Integrated Mechanical Pulse Jet Coolant Delivery System Performance for Minimal Quantity Lubrication

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Abstract

Minimum quantity lubrication (MQL) machining is one of the promising solutions to the requirement for decrease in cutting fluid consumption. This research describes MQL machining in a range of lubricant consumption 2.0ml/h, which is 10–100 times smaller than the consumption usually adopted in industries. MQL machining in this range is called pulse jet coolant delivery system in this research. A specially designed system was used for concentrating small amounts of lubricant onto the cutting interface. The performance of concentrated spraying of lubricant in pulse jet coolant delivery system design was compared with that of current 'Pulse Jet MQL' systems. The concentrated spraying of lubricant with a specially designed of system was quite effective in increasing tool life in the pulse jet coolant delivery system range.

Keywords: MQL, Pulse Jet, Cutting Fluid and Machining.

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1. INTRODUCTION

During cutting operations one of the most important problems is tool wear, caused by the normal load generated by the interaction between tool and workpiece and by the relative motion between tool and chip and workpiece and tool [1]. Tool wear, which results in tool substitution, is one of the most important economical penalties to take into account during cutting, so it is very important to improve tool life, minimizing the wear and optimizing all the cutting parameters and factors: depth of cut, cutting velocity, feed rate, cutting fluids and cutting fluids application. In cutting operations fluids play an important role. They must mainly guarantee lubrication and cooling, secondly protect workpiece and tool from corrosion and promote the chip evacuation. Many application methods can be used. Each application method is selected depending on the advantages that it can give. The main types of application are:

• Hand application: this type of application is used only in small batch production, because, using this lubrication method, it is not easy continuously to apply the cutting fluids and sufficiently to cool the workpiece. It guarantees a low level of lubrication, cooling and chip removal [1].

• Flooding: this application is the most common one. It guarantees a very good level of lubrication, cooling and chip removing. Applying this method of lubrication, it is also possible to orientate the nozzle to the clearance tool surface, reducing the flank wear, especially when the cutting speed is slow.

• Minimal quantity lubrication (MQL): in MQL a very small lubricant flow (ml/h instead of l/min) is used. In this case, the lubricant is directly sprayed on the cutting area. It guarantees a good level of lubrication, but the cooling action is very small and the chip removal mechanism is obtained by the air flow used to spread the lubricant.

In this work, the attention has been focused on minimal quantity lubrication and its influence on lubricant costs and workpiece/tool/machine cleaning cycle time. Minimum quantity lubrication (MQL) presents itself as a viable alternative for hard machining with respect to tool wear, heat dissertation, and machined surface quality [2]. Minimum quantity lubrication refers to the use of cutting fluids of only a minute amount–typically of a flow rate of 50 to 500 ml/hour – which is about three to four orders of magnitude lower than the amount commonly used in flood cooling condition, where, for example, up to 10 liters of fluid can be dispensed per minute. The concept of minimum quantity lubrication, sometimes referred to as "near dry lubrication" [3] or "microlubrication" [4], has been suggested since a decade ago as a means of addressing the issues of environmental intrusiveness and occupational hazards associated with the airborne cutting fluid particles on factory shop floors. The minimization of cutting fluid also leads to economical benefits by way of saving lubricant costs and workpiece/tool/machine cleaning cycle time.

2. LITERATURE SURVEY

A recent survey conducted on the production of the European automotive industry revealed that the expense of cooling lubricant comprises nearly 20% of the total manufacturing cost [5]. In comparison to cutting tools (7.5%), the cooling lubricant cost is significantly higher. As a result, the need to reduce cutting fluids consumption is strong. Furthermore, the permissible exposure level (PEL) for metalworking fluid aerosol concentration is 5 mg/m3, per the U.S. Occupational Safety and Health Administration (OSHA) [6], and is 0.5 mg/m3 according to the U.S. National Institute for Occupational Safety and Health (NIOSH) [7]. The oil mist level in U.S. automotive parts manufacturing facilities has been estimated to be generally on the order of20-90 mg/m3 with the use of traditional flood cooling and lubrication [8]. This suggests an opportunity for improvement of several orders of magnitude.

On the other hand, completely dry cutting has been a common industry practice for the machining of hardened steel parts. These parts typically exhibit a very high specific cutting energy. Traditional beliefs indicate that completely dry cutting of them, as compared to flood cutting, lowers the required cutting force and power on the part of the machine tool as a result of increased cutting temperature. However, achievable tool life and part finish often suffer under completely dry condition. Therefore, the permissible feed and depth of cut have to be restricted. Under these considerations, the concept of minimum quantity lubrication presents itself as a possible solution for hard turning in achieving slow tool

wear while maintaining cutting forces/power at reasonable levels, provided that the minimum quantity lubrication parameters can be strategically tuned.

Metal cutting fluids changes the performance of machining operations because of their lubrication, cooling, and chip flushing functions. Typically, in the machining of hardened steel materials, no cutting fluid is applied in the interest of low cutting forces and low environmental impacts. Minimum quantity lubrication (MQL) presents itself as a viable alternative for hard machining with respect to tool wear, heat dissertation, and machined surface quality. This study compares the mechanical performance of minimum quantity lubrication to completely dry lubrication for the turning of hardened bearing-grade steel materials based on experimental measurement of cutting forces, tool temperature, white layer depth, and part finish. The results indicate that the use of minimum quantity lubrication leads to reduced surface roughness, delayed tool flank wear, and lower cutting temperature, while also having a minimal effect on the cutting forces. [2]

In 2002, A. S. Vadarajan et al. 2002 have introduced a new MQL application technique which overcomes the problems caused by mist. In this method, small quantities of cutting fluid were applied in form of high velocity, narrow, pulsed jet. The amount of cutting fluid used was only 2 ml/min. The performance in hard turning of hardened tool steel during minimal cutting fluid application was superior to that during dry turning and conventional flood turning on the basis of cutting force, tool life, surface finish, cutting ratio, cutting temperature and tool-chip contact length. Anyway, focusing a pulsed jet to the cutting zone poses no problem in turning because the cutting tool is stationary [9]. This process also can be done on high speed milling as proven by Thanongsak Thepsonthi in May 2005 with his paper "Investigation into minimal cutting fluid application in high speed milling of hardened steel using carbide mills".

From all investigations, the minimal cutting fluids application in pulse jet form has shown to be a viable alternative to the current, flood and dry cutting method that being used widely in industries. However, to comply with industry application, the system need an improvement because recent research only introduced the basic technique" – Lab

prototype. Therefore, this study would explore the feasibility of designing MQL application technique which can be used in more advanced machining strategies.

3. EXPERIMENTAL PROCEDURE

The experimental set-up is shown in Fig. 1. The set-up consists of a high speed vertical machining center MITSUI SEIKI VT3A, a Kistler three components dynamometer (type 9255B), a Kistler charge amplifier and an oscilloscope. A special design Of MQL was developed and a special fixture was designed and installed at the spindle so that the injection nozzle could be located at any desired position without interfering with the tool or workpiece during the cutting process. The diameter of nozzle orifice was 1 mm. The workpiece material was ASSAB DF3 hardened tool steel of hardness 51 HRc, with a composition of 0.95%C, 0.11%Mn, 0.6%Cr, 0.6%W and 0.1%V. It was prepared in blocks of a size 50mm x 100mm x 250mm. 12 mm, P20 grade, Titanium Aluminum Nitrite (TiAlN) coated carbide ball end mill inserts from TaeguTec[®] were used in this study. The cutter was a two-flute type which has better chip ejection feature as a result of a larger chip pocket and suitable for slot cutting.

A general propose water miscible coolant ECOCOOL 6210 IT from FUCHS[®] was used as the flood coolant with a volumetric concentration of 1:10. It is free from phenol, chlorine and other harmful additive. Flood coolant was applied from 5 nozzles around the tool at the rate of 7,000 ml/min. Dry cutting was performed without any air blow or internal cooling system. The pulsed jet application was carried out using the developed fluid delivery system. The parameters of application were set in an optimal condition based on preliminary tests at a pulsing rate of 400 pulse/min, pressure of 20 MPa and delivery rate of 2 ml/min. The direction of application was set against the feed direction. The cutting fluid used for the pulsed jet application was an active sulphurized anti-mist neat cutting oil RATAK SSN 321 from FUCHS[®].

The experiments were conducted in two types of milling processes which are generally applied to ball end milling. The first process was slot milling where the tool immersion is equal to the effective tool diameter. The second process was down (climb) milling which is generally used to machine complex

3D shapes. The tests were carried out in different cutting conditions in order to investigate the effects of cutting parameters to the performance of pulsed jet application. The cutting parameters used in the experiment are shown in Table 1.

The performance of the lubrication modes were evaluated in terms of tool wear, surface roughness, cutting force and cutting temperature.

During the experiment, cutting forces were measured in terms of the maximum force recorded by the dynamometer. Tool wear was measured in term of maximum flank wear using a microscope. Surface roughness was measured in terms of the average roughness (Ra) using a portable surface roughness tester at 6 specific points. Chips were also collected during each experiment for an estimation of the cutting temperatures.

4.   RESULTS

Flank wear and surface roughness during slot milling at different cutting velocities are shown in Fig 2(a) and (b). Feed rate, depth of cut and cutting length were kept constant at 0.01 mm/tooth, 0.2 mm and 6 m, respectively. The figure clearly shows that the flank wear in pulsed jet mode is lower than flood and dry modes, especially at high cutting velocity. Considering at cutting velocity of 175 m/min, flank wear in pulsed jet mode is 7 times lower than in dry mode. An increase in the cutting velocity results in significant increase of flank wears in dry and flood modes. While, the flank wear in pulsed jet mode is not affected.

The surface roughness in pulsed jet mode increases with the increase of cutting velocity, while in flood and dry modes surface roughness decreases with the increase of cutting velocity. It should be noted that the surface roughness in pulsed jet mode at the cutting velocity 175 m/min is even higher than in dry cutting.

The performance of high speed slot milling was also investigated under various feed rates. Cutting velocity, depth of cut and cutting length were kept constant at 150 m/min, 0.2 mm and 6 m, respectively. Fig. 3(a) shows flank wear of three lubrication modes at various feed rates. It can be seen that flank wear in flood mode was the highest followed by dry and pulsed jet mode. At low feed rate (0.01 mm/tooth) the large difference of flank wear in dry and pulsed jet mode can be observed but as feed rate increases, flank wear in dry mode reduces and appears to be almost equal to flank wear of pulsed jet mode. However, flank wear in pulsed jet mode was still lower than in flood mode.

Surface roughness at various feed rates is shown in Fig. 3(b). It can be seen that surface roughness in pulsed jet mode increases with an increase of feed rate. At low feed rate (0.01-0.02 mm/tooth) surface roughness of pulsed jet mode is better than the others but as feed rate increases to 0.03 mm/tooth, surface roughness in minimal mode is worse than in flood mode.

The experiment was also conducted using the down milling technique at various cutting velocities and feed rates. A radial depth of cut or pickfeed was set constant at 0.2 mm.

The effect of cutting velocity on flank wear and surface roughness during down milling at feed rate of 0.02 mm/tooth and axial depth of cut of 0.2mm is shown in Fig. 4(a) and (b), respectively. It can be seen that flank wear in pulsed jet mode is the lowest. It is around 3 times lower than flank wear in flood and dry mode at a cutting velocity of 175 m/min. Better surface finish was also obtained during machining with pulsed jet mode.

The effect of feed rate on flank wear and surface roughness during down milling at the cutting velocity of 150 m/min and axial depth of cut of 0.2 mm is shown in Fig. 5(a) and (b), respectively. It can be seen that machining with pulsed jet application always obtains the lowest flank wear and surface roughness.

Tool life test was conducted using the slot milling technique at cutting velocity of 175 m/min, feed rate of 0.01mm/tooth and depth of cut of 0.2 mm. The milling test was done until the tool failed in order to investigate the progression of cutting force, surface roughness and flank wear against cutting duration. The tool failure criterion was set as;
1.Maximum flank wear exceeds 0.35 mm.
2.Catastrophic failure or localized chipping.
3.Total edge fracture.

Fig. 6 (a), (b) and (c) show the progress of cutting force components during the process. Considering the whole period of cutting, it can be seen that cutting forces in pulsed jet mode are lower than in flood and dry mode.

Fig. 6 shows the flank wear progression for all lubrication modes. It can be seen that the increase of flank wear in pulsed jet mode is slow at the beginning, and then it increases at a higher rate after 50 min. On the other hand, the

increase of flank wear in flood and dry modes are rapid at the beginning then become slower after around 30 min. The tool life for in all modes is found to be about the same for all lubrication modes when the tool failure criterion is set at 0.35 mm.

Fig. 7 shows the surface roughness versus time. The result shows that the surface roughness in pulsed jet mode is the lowest compared to either flood or dry modes. Sparks and metal lumps on the finished surface were visually observed in all lubrication modes after a certain time of cut. The sparks started to appear during dry, flood and pulsed jet modes when time equals to 18, 30 and 54 minutes, respectively. The metal lumps on the finished surface started to form during dry, flood and pulsed jet modes when time equals to 36, 50 and 54 minutes, respectively. These metal lumps occurred on the finished surface resulting in the rapid increase of surface roughness as can be seen in the graph. However, the formation of spark and metal lumps in pulsed jet mode was slower than in other modes.

The photographs from Scanning Electron Microscope (SEM) on the flank face of the worn tool are shown in Fig. 8(a), (b) and (c). These tools were used for the slot milling process at the cutting velocity of 175 m/min, feed rate of 0.01 mm/tooth, and depth of cut set at 0.2 mm. The SEM photographs were taken after 90 minutes of cut. The result shows that the dominant tool wear mechanism was a classic flank wear and no cutting edge chipping or fracture can be seen in all lubrication modes. The presence of adhesion on the flank wear is extensive in dry and pulsed jet modes but not as extensive in flood mode. Central wear can be seen only in flood mode. Damages to the protective coating and adherence can be seen in pulsed jet mode.

Chips obtained from all modes can be defined as stable chips, because the shape and geometry agrees well with the in-cut segment of the cutter in the stable process [10]. Chips acquired for each mode had different colors. Chips produced in dry mode have a dark blue color while chips in flood mode are silvery and light brown. Chips obtained in pulsed jet mode have a blue and golden brown color.

The colors of these chips reflect the degree of oxidation on the surface of the chip owning to the different temperature level. Thus the temperature at the cutting zone can be estimated by the color of chips. Venkatesh [11] has found the chip temperature vs. color chart as shown in Table 2. Table 3 shows the color of chips in each mode and their estimated temperature based on Venkatesh's table.

The estimated temperature from chips indicates that the temperature during dry milling was the highest followed by pulsed jet mode and flood mode. It can be seen that the pulsed jet application cannot provide a better cooling property than the flood application can. The cooling provided by convection and vaporization of cutting oil in pulsed jet application is still lower than the cooling provided by convection in flood application.

Chips removal in each lubrication modes was different in term of the mechanism. In dry mode chips were flown away by the rotational force caused by the rotation of cutting tool. In flood mode chips were flushed by the large amount of cutting fluid that flows during the machining process. These two modes left no chips on the machined surface. Accumulation of chips on the machined surface during the machining process can be observed in the pulsed jet mode. The cutting oil used in pulsed jet mode is viscous thus it promotes the chips to stick on the machined surface. However, the momentum generated from the fluid injection at high pressure (20MPa) was high enough to move some of the chips away from the cutting area but some were still on the machined surface.

5. DISCUSSION

The pulsed jet application shows a good performance in reduction of tool flank wear. The lowest flank wear were obtained in pulsed jet mode for most cutting conditions. The reduction of flank wear when machined with pulsed jet mode is attributed to its good lubricity. The cutting oil used in pulsed jet mode lubricates the tool-chip and tool-workpiece interfaces. The sulfur, extreme-pressure additive in cutting oil chemically react with the freshly generated metal surface of the chip to produce a metallic sulfide film which has lower shear strength than the chip material, thus reducing friction and cutting forces [12]. These compounds are protective in that they inhibit welding which would occur with bare metal surface in contact. This welding act as a peeler, every time it is broken up mechanically some tool material is pulled away with it [13].

The reduction of tool wear in pulsed jet mode indicates that the cutting oil can reach the tool-chip and tool-workpiece interfaces. Penetration of cutting oil into the cutting zone is facilitated by the high velocity of the high-pressure jet application. The high-pressure injection of cutting oil (20MPa) also causes it to be fragmented into tiny droplets after it hits the cutting tool. This fragment allows the small amounts of cutting oil to wet the tool rake face prior to its entering the workpiece and penetrate into the interfaces during cutting period.

Even thought the soluble oil used in flood application can also lubricate the cutting interfaces, its lubricity is not as good as the cutting oil used in pulsed jet mode. This may be one of the reasons why flood application fails to protect the cutting tool wear. Another reason is that the soluble oil may not be able to enter the cutting interfaces due to the low application pressure of flood application.

The higher tool wear during flood mode compared to dry cutting also indicates that flood application has negative impacts on the cutting tool wear. However, flood application exhibited a good performance in terms of cooling. Lowest cutting temperature was obtained from flood mode. Generally, a reduction in cutting temperature results in a decrease of wear rate and an increase of tool life [14]. However, the result of flank wear in flood mode is worst compared to other modes regardless of its lowest cutting temperature. So we may be able to conclude that the lubricity of cutting fluid has a dominant effect on tool wear rather than cooling. Selection of cutting fluid to be used in this high speed end milling of hardened steel should be focused on lubricity of cutting fluid.

Machining with minimal application shows the low flank wear rate at the beginning but it fails to maintain that rate along the whole duration of cut. The increase of wear rate after certain time of cut may be due to an absence of protective coating which has been worn or chipped. Thus, the carbide substrate can be worn out easily resulting in high increase of wear rate [15]. In addition, the cutting temperature increased with the increase of tool wear. This high temperature also increases the wear rate because it facilitates adhesion and oxidation [16].

Even though the tool life in pulsed jet mode was not different from tool life in dry and flood mode when assigning 0.35 mm of flank wear as a tool failure criterion, it succeeded in maintaining the tool in a serviceable condition longer than flood and dry mode. If tool failure criterion was set at 0.2 mm of flank wear, the tool lives of dry, flood and pulsed jet mode would be 24 min, 28 min and 66 min, respectively. It can be seen that tool life in pulsed jet mode is 2 times longer than dry and flood modes.

Generally, cutting velocity is the dominant factor to the cutting tool wear. Increase in cutting velocity significantly results in a reduction of tool life [17]. The result of this work also shows the significant effect of cutting velocity. The tool flank wear increased with the increase of cutting velocity regardless of the lubrication mode. However, the flank wear in pulsed jet mode at high cutting velocity seemed not to be much affected by the cutting velocity (small increase in flank wear when increased cutting velocity). From the result, it showed that 3 times reduction of flank wear can be obtained when machine in pulsed jet mode at the cutting velocity of 175 m/min. Flank wear affects parts quality, especially geometric accuracy. Pulsed jet application reduces the flank wear thus it can improve parts quality. The reduction of flank wear when using pulsed jet application also allows the use of high cutting velocity thus shorten a process time and save a production cost.

The result from SEM shows that cutting edge chipping and fracture are not the cause of tool failure. Comb crack which normally occur on the intermittent cutting like milling especially when operating with cutting fluid was not evident in this experiment [18]. In addition, there are some damages to the protective coating on the insert used in pulsed jet mode. Some of the damages occurred on the clearance face of the tool which is not involved with the cutting. Thus they were not subjected to a high pressure, consequently no adhesion takes place. It is possible that the thermal stress was the cause of protective coating damaged. During cutting process the tool was heated by the heat generated at cutting zone while the surface of the tool was cooled by the vaporization of cutting oil droplet. This can lead to cyclic thermal stress at the surface of the tool which cause the chipping or fracture of the protective coating [19].

Surface roughness of ball end milling when the cutter is perpendicular to the workpiece is

highly affected by the rubbing at the tool tip [20]. The tool tip of ball end mill is very small in size and actually does not involve in shearing but it instead rubs the workpiece in the feed direction because its cutting velocity is zero. Its ability to improve surface finish in pulsed jet mode may be attributed to the fact that the cutting oil lubricates the tool tip, consequently reduces the negative effect caused by the rubbing of the tool tip against the surface finish. The flood application failed in lubricating the tool tip resulting in a large central wear at the tool tip. This central wear affects the surface roughness as well as geometric accuracy of the machined parts [20].

In down milling, the surface quality obtained from pulsed jet mode was excellent compared to those obtained from dry and flood mode. The surface roughness when using pulsed jet application was maintained under the level of 1.5 μm while the surface roughness in dry and flood mode are at the level of 2.0-6.0 μm.

The surface roughness of all modes increases with increase of cutting time. However, surface roughness in pulsed jet mode was lower than the surface roughness obtained from dry and flood modes. This is due to the fact that tool wear in pulsed jet mode was lower than flood and dry mode. In addition, the minimal application can slows the occurrence of metal lump on the surface which deteriorates the quality of surface finish.

Slot milling with pulsed jet application shows the best surface roughness only at low cutting velocity and low feed rate. The increase of surface roughness at high cutting velocity and high feed rate may be attributed to a lacking of an ability to flush away chips out from the cutting zone during machining with pulsed jet application. Actually, the fluid injection in pulsed jet application can flush the chips away from the cutting zone but not enough to flush them away from the workpiece surface. However, the injection is in discontinuous form; so its performance of flushing chips depends on the number of pulse per feed distance. The higher the number of pulse per feed distance, the better the performance is. An increase of the cutting velocity and feed rate will result to a faster table feed. Since the pulsing frequency was kept constant, faster table feed results in the decrease of the number of pulse per feed distance, consequently reducing the ability to flush the chips away. Poor chips control may increase the chance of chips reentering the cutting zone. Chips which are normally harder than the workpiece may cause scratches on the finished surface or behave like debris which cause abrasion [21]. Nevertheless, this problem does not occur in the down milling technique.

6. CONCLUSION

The result clearly indicates the advantages of using this pulsed jet application over flood application and dry cutting. Cutting forces, surface roughness, tool wear and cutting temperature were affected beneficially when using the pulsed jet method. The following conclusions can be deduced from the finding of this study.

1. The pulsed jet application performance was better compare to dry cutting and flood application in terms of surface finish and tool wear.

2. The pulsed jet application was suitable for high speed end milling since the performance at high cutting velocity was better compare to performance of dry cutting and flood application especially in term of tool wear.

The better performance over flood application and dry cutting, also the drastic reduction of cutting fluid consumption lead to the conclusion that the integrated mechanical pulse jet coolant delivery system for minimal quantity lubricant (MQL) operation is feasible to be used in high speed milling processes. It is also considerable as an alternative of flood application and dry cutting.

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Table 1 Experimental parameters

Constant conditions	
Workpiece material	Tool steel ASSAB DF3
Tool diameters	12 mm
Length of cut	6 m
Depth of cut	0.2 mm
Experimental variables	
Cutting speed	125, 150, 175 m/min
Feed rate	0.01, 0.02, 0.03 mm/tooth
Type of operation	Slot milling, Down milling
Lubrication mode	Dry, Flood, Pulsed jet

Table 2 Chip temperature vs. chip color

Chip temperature (°C)	Chip color
981	Dark blue
900	Dark blue + brown
881	Brown
837	Light brown

Table 3 Chip temperature in different mode of lubrication

Lubrication mode	Chip color	Chip temperature (°C)
Dry	Dark blue	981
Pulsed jet	Blue + golden brown	880-900
Flood	Silvery +light brown	<837
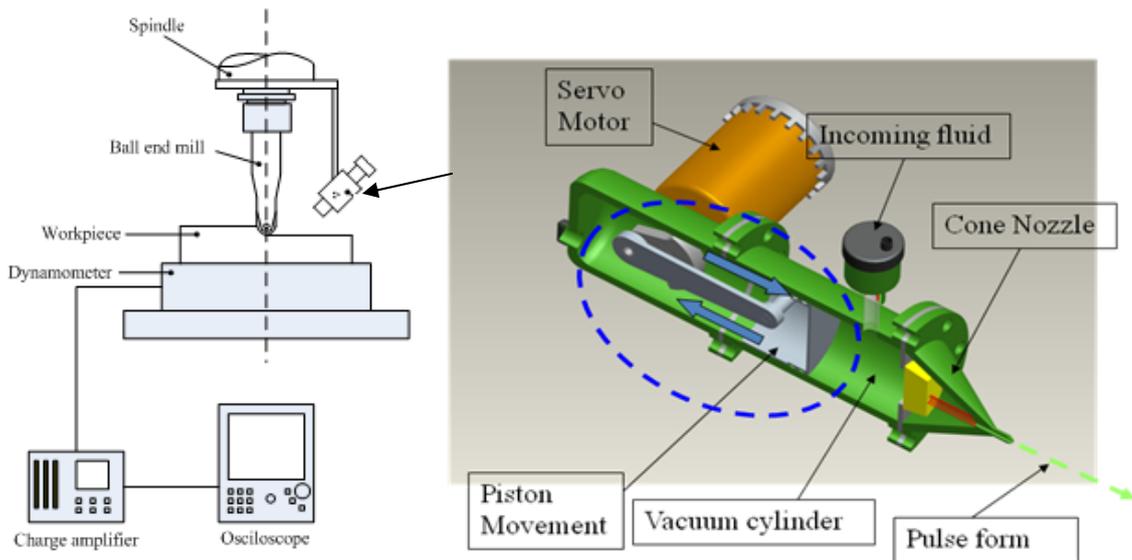
Fig. 1 Schematic diagram of experimental set-up

(a)

(b)
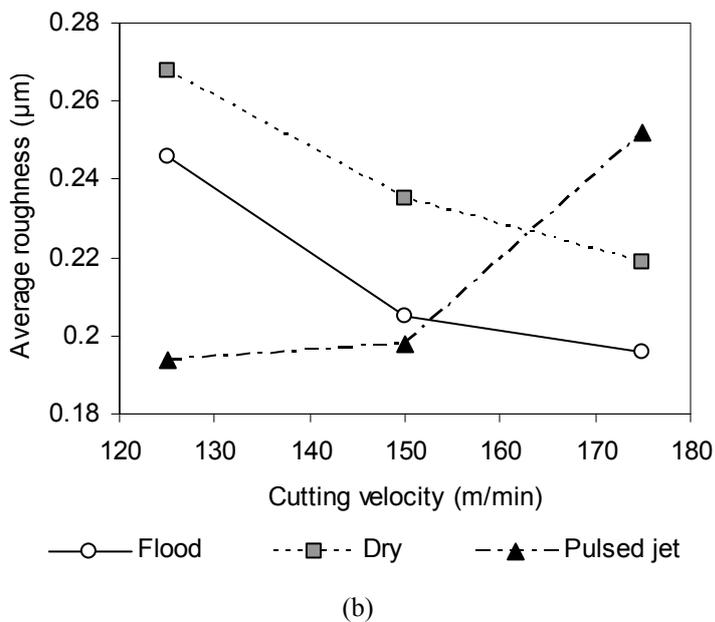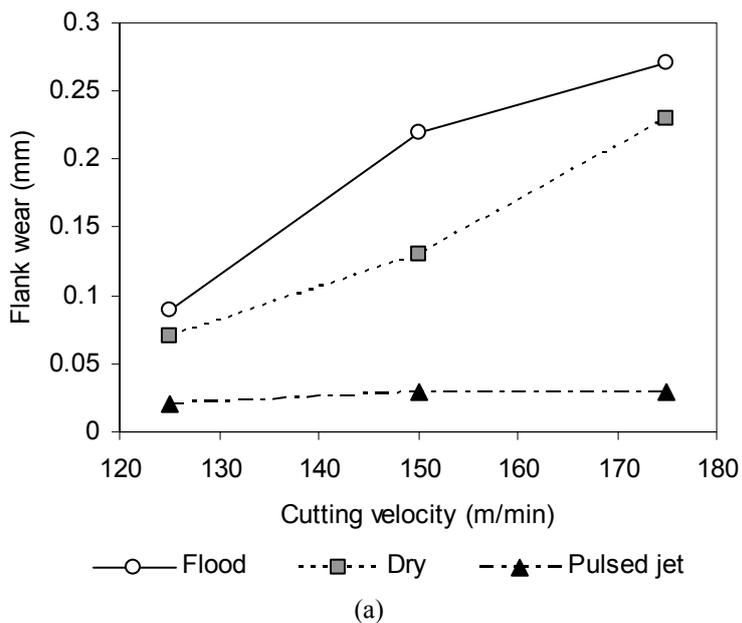
Fig. 2 Effect of cutting velocity on (a) flank wear and (b) surface roughness in slot milling test

(a)

(b)
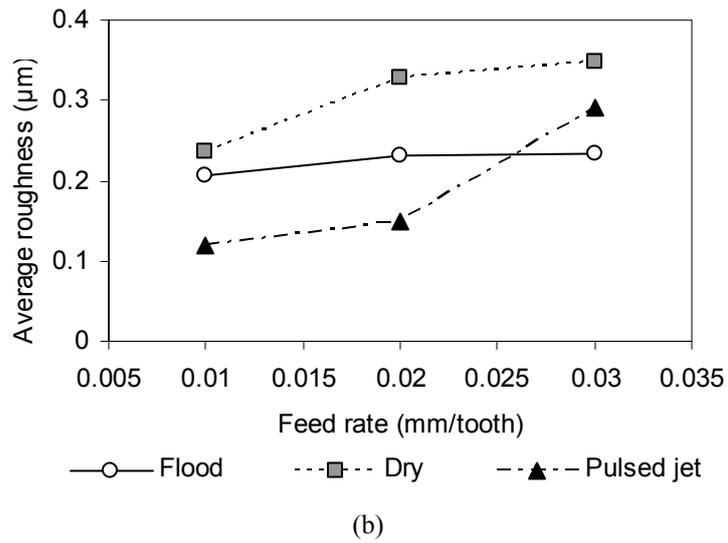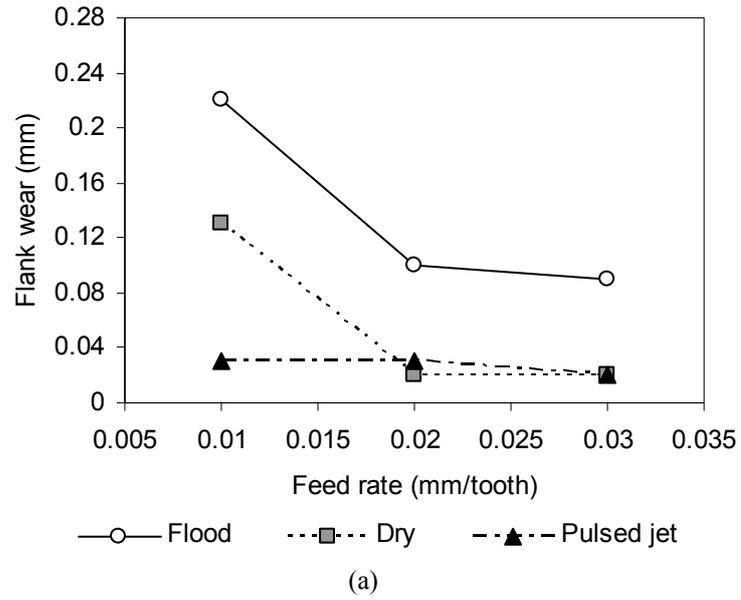
Fig. 3 Effect of feed rate on (a) flank wear and (b) surface roughness in slot milling test
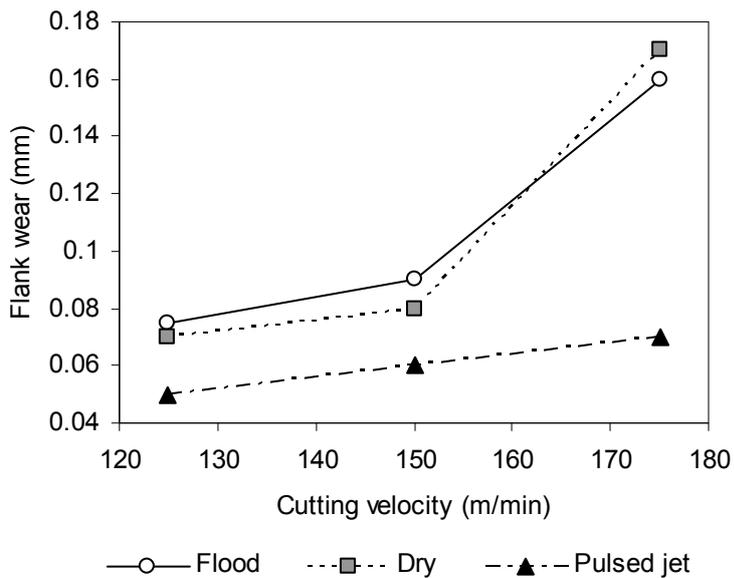
(a)
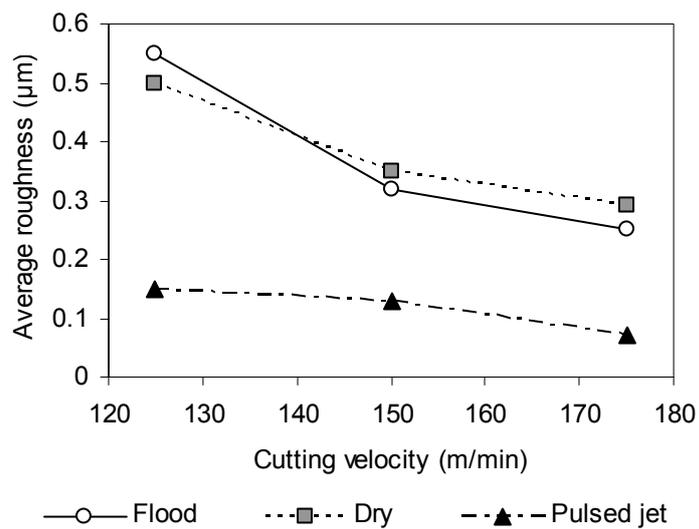
(b)

Fig. 4 Effect of cutting velocity on (a) flank wear and (b) surface roughness in down milling test
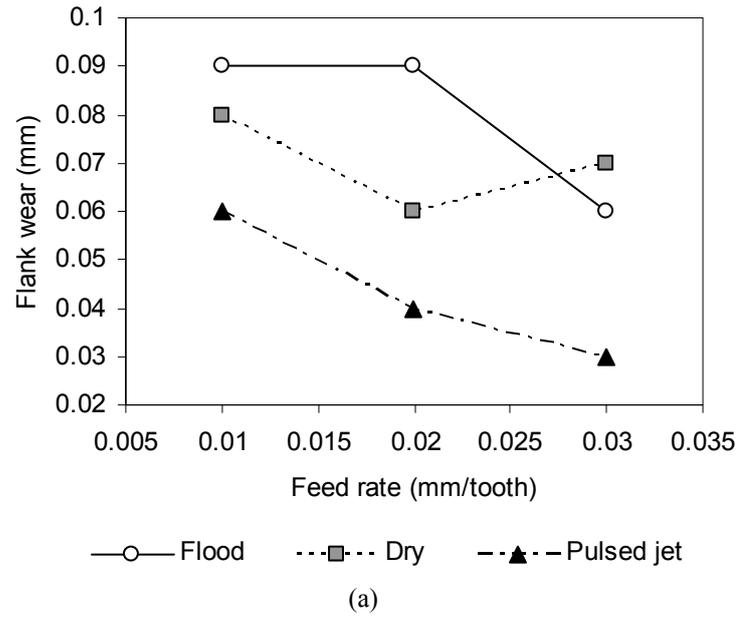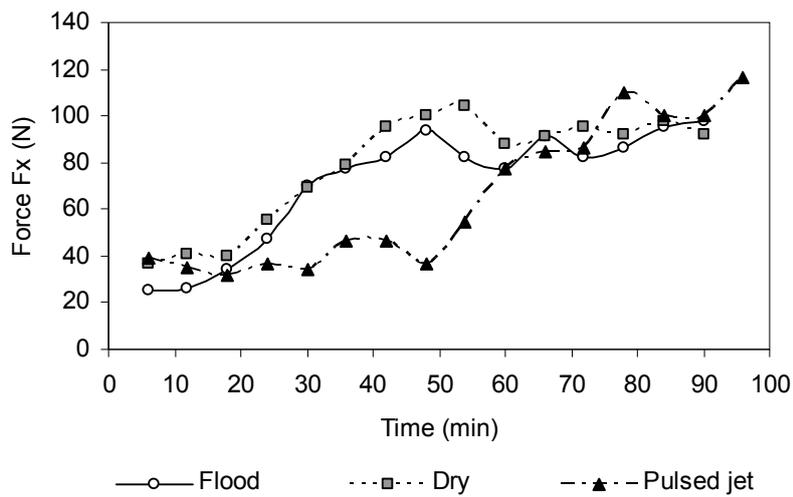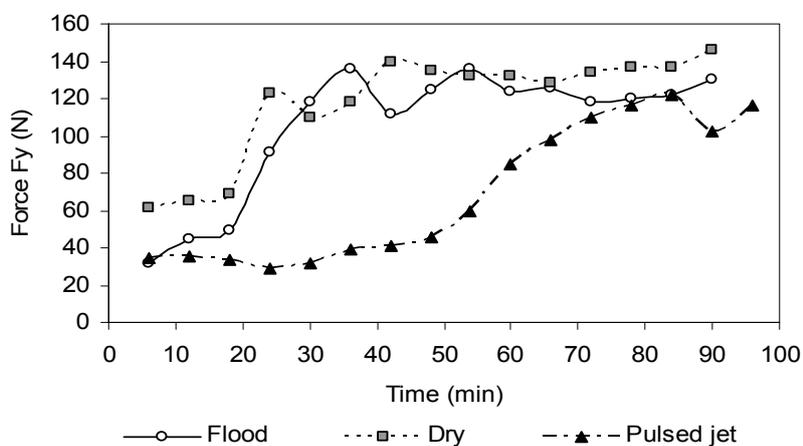
(a)

(b)
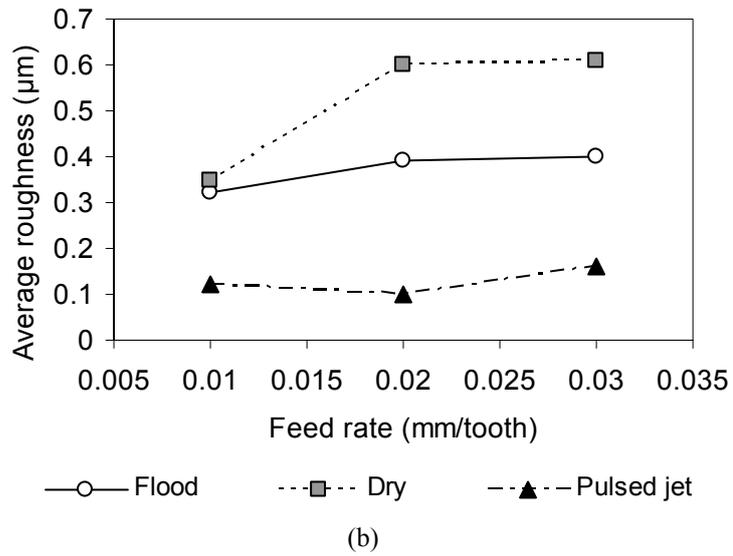
Fig. 5 Effect of feed rate on (a) flank wear and (b) surface roughness in down milling test

(a)

(b)
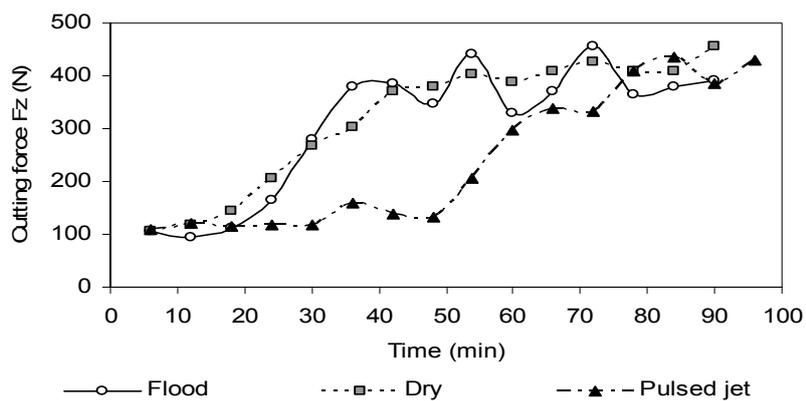
(c)

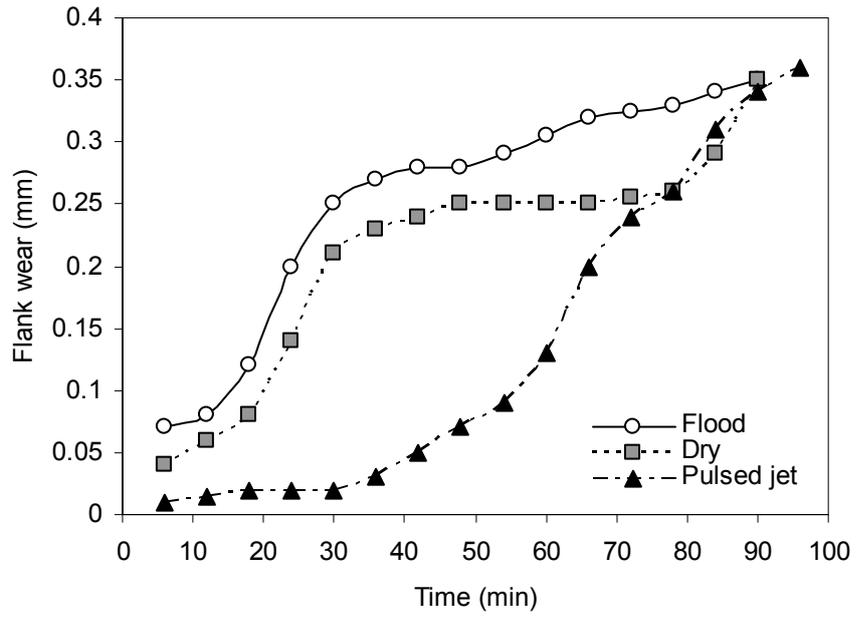Fig. 5 Cutting force progress for slot milling (a) F_x, (b) F_y and (c) F_z

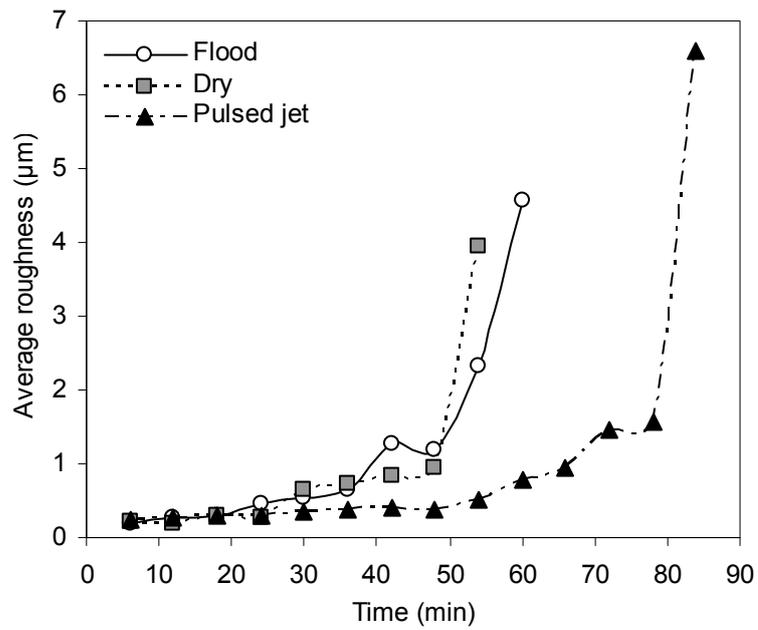Fig. 6 Flank wear progress for slot milling
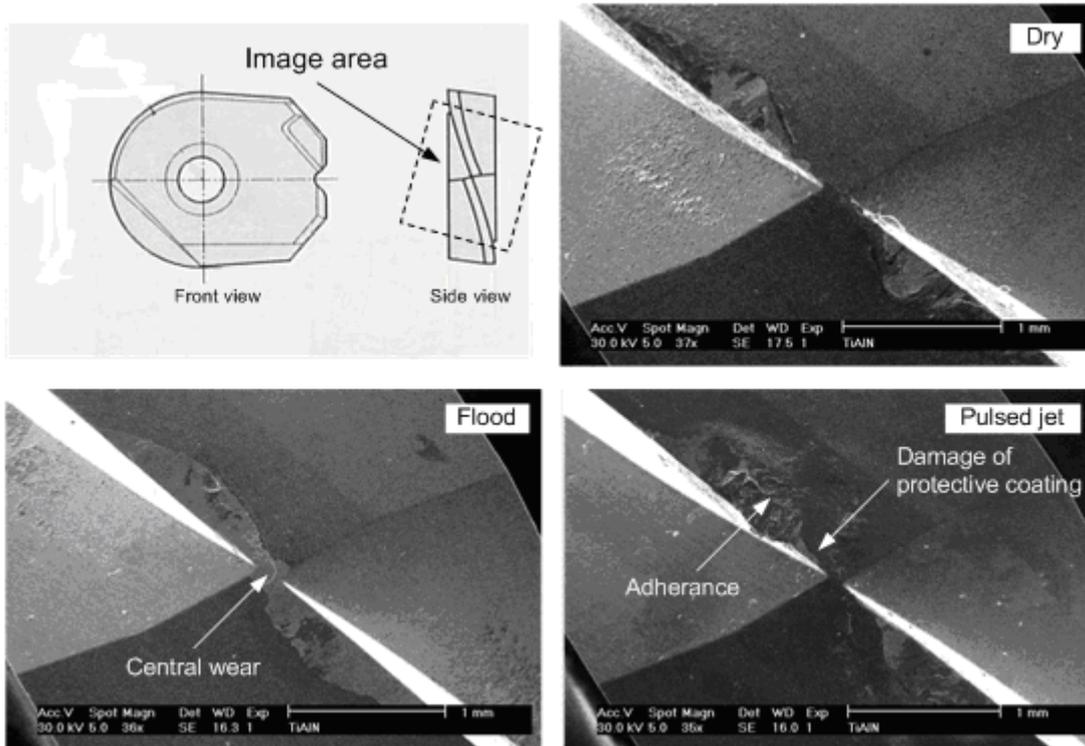

Fig. 7 Surface roughness progress for slot milling

Fig. 8 Tools wear images when cutting in dry, flood and pulsed jet mode