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A study of micropool lubricated cutting tool in machining of mild steel

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ABSTRACT

This paper presents an experimental study of the performance of micropool lubricated cutting tool in machining mild steel. Microholes are made using femtosecond laser on the rake face of uncoated tungsten carbide (WC) cutting inserts. Finite element analysis is conducted to assess the effect of microholes on the mechanical integrity of the cutting inserts. Liquid (oil) and solid (tungsten disulfide) lubricants are used to fill the microholes to form micropools. A comparative study is conducted between micropool lubricated (surface-textured) cutting tools and dry/flood-cooled conventional (untextured) cutting tools. Three cutting force components are measured and compared. Tool–chip contact length and chip morphology are examined using optical microscope. It is found that the mean cutting forces (F_f, F_t, and F_c) are reduced by 10–30% with micropool lubrication. The chip–tool contact length is reduced by about 30%. Coiling chips are produced with micropool lubricated cutting tool while long and straight chips are formed with the conventional cutting tool. Liquid and solid lubricants are found to be equally effective in reducing the contact length and coefficient of friction at the chip–tool interface. There is no adverse effect on the performance of the insert with microholes on the rake face.

1. Introduction

In metal cutting with continuous chips, severe friction exists as the chip flows over the rake face of the cutting tool at high normal load and speed. The high normal load causes an increase in the real area of contact and thus producing an intimate contact between the chip and the tool rake face. Relative motion between the surfaces produces frictional heating to the cutting tool, resulting in high temperature at the tool–chip interface. As a result, crater wear develops quickly on the tool rake face under the very high pressure, high temperature and sliding speed at the interface. Gradual tool wear such as crater wear is a commonly seen wear form in metal cutting and usually is very difficult to eliminate.

Cutting fluids are often applied in machining to alleviate the severe friction and wear conditions. As summarized by Shaw (2005), the two main functions of cutting fluids are lubrication and cooling. Lubrication is effective when cutting fluid is introduced to the tool–chip interface through either penetration or diffusion, which is more likely to happen at low cutting speeds. However, the lubrication action diminishes at normal cutting speeds used in turning and milling as considered in this study. Therefore, the main function of cutting fluid changes to cooling and the cooling effectiveness reduces as cutting speed increases because the time allowed for cooling

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becomes extremely short (on the order of milliseconds). As far as cooling is concerned, the use of high-pressure waterjet and liquid nitrogen as coolant appears to be more effective than conventional application of cutting fluids.

For example, waterjet-assisted machining of titanium alloys has been reported by several investigators. The use of high-pressure coolant jet resulted in prolonged tool life, increased material removal rate, and short chip segments with easy chip disposal, regardless the way it is applied, i.e., either with a through-insert hole (Lindeke et al., 1994) or against the chip flow at the rake face (Machado and Wallbank, 1994). Cryogenic cooling has also been shown to significantly reduce friction and wear, cutting force, and cutting tool temperature, in comparison with conventional coolant (Hong et al., 2002). Another recent development in reducing tool wear in machining is by means of an external electromotive source. El Mansori et al. (2003) summarized the results of tool wear, temperature and chip morphology during cutting subjected to an external magnetic field. They performed various experiments on carbon steel using a HSS tool and showed that crater wear was clearly decreased at higher level of magnetic excitation.

Besides external cooling of cutting tool, some internal cooling and lubrication approaches have been attempted. Among those methods, thermosyphon cooling by Jen et al. (2005) and heat pipe cooling by Chiou et al. (2005) were reported. In a drilling application, reduction of drill tip temperature by as much as 60% was achieved using a thermosyphon drill. In an earlier study by Sharma et al. (1971), cutting fluid was injected into the chip–tool interface through a small hole in the cutting tool. It was found that the hole was filled in by chip material after some time of cutting.

Virtually all the above-mentioned techniques focus on cooling rather than lubrication, i.e., how to remove heat after it is generated rather than how to reduce the heat generation due to frictional sliding of the chip on the tool face. This paper focuses on cutting tool lubrication and investigates the use of internal micropool lubrication for a cutting tool. It is believed that microholes created on the tool face by surface texturing and filled with lubricant can act as micropools and thus reducing friction and wear at the chip–tool interface. This idea is a new application of the concept of enhanced lubrication through surface texturing in general tribological applications, which has been shown to be very effective. Some of the work in this area is summarized as follows.

In a series of studies, Etsion and Burstein (1996), Etsion et al. (1999), Etsion (2004) conducted theoretical and experimental investigations on the effects of laser surface texturing on tribological performances of mechanical components including mechanical seals, piston rings and thrust bearings. They used laser to create microdimples in a regular pattern on the contact surface. Significant improvement in load capacity, friction coefficient and wear resistance was found using the textured surface, which is attributed to the role of microdimple acting as either a micro-hydrodynamic bearing in full/mixed lubrication or a micro-reservoir in starved lubrication. Laser textured surfaces with microdimples were also shown to expand the hydrodynamic lubrication regime in terms of load and sliding speed by Kovalchenko et al. (2004). Compared with untextured surfaces, the friction coefficient was reduced substantially under similar operating conditions. The beneficial effects of surface texture on tribological behavior was found to extend to the high pressure regime by Dumitru et al. (2005) in their study of sliding friction between TiN-coated WC–Co and low-carbon steel. A mineral oil-based lubricant was applied to the interface before the friction test and then the contact pressure was increased gradually to 250 MPa. The results showed that the textured surfaces with micropores maintained a low and stable friction coefficient over a period more than 15 times longer than that of the untextured surfaces.

From the above-mentioned studies, it appears that microdimples or micropores filled with lubricant can significantly reduce friction and wear for sliding contact, even under very high contact pressures. In fact, in their analysis of micropool lubrication for metal forming, Lo and Wilson (1999) showed that the lubricant trapped in the micropits between the tool and workpiece could be squeezed into the interface to reduce friction under proper viscosity and sliding speed. Thus, it is hypothesized that micropool lubrication may also be used in metal cutting at the chip–tool interface to reduce friction and tool wear, i.e., by embedding micropools of lubricant in the cutting tool, direct lubrication can be achieved at the chip–tool interface. Although the frictional boundary conditions in metal cutting are different from the above-mentioned cases with sliding contact, it is believed that micropool lubrication could reduce friction and wear in metal cutting because of the following: first, the micropools reduce direct chip–tool contact area, i.e., a portion of the contact area is between chip and lubricant; second, the lubricant may be squeezed out of the holes due to thermal expansion at the chip–tool interface. The purpose of this paper is to experimentally investigate the effect of micropool lubrication in metal cutting.

The rest of the paper is organized as follows. Section 2 describes the femtosecond laser micromachining process used to make microholes on cutting tool surface. Section 3 reports a finite element analysis (FEA) of the cutting inserts, Sections 4 and 5 present a comparative machining study between conventional and micropool lubricated cutting tools. Finally, some conclusions are summarized in Section 6.

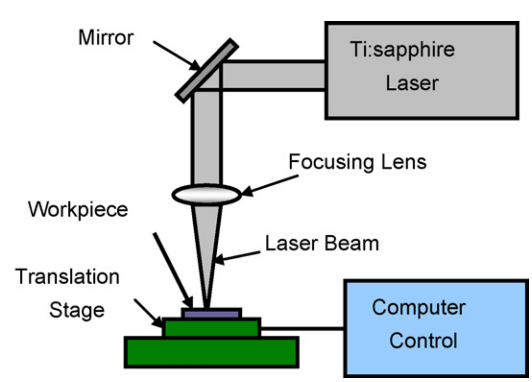

Fig. 1 – Experimental setup for femtosecond laser micromachining.

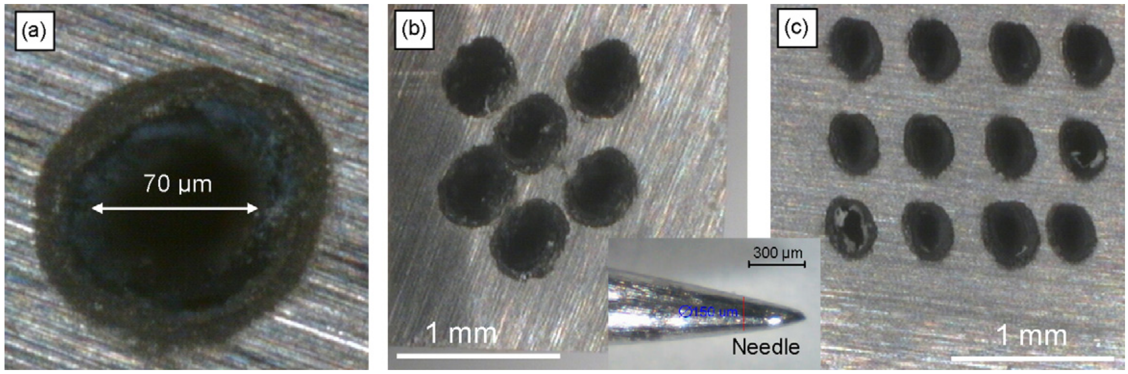

Fig. 2 – Optical images of example microholes created on tungsten carbide insert.

2. Femtosecond laser surface texturing of cutting tool

2.1. Experimental setup

A schematic of the experimental setup of the femtosecond laser micromachining system is shown in Fig. 1. The femtosecond laser pulses are generated using a Ti:sapphire laser system at a center wavelength of 790 nm and repetition rate of 1 kHz. The laser is able to deliver 4 mJ pulse energy with 20 fs pulse duration and 0.6 mJ pulse energy with 6 fs duration (Shan et al., 2006; Ghimire et al., 2005). The pulse energy is varied from a few μJ to 2 mJ in our experiments. The energy stability is better than ±10% of the average value. The beam is focused by a lens on the sample perpendicularly. The laser spot size ranges from 10 to 100 μm. The specimen is mounted on a computer controlled translation stage. This translation stage is controlled by a computer. The resolution and backlash of the translation stage are 0.1 and 2 μm, respectively. Prior to a laser machining experiment, the specimen is cleaned with methanol. All the experiments are performed in air. Inspection of the laser micromachined surface is performed using an optical microscope.

2.2. Microholes on tungsten carbide insert

Tungsten carbide (WC) was selected as cutting tool material for this study. Small holes were made on the rake face of the insert and close to the main cutting edge. The intention was to create hole patterns that consist of rows of small holes aligned with the main cutting edge, which cover the chip–tool contact area. Circular holes were used in this study because this shape was easy to produce with the laser system. In these experiments, cutting inserts are mounted on the translation stage and a computer controls its movement. The pulse energy and time duration are varied to control the hole depth. The focal plane is moved inside the bulk to create deeper holes during the process. Fig. 2(a) shows an enlarged view of a single hole. The hole diameter is about 70 μm and the depth is estimated to be a few times the hole diameter by means of a duplication method. The goal was to make deep holes so that they contain more lubricant. It should be noted that, even though the laser pulse duration is extremely short, heat affected zone is obvious, which is mainly due to the repeated ablations at a fixed location for a prolonged time (∼60 s). Fig. 2(b) and (c) shows two examples of microhole patterns made on WC inserts. The diameters of these holes are around 200 μm, much larger than 70 μm hole in Fig. 2(a).

3. Effect of microholes on the mechanical strength of the cutting tool

To evaluate the effect of microholes on the mechanical strength of the cutting tool when in use, FEA is performed to study the stress and deformation of the insert using Algor® (commercial FEA package). Fig. 3(a) shows the FEA model for the WC insert without holes. Only 1/4 of the original insert size is used because the load is concentrated at the cutting tip. The clearance angle is 11°. The nose radius is not considered in this simplified geometry. The element size is 200 μm in the vicinity of the cutting edge. A linearly decreasing normal pressure from the main cutting edge is applied on the chip–tool contact area of approximately 1 mm × 1 mm, resulting in an average pressure of 600 MPa which is determined based on the main cutting force. The feed force (F_f = 330 N) and thrust force (F_t = 300 N) are evenly divided along the main and side cutting edge as nodal forces, respectively. The bottom face is constrained in the z direction while the two backside faces are constrained in the x and y directions, respectively. Fig. 3(b) shows the FEA model for the WC insert with holes. The holes are represented by the rectangular pockets (two-element deep) on the rake face. The same type of load and boundary conditions are applied with the only difference being that the average pressure, feed force and thrust force are 540 MPa, 252 and 228 N, respectively. The mechanical properties for the WC insert (with 10 wt% cobalt) are selected as follows: density ρ = 14500 kg m^{-3}, Young's modulus of elasticity E = 580 GPa, and Poisson's ratio ν = 0.22 (Yao et al., 2002).

The simulation results are given in Fig. 4(a–d). The von Mises stress field for the insert without holes (Fig. 4a) indicates a highly non-uniform distribution. Large stresses occur at the cutting tip. In comparison with the insert with holes (Fig. 4b), the general stress profile is similar but the stress magnitude is less, which is because the cutting forces are less for the inserts with micropool lubrication. It should be noted that there is no significant stress concentration due to the embedded holes

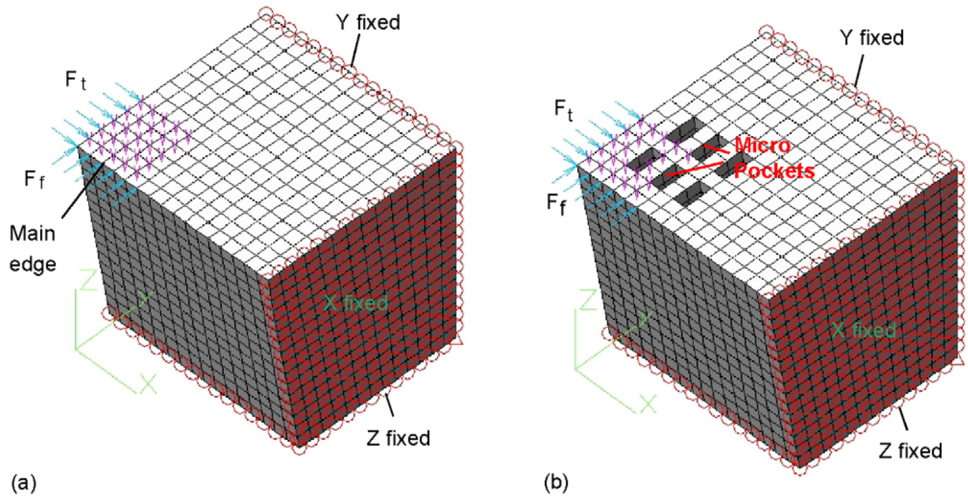

Fig. 3 – FEA model of WC insert. (a) Without holes and (b) with holes on the rake face.

on the rake face. Fig. 4(c) and (d) shows the displacement contours of the two types of inserts, respectively. The profiles for both cases are similar but they differ in both displacement gradient and magnitude. The conventional insert has a higher displacement gradient with the maximum at the cutting tip and also a higher magnitude when compared to the insert with holes. Overall, it can be seen that the displacements are very small for both cases, only a few μm. Therefore, it can be concluded from this analysis that the microholes embedded in the rake face of the cutting insert do not affect the mechan-

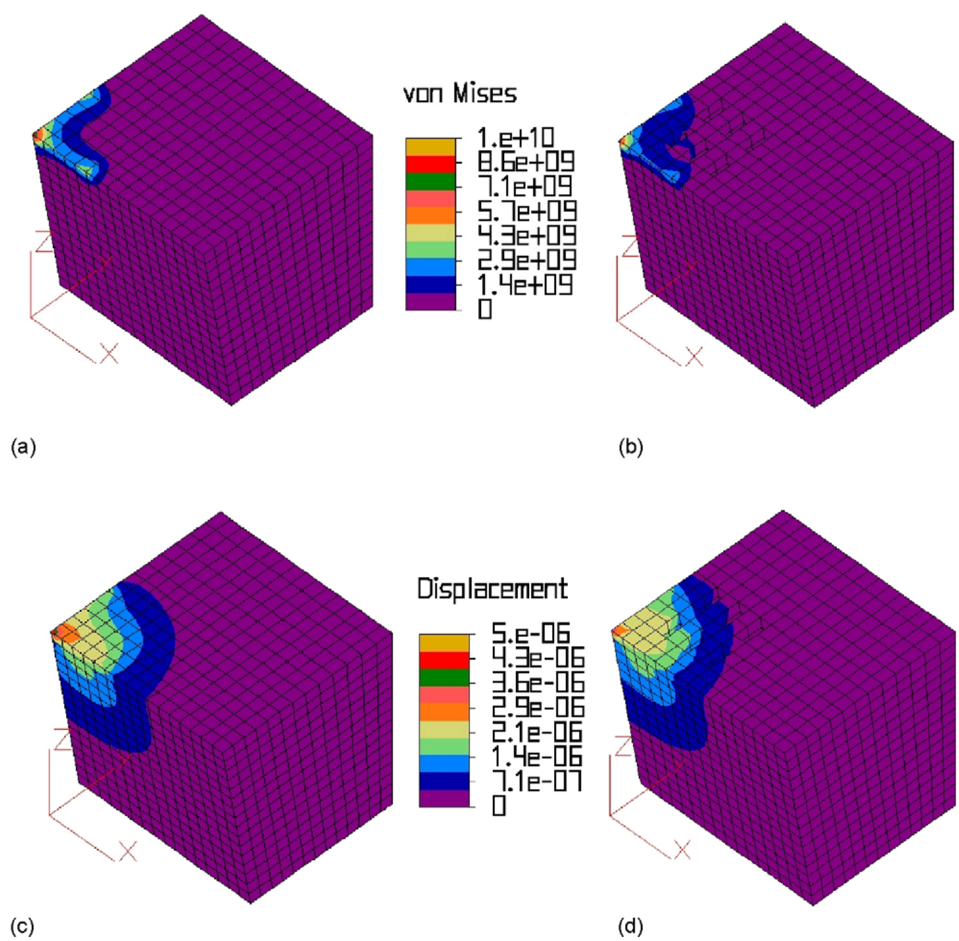

Fig. 4 – FEA analysis results. Stress distribution: (a) no hole (Pa); (b) hole (Pa). Displacement contours: (c) no hole (m); (d) hole (m).

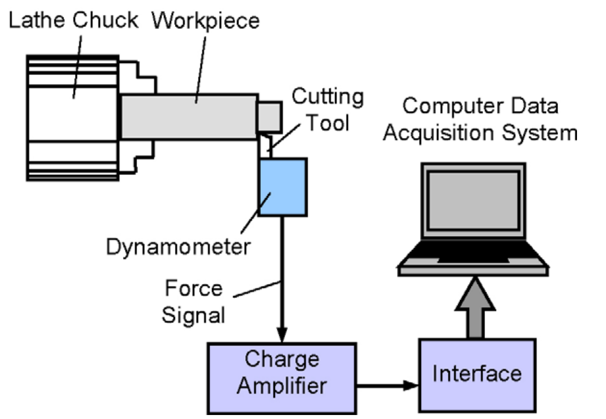

Fig. 5 – Schematic of the setup for machining experiments.

ical strength of the insert. This conclusion is supported by the actual machining experiments described later, because no catastrophic failure occurred for the tools with holes. The main reason is that the holes are relatively far away from the cutting edge where the load is most severe during machining.

4. Machining experiments

4.1. *Machining setup*

Machining tests are performed on an engine lathe with continuously variable spindle speed up to 3000 rpm. Fig. 5 shows the setup for the machining experiments. Cutting insert is mounted on the tool holder, which is firmly attached to the dynamometer. To gather the cutting forces, a Kistler three-component dynamometer is used during the experiments. A Kistler dual-mode charge amplifier converts the electric charge into voltage in the range of 0–10 V. The data are then digitized and processed with a computer data acquisition system, which is controlled by LabVIEW. Prior to the machining tests, calibration of the dynamometer is done. For each experiment, cutting forces are recorded and chips are collected for analysis. Tool wear is examined using an optical microscope.

4.2. *Experimental design*

The purpose is to study the effects of surface texture and lubrication type on cutting performance. Table 1 shows the operating conditions for the machining experiments. The machining conditions are selected after some initial tests such that well defined wear marks on the tool rake face are generated under such conditions. Commercially available uncoated WC inserts are used. The workpiece is cold rolled 1045 steel cylindrical bar of 127 mm long and 51 mm in diameter. Three different types of lubricant/coolant are used: (i) water-based cutting fluid (flood coolant), (ii) cutting oil from Mobil, and (iii) solid lubricant—tungsten disulphide powder from GoodFellow (particle size is 0.1–2 μm). Three different ways of lubricant application are compared: (i) dry machining, i.e., no lubrication, (ii) flood lubrication, i.e., flood cooling, and (iii) micropool lubrication, i.e., microholes filled with lubricant. It should be noted that it is important to fill the small holes completely

Table 1 – Operating conditions for machining experiments

Machining condition	Cutting speed	2.0 m/s
	Feed	0.3 mm/rev
	Depth of cut	1.0 mm
	Length of cut	50 mm
Cutting tool	Uncoated tungsten carbide and grade K313 (Kennametal)	
Tool holder	Rake angle of 5°, side cutting edge angle Cs = 15°	
Workpiece	1045 steel, cold rolled	
Surface texture	Microholes	
Lubricant	Water-based cutting fluid, cutting oil (Mobil), solid powder—tungsten disulphide (GoodFellow)	

with lubricant without leaving air trapped inside. In the filling process, a sharp needle as shown in the inset of Fig. 2 was used to poke into the holes to drive the air out. The solid lubricant is in powder form with particle sizes of 0.1–2 μm, which is much smaller than the hole diameter. Table 2 shows the test matrix. All the experiments are repeated for a number of times to determine the consistence of results.

5. Results and discussions

5.1. *Results*

The results are discussed in terms of cutting force, tool wear and chip morphology. In the comparisons, dry machining without coolant/lubricant is used as a reference. As mentioned earlier, the repeatability is confirmed for each experiment and thus the results reported here are typical under such conditions.

5.1.1. *Cutting force*

The three cutting force components and the friction coefficient at the chip–tool interface are plotted against machining time in Fig. 6 for the four cases listed in Table 2. Several observations can be made based on the results. First, the cutting force has no significant difference between dry machining and cutting with flood cooling. All the force components show fluctuations, which is typical in machining and

Table 2 – Test matrix

Test case #	Lubricant type	Application method
1	None	Dry machining
2	Water-based cutting fluid	Flood cooling
3	Cutting oil	Micropool
4	Solid lubricant	Micropool

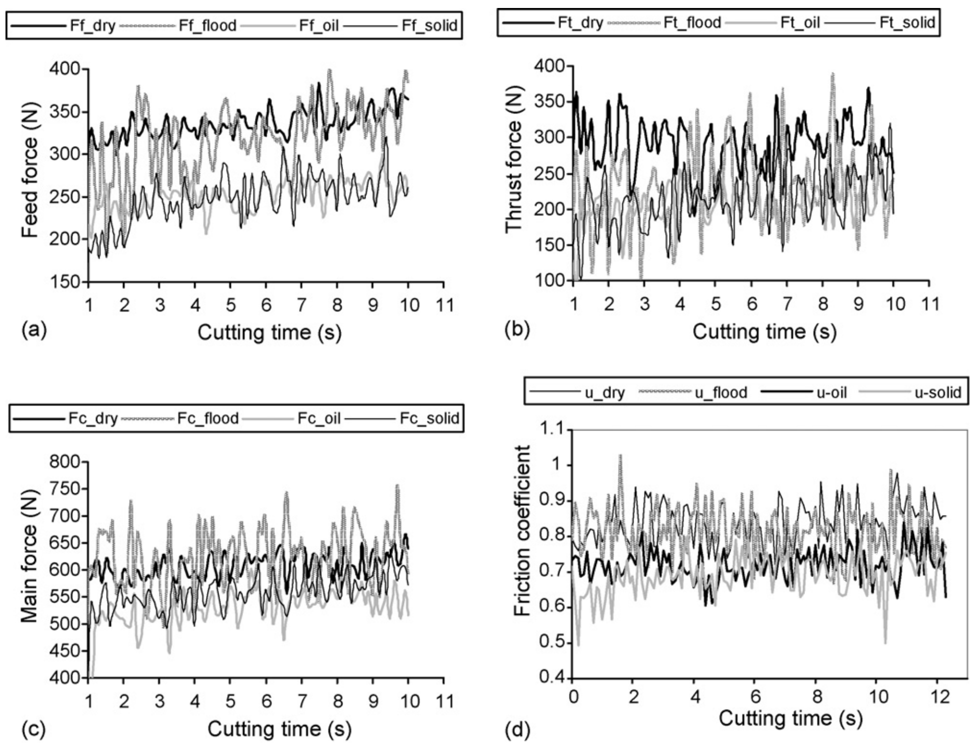

Fig. 6 – Variations of cutting force and friction coefficient with machining time. (a) Feed force; (b) thrust force; (c) main cutting force; (d) friction coefficient.

is attributed to vibration, built-up edge, and the frictional conditions (e.g., stick-slip) at the chip–tool and tool–workpiece interfaces. Second, there is no significant difference in cutting force between micropool oil lubrication and micropool solid lubrication. Third, there is a clear decrease in cutting force between micropool lubrication and dry/flood cooling. The percentage reduction in the mean force components (F_f, F_t, and F_c) between micropool lubrication and dry machining is found

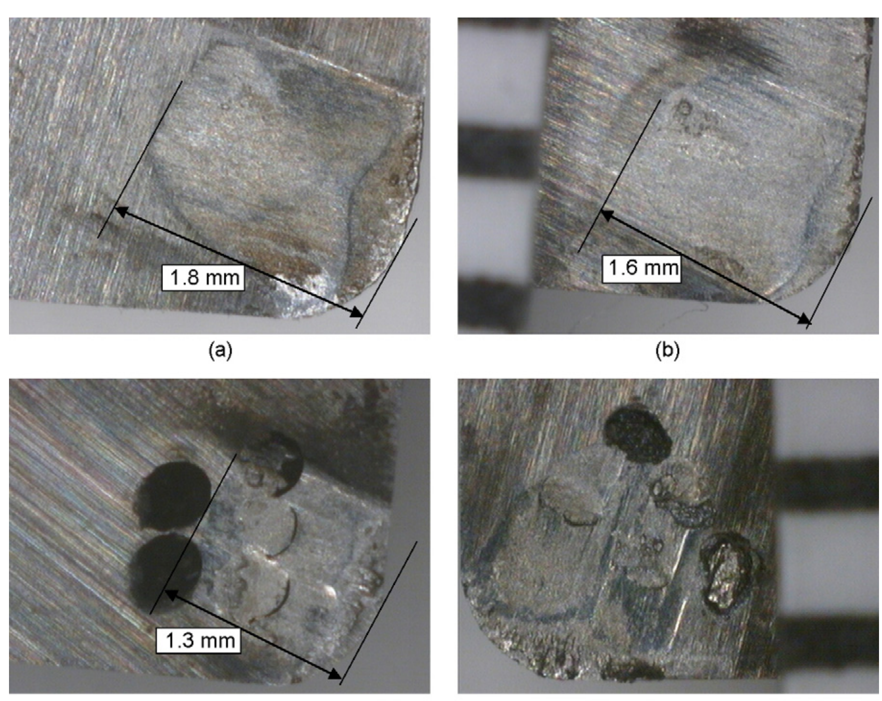

Fig. 7 – Optical images of the chip–tool contact area (crater wear). (a) Dry cutting; (b) flood cooling; (c) oil lubrication; (d) solid lubrication.

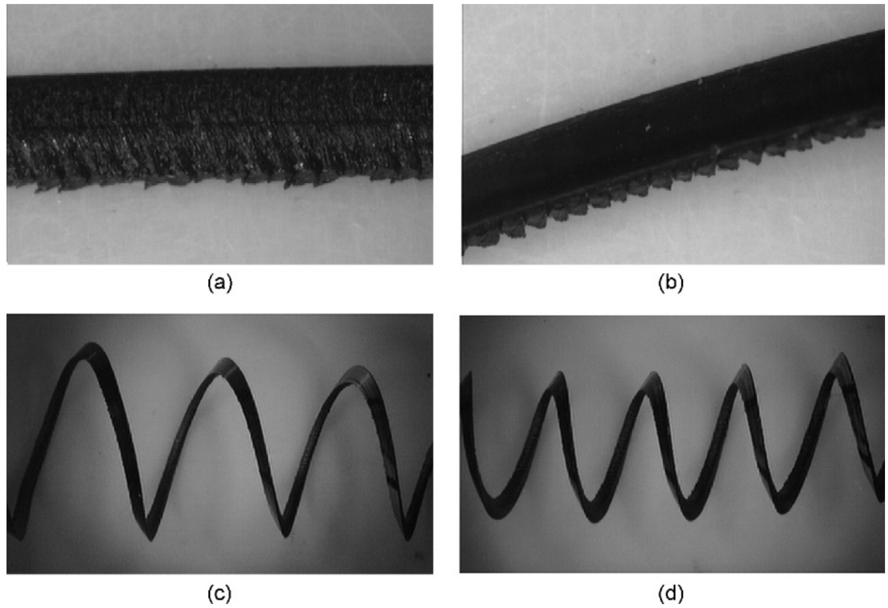

Fig. 8 – Optical images of the chips. (a) Dry cutting; (b) flood cooling; (c) oil lubrication; (d) solid lubrication.

to be 25%, 27% and 11%, respectively. Finally, the friction coefficients are calculated and, as shown in Fig. 6(d), follow the same trend as the cutting forces. And the value for micropool lubrication is reduced by 16% compared to dry machining. Several experiments were carried out under the same conditions to study the repeatability of the results. All the experiments showed similar results.

5.1.2. *Chip–tool contact area*

Chip–tool contact area can be seen from the wear mark (crater wear) on the tool rake face after cutting. Fig. 7 shows the tool–chip contact areas for the four test cases listed in Table 2. For all the conditions, small built-up edges are noticeable at the cutting edge, and the wear boundary is clear except for the case with solid lubrication. The wear shape is similar under dry cutting and flood cooling, with the chip–tool contact length being 1.8 and 1.6 mm, respectively. The width of the contact area is expected to be the same because of the same depth of cut used in all the cuts. In contrast, the chip–tool contact length for micropool oil lubrication is only 1.3 mm (Fig. 7c), a nearly 28% reduction compared to dry cutting. The contact length for the solid lubrication is not indicated because of the fuzzy wear boundary. It can be seen from Fig. 7(c) and (d) that some of the holes are either fully or partially covered by the chip material due to the high pressure and high temperature at the chip–tool interface as chip flows over the tool rake face.

5.1.3. *Chip morphology*

The chip morphology for the four cases is compared in Fig. 8. Continuous straight chips are observed for both dry cutting and flood cooling. Continuous coiled chips are observed for micropool lubrication with either oil or tungsten disulphide. The diameter of the chip coil is from 11 to 15 mm. It should be noted that the shape of the chip is consistent throughout the cut from start to end. It is natural to think that the curled chip geometry may be related to the force reduction due to micropool lubrication. A simplified analysis is attempted next to relate the decrease in main cutting force to the radius of the coiled chip.

As shown in Fig. 9, the straight chip is from cutting with a regular insert while the dotted curled chip is from insert with micropool lubrication. It is argued that the decrease in the main force (F_n in the figure) is equivalent to the force that bends the straight chip to the curled one with the radius of R. Here the chip is treated as a beam. Then using beam theory, the following relation for the bending moment can be established:

$$M = \frac{EI}{R} = F_n L_c.$$

Then it follows,

$$F_n = \frac{EI}{RL_c},$$

where E is the elastic modulus, $I = 1/12\, bt_c^3$ is the moment of inertia (b is chip width and t_c is chip thickness), and L_c is the chip–tool contact length. Using the following values for textured tool with oil lubrication: $b = 1$ mm, $t_c = 0.38$ mm, $R = 12$ mm, $L_c = 1.6$ mm, and $E = 200$ GPa, F_n is calculated as 95 N,

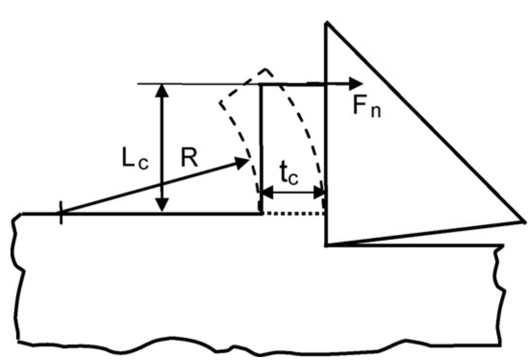

Fig. 9 – Schematic of chip formation geometry.

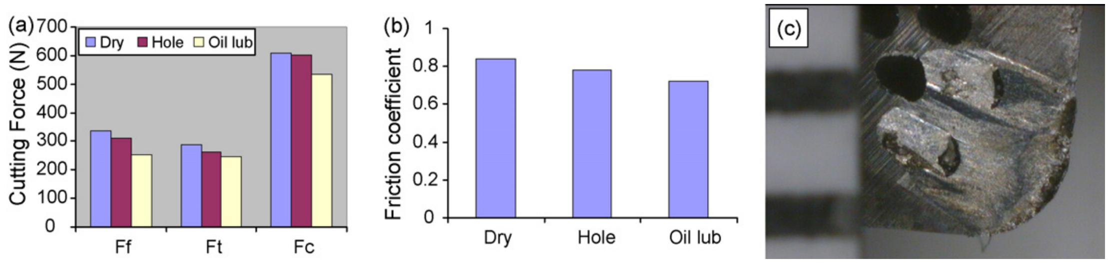

Fig. 10 – (a) Comparison of cutting force, (b) comparison of friction coefficient, and (c) optical image of chip–tool contact area in cutting with textured tool only.

which has a fair comparison to the reduction in the main force (76 N) from the experiment. With this relationship, chip curl radius may be used as an estimate for the frictional condition at the chip–tool interface.

5.2. *Discussions*

5.2.1. *Lubrication mechanisms*

In comparison with dry cutting, micropool lubricated cutting tool leads to reduced cutting force, smaller friction coefficient, shorter chip–tool contact length, and coiling chips, which are consistent with the effects of cutting tool lubrication as summarized by Bailey (1975) and Shaw (2005). But how does the lubrication effect happen? It is believed that lubrication is accomplished through the following two mechanisms. First, the direct chip–tool contact area is reduced with the embedded micropools that contain liquid or solid lubricants. As shown in Fig. 7(c) and (d), the micropool area is approximately 20–30% of the total chip–tool contact area. The smaller direct contact area between the chip and tool rake face leads to less friction force. Second, the lubricant may be squeezed out or spread over by the rubbing action of the chip flowing over the micropools to form a thin film (liquid or solid) at the chip–tool interface so that direct chip–tool contact (weld) can be further reduced. For liquid lubricant, there is a large mismatch in the coefficient of thermal expansion, with the coefficient of oil lubricant being more than 100 times that of WC tool (Booser, 1983; Yao et al., 2002). Hence, the large expansion of the lubricant should help bring the lubricant into the chip–tool interface under the high interface temperature during machining.

The lubrication effect is found to be more pronounced further away from the cutting edge, where the contact pressure is relatively low, and it is evidenced by early separation of the chip from the tool and thus coiling chips. Reduced friction results in reduced cutting forces, especially the feed and thrust components in which friction plays a bigger role than for the main force. It is noted that some microholes are blocked by the chip material, and those are the holes that are close to the cutting edge because the pressure is higher compared to the region farther away from the edge. But the lubrication effect appears to sustain throughout the entire cut because the consistent coiling chips produced and the low cutting forces from the beginning to the end of the cut. Another support for the enduring lubrication effect can be inferred from the cutting force history, with smoother force profiles produced for micropool lubricated cutting tools.

To further clarify the independent role of microhole and lubricant on the results, the same experiment (i.e., same conditions) was conducted using textured insert but without lubricant added. The average cutting force and friction coefficient are plotted in Fig. 10 in comparison with the data from dry cutting and machining with oil lubrication. It can be seen that the three force components and the friction coefficient with textured tool fall between the values of dry cutting and oil lubrication, with the feed force and main force being much closer to those values in dry cutting. It can be said that the microholes alone possess some “lubrication” capability. And the main reason is believed to be related to the reduction of chip–tool contact area as discussed earlier.

5.2.2. *Future research*

From this comparative study, it is certain that the realization of ideal lubrication for cutting at high speeds requires that lubricant be brought directly to the chip–tool interface. Normal ways of cutting fluid application mainly provide general cooling for cutting tool and workpiece, with virtually no lubrication effect, as shown in this study by flood cooling as well as other investigations (Bailey, 1975; Shaw, 2005). Micropool lubrication of cutting tool has the potential to be an economic way of realizing minimum quantity lubrication in high speed machining applications. Further research is needed to improve the design of micropool lubrication (hole geometry, arrangement, etc.), study tool life, and investigate different types of lubricants. As noted earlier that the microholes close to the cutting edge are blocked with chip material due to high pressure, such problem could be alleviated by injecting high-pressure lubricant through the microholes. Therefore, it could be a worthy research direction to develop an economical mechanism to inject high-pressure lubricant into the small chip–tool interface.

6. Conclusions

Surface texturing of cutting inserts with microholes are successfully made by means of femtosecond laser micromachining without affecting the performance of the inserts. The machining performance of micropool lubricated cutting tools are assessed in terms of cutting force, chip–tool contact and chip morphology. The comparative results played a vital role in clarifying the potential of micropool lubrication in reducing friction and wear in metal cutting. The main conclusions from this study are summarized in the following:

(1) Micropool lubrication brings minimum amount of lubricant into the chip–tool interface and improves the severe contact conditions by reducing the coefficient of friction, and thus reduces the energy loss due to friction in metal cutting. The finite analysis indicates that the cutting tool is not weakened with the microholes.
(2) Micropool lubrication is very effective in reducing cutting force, thus cutting energy, and chip–tool contact length. It also promotes chip curl and eases chip removal. In contrast, conventional flood cooling has no such effects because it cannot penetrate to the chip–tool interface.
(3) Large amount of cutting fluid could be avoided with minimum lubricant in micropool lubricated cutting tool and therefore it is environmentally friendly. Further work is needed to study longer cuts and tool life. Ways of minimizing microhole blockage should be explored.

Acknowledgements

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