrity and further studies are in progress at the authors' research laboratory to study how controlled texturing of flank surfaces on cutting tools may be exploited to achieve improved workpiece surface integrity, and hence improved product life under service conditions involving failure through fatigue, corrosion, wear, etc.

It was further confirmed with the aid of 2-tailed t-tests that even though the surface texture on the cutting tool's flank surface was unable to significantly influence either cutting force (Table 2, Figs. 2–3) or thrust force (Table 2, Figs. 4–5) under most combinations of cutting speed and feed, except for the higher speed and lower feed combination (*V* = 150 m/min, *f* = 0.157 mm/rev), it had a significant effect on the surface roughness of the machined workpiece (Table 2, Figs 6–7) at the two lower feed conditions. Under all conditions where some statistically significant effect of tool flank surface texture existed the textured cutting tools performed better than the untextured tools.

For example, as shown in Figs. 3 and 5, tool flank surface texturing significantly reduced both cutting (F_x) and thrust force (F_y) components by roughly 36% and 47%, respectively, at the higher cutting speed (150 m/min) and lowest feed (0.157 mm/rev). Similarly, as shown in Figs. 6–7, tool flank surface texturing significantly reduced the workpiece surface roughness by approximately 42% and 69%, respectively, at the lower feed levels employed at each cutting speed–i.e., at the combinations of *V* = 100 m/min and *f* = 0.236 mm/rev, and *V* = 150 m/min and *f* = 0.157 mm/rev, respectively.

Due to the low magnitude of radial depth of cut (0.3 mm) compared to the cutter diameter (50 mm) the workpiece surface roughness did not display the usually expected clear relationship with feed rate (Table 2).

Table 2: Correlation Coefficients Between Various Independent and Dependant Variables

	F_x	F_y	Workpiece R_a	Tool Flank R_a
V	-0.29	-0.59	-0.35	0.06
f	0.70	0.50	-0.34	-0.11
F_x		0.65	-0.16	0.41
F_y			0.36	0.52
Workpiece R_a				0.58

V = cutting speed; *f* = tool feed rate; F_x = cutting force; F_y = thrust force; R_a = average absolute roughness (measured with 0.8 mm cut-off)

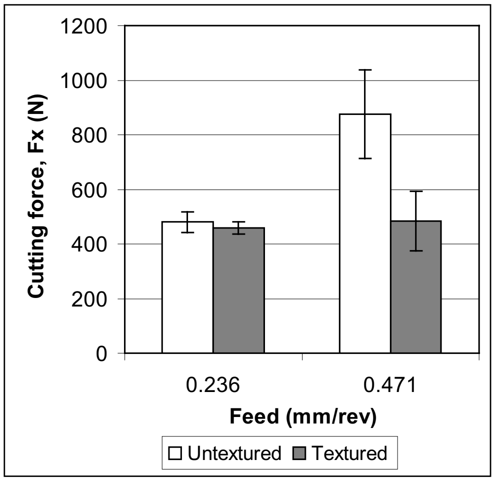

Fig. 2: Effects of Feed and Tool Flank Surface Texture on Cutting Force (F_x) at *V* = 100 m/min. Error Bars Represent ± 1 Standard Deviation in the Data for each Experimental Condition

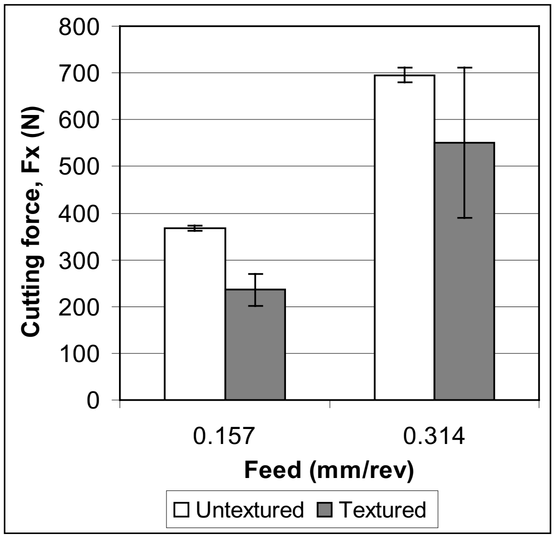

Fig. 3: Effects of Feed and Tool Flank Surface Texture on Cutting Force (F_x) at V = 150 m/min

Instead, the effects of the surface texture on the tool's flank surface were more dominant, particularly at the two lower feed levels employed in the experiment (Figs. 6–7). This again highlights the importance of studying the influence of tool flank surface texturing on machined surface integrity because these effects are more critical in the case of finish machining conditions involving low feed values.

Since there is a possibility that the grinding procedure on the tools' flank surfaces may be altering the cutting edge radius it is necessary to investigate whether variability in edge radius is confounding the results obtained. If this was the case, then the effect of tool edge radius should be most prominent at low feed rates that approach the magnitude of the edge radius [15]. However, as shown in Figs. 6–7, the beneficial effects of employing tools with different flank surface textures extend up to medium range feed rates (0.236 mm/rev), which are almost an order of magnitude higher than the typical edge radius of TPUN160308 carbide tools [10]. Hence, any possible difference in edge radii of untextured and textured tools is not considered to be an uncontrolled variable confounding the results, and all observed differences are attributed to differences in flank surface texture of cutting tools.

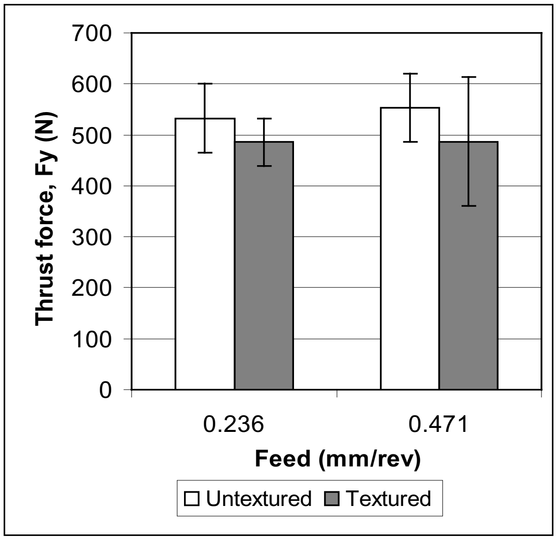

Fig. 4. Effects of Feed and Tool Flank Surface Texture on Thrust Force (F_y) at V = 100 m/min

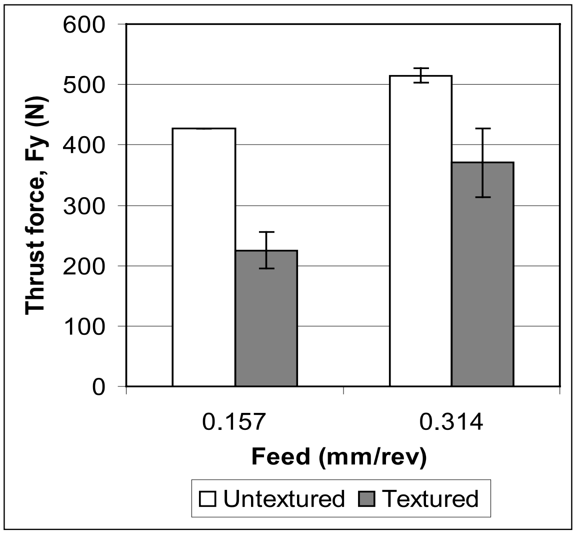

Fig. 5. Effects of Feed and Tool Flank Surface Texture on Thrust Force (*Fy*) at V = 150 m/min

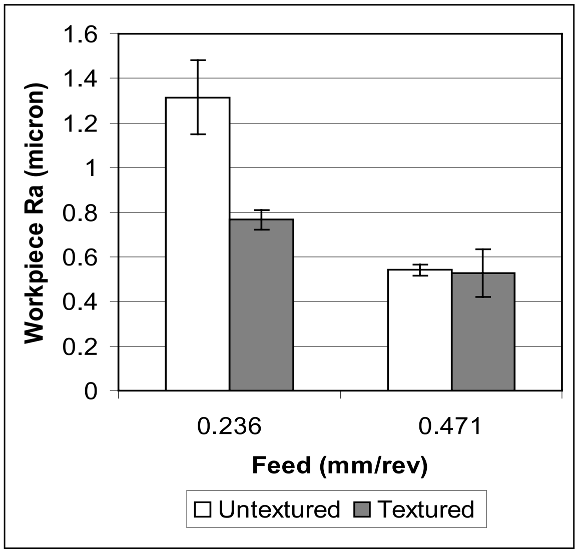

Fig. 6. Effects of Feed and Tool Flank Surface Texture on Workpiece Surface Roughness (R_a) at V = 100 m/min

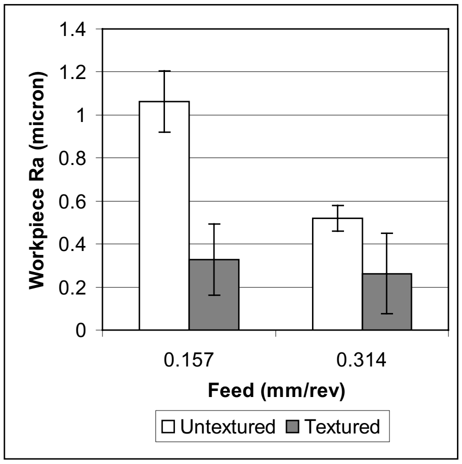

Fig. 7: Effects of Feed and Tool Flank Surface Texture on Workpiece Surface Roughness (R_a) at V = 150 m/min

It must be highlighted that several factors were not considered in this preliminary study and these are currently being studied in greater detail in the authors' research laboratory. Most importantly, characterizing surface texture is a complex issue and this is indicated by the fact that there are dozens of recognized amplitude, spacing, and derived parameters that attempt to quantify the various performance-related aspects of tribological surfaces [16]. Unfortunately, most research work, including the preliminary study presented here, has focused on a single roughness parameter: the absolute roughness value, R_a, which makes no distinction between peaks and valleys since it evaluates the average absolute deviation of points on the surface profile from their mean level. Thus, there is a need to also consider various other surface texture parameters to identify the ones having the greatest influence on the functional performance of textured cutting tools. For example, Jayal *et al.* [10] found that the skewness of the tool's rake surface roughness profile, in combination with other textural parameters, has an important influence on machining performance, while Koshy and Tovey [14] observed that both skewness and kurtosis of the cutting tool's rake surface texture have a significant bearing on the observed machining effects.

Commercially available carbide tools are typically ground on the rake surface during production in order to achieve the required tolerance in thickness of the insert, while other surfaces are left with the surface texture that remained after powder compaction in the die. No attempt was made to control the rake surface texture in this study and rake surfaces were left in the as received/purchased condition. Considering that the grinding procedure employed on the rake surface during production of cutting tools can have significant effects during machining [10] this needs to be accounted for in future work. Ongoing studies by the authors are exploring the interactions between different surface texture conditions on the rake and flank surfaces for a wide range of textural parameters.

The scope of this study was limited to dry cutting whereas textured cutting tool surfaces may prove beneficial under near-dry, cryogenic and conventional (flood coolant-based) machining situations as well. Thus, there is a need to explore the design of cutting tools with surfaces textured specifically for the desired application and intended lubricant/reactant–oxygen in the case of dry cutting, MQL oil in the case of near-dry machining, liquid nitrogen in the case of cryogenic machining, and flooded cutting fluids in the case of conventional cutting. Through appropriate manipulation of the different texture parameters affecting the tool's tribological interaction with the chip and workpiece it may be possible to decrease the intensity of tribological conditions at the tool-chip and tool-work contact zones and thus further advance the development and commercial implementation of sustainable manufacturing methods, such as dry, near-dry and cryogenic machining, as well as provide general machining performance improvement (reduction in cutting forces and energy consumption, improved surface integrity, improved tool life, etc.) in the case of conventional coolant-based machining.

SUMMARY

An experimental study involving dry intermittent orthogonal machining of AISI 1045 steel using P30 grade uncoated cemented tungsten carbide tools with different textures on the flank surfaces was conducted to investigate how texturing of cutting tools' flank surfaces may influence machining performance under dry cutting condition. Machining performance, as indicated by measured cutting and thrust forces, and workpiece surface roughness, was found to be significantly influenced by the tool's flank surface texture, especially at lower feed values that are typical of finish cutting conditions. Under all experimental conditions where the effect of texturing was statistically significant the tools subjected to grinding performed better than the tools that were left in the as-received/purchased state. With further study the effects of providing engineered textures on cutting tools' rake and flank surfaces may possibly be exploited for development of engineered tool surfaces for sustainable dry, near-dry and cryogenic machining applications.

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