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Performance of electrical discharge textured cutting tools

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ABSTRACT

Tool face friction adversely affects chip formation and consumes about 25% of the total cutting energy. Friction in cutting can be controlled by introducing a lubricant into the tool-chip interface, the effectiveness of which may be enhanced by surface texturing the tool. This paper details the innovative application of electrical discharge machining for generating an isotropic texture on the tool rake face, with a view to facilitating lubricant penetration and retention. A significant reduction in feed and cutting forces that ensues from said texturing is demonstrated, followed by a presentation of the features and application areas of the technology.

1. Introduction

The influence of lubrication on chip formation was first reported by Mallock about 130 years ago in one of the first papers ever published on machining [1]. Theoretical analyses and intricate experiments have since enabled a fair insight into the nature of cutting friction. It is now understood that the high normal stresses in the vicinity of the cutting edge precludes lubricant penetration therein, and that lubricant infiltration into the tool-chip interface occurs through micro-channels in the rear of the contact away from the edge. The transport of liquid lubricants into the tool-chip interface is governed by the mechanisms of capillary action that promotes it and chip velocity-induced shear flow that restrains it. As the effectiveness of a lubricant is dependent on the time available for it to be adsorbed into and/or chemically react with the chip to reduce the interfacial shear strength, retention of the lubricant in the interface is as critical as its ingress.

One avenue to promoting lubrication is surface texturing, which refers to appropriately structuring the topography of a functional surface [2]. Commonly known surfaces that entail a texture to control friction are generated in such processes as honing, scraping and knurling, wherein the texture is essentially continuous. Surface textures can also be discrete to comprise an array of microscopic dimples or a series of grooves distributed over the surface, which serve to reduce friction and wear by functioning as micro-bearings and debris traps, respectively.

The literature on tribological applications of surface texturing predominantly refers to automotive components such as bearings, seals and piston ring assemblies. Notwithstanding the significant potential, attempts at extending this concept to cutting tools have been relatively few and recent. Enomoto and Sugihara [3] present experimental evidence to show that nanoscale grooves on the tool rake face are more effective than microscale grooves in decreasing friction and adhesion when face milling aluminum. Similar results have been reported by Kawasegi et al. [4] in turning of aluminum. Lei et al. [5] machined micro-hole arrays on the tool rake face with a view to facilitating lubrication, and observed a 10–30% reduction in machining force when turning steel. Jiang et al. [6] demonstrated the prospect of friction reduction in tooling applications by electrostatic spray coating a soft lubricant layer over a textured hard coating, with the latter biomimetically structured to resemble the topography of a lotus leaf for enhanced lubrication.

Texturing techniques span a wide spectrum of diverse technologies ranging from chemical etching to forming, a review of which can be found in [2]. In the cutting tool applications mentioned previously [3–5], femtosecond lasers have been used to fabricate microscale textures through conventional ablation, and nanoscale textures through laser-induced periodic structuring brought about by laser interference. As fine and versatile femtosecond laser texturing is, the technology is limited by throughput: texturing 64 mm^2 of TiN-coated steel with dimples of depth 18 μm at a pitch of 80 μm corresponds to a processing time of about 25 min [7]. Alternatively, through-mask electrochemical machining [8] may be employed; however, the corresponding dimple size is larger, reportedly on the order of 250 μm, which increases the likelihood of the chip material extruding into and clogging the texture [3–5], thus affecting its function and performance.

In the context of the background presented above, this paper proposes the innovative application of sink electrical discharge machining (EDM) for the rapid texturing of the rake face of a cutting tool with the intent of promoting lubrication in the tool-chip interface. This idea is conceptually different from texturing of steel rolls using EDM [9] wherein the objective is to transfer the spark eroded texture from the roll onto sheet steel or aluminum, during the rolling operation.

The motivations towards using EDM for texturing cutting tools are several. As material removal in EDM inherently entails high-frequency localized melting and vaporization at the microscale, the generated surface comprises a large number of microscopic, overlapping craters. Accordingly, EDM is one of the few processes with the capability to generate surfaces with a positive skewness [10], which means that the surface consists of peaks interspersed

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among relatively wide valleys that are ideally predisposed to entraining lubricant. As highlighted in [3,4], textures are preferably oriented normal to the chip velocity vector with a view to limiting chip flow from expediting the egress of lubricant from the tool-chip contact zone; to this end, the isotropic nature of EDM surfaces is advantageous, as it renders the texture performance to be independent of the direction of chip flow. EDM further offers the flexibility to tailor the size and shape of the characteristic craters that collectively constitute the texture towards a specific application, by tuning the pulse parameters.

2. Experimental

The objective of the experimental work was to prove the concept of electrical discharge texturing of cutting tools, and to determine the envelope of EDM and cutting parameters in which such textures are effective in reducing friction. Texture performance was assessed in continuous and intermittent orthogonal cutting, realized in a turning process by appropriately configuring the workpiece geometry. Experiments involved annealed 1045 steel and 6061 aluminum workpieces, with the textures evaluated in terms of cutting (F_c) and feed (F_f) force components.

This research referred to two types of textures. The areal texture schematically represented in Fig. 1a was machined by using sink EDM with a block electrode, such that the texture was continuous, comprising overlapping craters typical of surfaces generated in EDM. Machining was accomplished in an oil-based dielectric, in a machine tool equipped with a solid state power supply, with copper electrodes in positive polarity. In generating the textures, an average gap voltage of 100 V and a duty factor of 0.5 were maintained, and the discharge current (i_e) and on-time (t_i) were varied up to a maximum of 72 A and 133 μs, respectively. To compare the performance of the continuous texture, limited tests related to a discrete linear texture (Fig. 1b) comprising grooves of depth and width of about 100 μm, which ran parallel to the cutting edge. These grooves were also machined by sink EDM using thin shim stock tooling. The location of the texture with respect to the cutting edge along the length of the tool, as specified by the distance d_e (see Fig. 1a), was found to markedly affect its performance, and hence the influence of this parameter was also investigated.

The cutting tools used in the experiments were finish-ground T-15 grade high speed steel inserts of SPG 432 geometry, with a 0° rake angle. The flat rake face of this insert type facilitated easy texturing. Cutting experiments corresponded to the cutting speed (v_c) and the feed (h) varied in the range of 2–75 m/min and 0.025–0.1 mm, respectively, with the cut width held constant at 3 mm. As shown in Fig. 1, the textures were designed to extend just half way across the tool width of 12.5 mm, so that reference cutting force data corresponding to the non-textured ground surface could be obtained with minimal tool-related variability, by just shifting the tool laterally by a distance more than the cutting width. The orientation of the insert was such that the surface lay on the ground surface was parallel to the cutting edge for better lubrication, relative to a lay that is perpendicular. A light-duty cutting oil (Chem Ecol 250A, 35 mm^2/s viscosity at 40 °C) with synthetic fat additives was used as the lubricant, which was applied as a flood along the tool rake face.

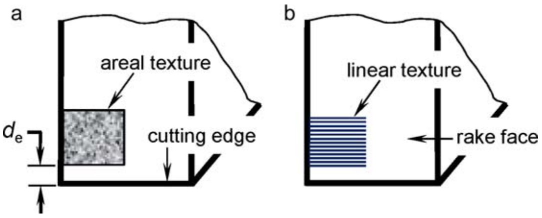

Fig. 1. Texture position and configurations.

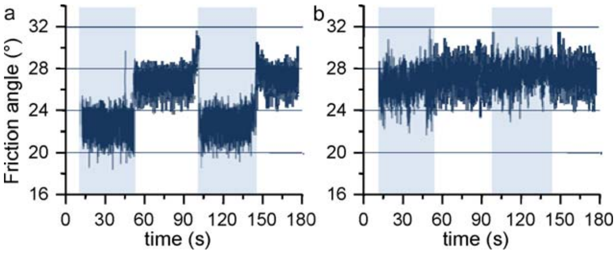

Fig. 2. Evolution of friction angle for: (a) textured; and (b) non-textured tools; shaded regions denote lubricant application.

3. Results and discussion

Fig. 2 compares the evolution of the friction angle for textured and non-textured tools, with the shaded vertical bars indicating intervals over which the lubricant was applied. The friction angle is a measure of lubrication effectiveness, and is given by $\tan^{-1}(F_f/F_c)$ for a rake angle of 0°. This test corresponded to continuous cutting of steel at $v_c = 2$ m/min and $h = 0.1$ mm, with a continuous texture (Fig. 1a) referring to optimized EDM parameters of $i_e = 39$ A and $t_i = 42$ μs, and $d_e = 0.2$ mm. All results reported in this paper refer to conditions above, unless noted otherwise. The effects of these parameters themselves are discussed later.

While the friction angle referring to the non-textured tool remained essentially stationary (Fig. 2b), the textured tool exhibited a conspicuous decrease over the intervals referring to lubricant application (Fig. 2a). This conclusively shows the effectiveness of the texture in enhancing lubrication at the tool-chip interface. As the ingress of the lubricant into the contact zone is by capillary action [1] that occurs in a time on the order of milliseconds, the effect of lubricant application in reducing friction is rather instantaneous (Fig. 2a). Similarly, the friction angle reverts back as soon as the lubricant flow is interrupted, as the tool chip interface is immediately starved of the lubricant, which is consumed in reaction with the nascent chip surface and transported off the contact zone.

During the texturing process, care was taken to limit the depth of the texture into the rake face, in order to prevent the tool from functioning as a restricted rake tool. This refers to a tool with a secondary rake face at an acute angle towards the tool flank, with a view to limiting the contact length [1]. Despite the consequent reduction in forces, such tools can in actual fact correspond to an increase in tool stresses and temperature that adversely affect tool performance, on account of insufficient material in the tool wedge. The friction angle assuming values similar to a non-textured tool on suspending lubricant flow (Fig. 2a) signifies that the texturing did not render the tool to be of restricted rake. This was further verified in experiments wherein the rake face of a textured tool was coated with a thin layer of Engineers' marking blue, which visibly indicated the tool-chip contact to have extended well into the textured area.

As compared to responses such as surface roughness and tool life, machining force is a better indicator of lubrication effectiveness in cutting with respect to repeatability and resolution [11], and hence texture performance was assessed in this work in terms of feed and cutting forces. Fig. 3 indicates the texturing to have

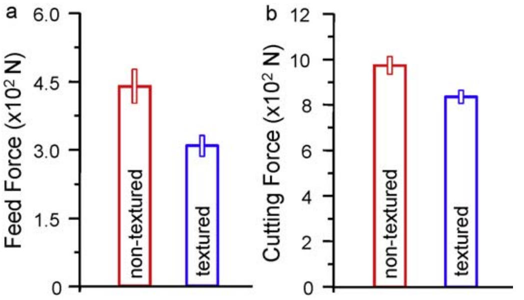

Fig. 3. Effect of texturing on forces in continuous cutting of steel.