

Development of a novel cooling system-assisted minimum quantity lubrication method for improvement of milling performance

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(Received 20 May 2013; accepted 16 April 2014)

This paper presents a novel lubrication method for milling processes that employs cooling system assisted minimum quantity lubrication (CSMQL) using a thermoelectric cooling system. The CSMQL method improves the cooling effect in the cutting area and enhances processing quality, in addition to reducing energy consumption. Four different coolant strategies including CSMQL, dry, minimum quantity lubrication (MQL), and wet methods were compared in processing mill die steel (SKD11), which is widely used in industry. Different aspects of the milling performance (e.g. surface roughness, morphology, milling temperature, and milling forces) were investigated using these coolant strategies. The experimental results show that not only is the surface roughness of steel milled using CSMQL better than that of steel milled using dry and MQL methods, but CSMQL also produces fewer tool marks on the workpiece surface. In addition, it was found from observations of chip color that using the CSMQL method reduced the cutting temperature by 27% and the cutting force by 22%, compared with dry machining. In summary, the use of CSMQL can not only improve the surface roughness and reduce the cutting force and cutting temperature, but also promote processing quality. This study will help researchers develop more efficient cooling strategies in the future.

Keywords: CSMQL; MQL; SKD11; thermoelectric cooling module

1. Introduction

Milling is an important and common machining operation because of its versatility and capability of producing various profiles and curved surfaces. In the milling process, a rotating cutter removes material while traveling along various axes with respect to the workpiece (Shaw 1996). Flooding with a cutting fluid is the most common strategy for controlling the cutting temperature in the contact zone. According to Kalpakjian and Schmid (2006), cutting fluids have been used extensively in machining operations to achieve the following results: (1) reduction in friction and wear, thus improving tool life and the surface finish of the workpiece; (2) cooling of the cutting zone, which also improves tool life, as well as reducing the temperature and thermal distortion of the workpiece; (3) reduction in cutting forces and energy consumption; and (4) flushing away of chips from the cutting zone, which prevents the chips from interfering with the cutting process. However, many of these fluids are health hazards, which raise major environmental concerns. They are also challenging to recycle and manage, which significantly increases total manufacturing cost (Brinksmeier, Heinzel, and Wittmann 1999). In recent years, all of the costs involved with cutting fluids have increased, due to environmental concerns and

increased regulations from national and international authorities (Arrazola et al. 2009). Barczak, Batako, and Morgan (2010) estimated that metal-working fluids constitute about 7–17% of the total machining cost, while depreciation and waste disposal contribute around 54% to the cooling cost.

All of these factors prompt investigation into the development of new cooling strategies that utilize dry machining and either minimum quantity lubrication (MQL) or full elimination of cutting fluids. Dry machining is considered as an effective alternative to conventional machining that uses a cutting fluid supply (Sreejith and Ngoi 2000; Weinert et al. 2004; Li and Liang 2007). However, dry cutting also has some negative effects, such as increases in friction, adhesion, and tool wear (Yildiz and Nalbant 2008). The MQL method is based on the principle that a drop of liquid is split by an airflow, distributed in streaks, and transported in the direction of airflow. In MQL machining, the consumption of oil in industrial applications is in the range of approximately 10–100 ml/h (Thamizhmanii and Hasan 2009). Choi, Lee, and Jeong (2002) investigated the cooling effects of compressed cold air and compared the results with those of normal coolant. They found that compressed cold air was efficient in minimizing the thermal

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defects of the workpiece and could also play a role in solving the problem of environmental pollution. Tawakoli et al. (2009) investigated the influence of workpiece hardness and grinding parameters including wheel speed, feed rate, and depth of cut on MQL grinding. They pointed out that compared to dry grinding, MQL grinding substantially enhanced cutting performance in terms of increasing wheel life and improving the quality of the ground parts. da Silva et al. (2007) analyzed the behavior of the MQL technique and compared it with the conventional cooling method. They concluded that the R_a values were substantially reduced with the use of the MQL technique. They also found that the use of MQL did not negatively affect surface integrity. Barczak, Batako, and Morgan (2010) presented a comparative study of three cooling methods: conventional flood cooling, dry grinding, and grinding with MQL. They noted that low grinding forces point to MQL as a low-temperature process. They also found that workpiece quality under MQL was comparable to and even better than that achieved with conventional flood cooling. Tawakoli and Azarhoushang (2008) and Tawakoli, Azarhoushang, and Rabiey (2009) introduced the concept of using ultrasonic vibrations in dry grinding of soft steel. They pointed out that using ultrasonic-assisted dry grinding it was possible to reduce normal grinding forces by up to 70% and tangential grinding forces by up to 50%.

Many studies have focused on cryogenic machining. For example, Paul and Chattopadhyay (1996) conducted experiments to study the effect of liquid nitrogen on the grinding forces. Their results indicated a substantial reduction in grinding forces with cryogenic cooling. Cryogenic machining using liquid nitrogen with the help of a modified tool holder provided longer tool life and more wear resistance, compared to dry machining (Ahmed et al. 2007). Kalyan Kumar and Choudhury (2008) presented an experimental investigation of tool wear and cutting force in cryogenic machining. They concluded that cryogenic cooling was a possible answer for high-speed, eco-friendly machining. Sun, Brandt, and Dargusch (2010) developed a new cooling approach using cryogenic compressed air to cool the edge of the cutting tool during turning of a Ti-6Al-4V alloy. The combined effects of reduced friction and the bending of the chip away from the cutting zone (as a result of the high-speed air) produced a thicker chip with compressed air cooling and a thinner chip with cryogenic compressed air cooling, when compared to dry machining alone. Bermingham et al. (2011) and Bermingham et al. (2012) investigated the effectiveness of cryogenic coolant during turning of a titanium-aluminum Ti-6Al-4V alloy at a constant speed and material removal rate under different combinations of feed rate and depth of cut. The influence of cryogenic coolant on the stability of the machining process in relation to conventional dry machining was

examined and presented by Pušavec et al. (2011). Khan and Ahmed (2008) pointed out that cryogenic cooling is more efficient at a higher feed rate, rather than at a greater depth of cut. Zhang, Li, and Wang (2012) proposed that minimum quantity cooling lubrication (MQCL) cutting with biodegradable vegetable oil could effectively improve the machinability of the nickel-chrome alloy, Inconel 718, by extending tool life and reducing cutting forces. The MQCL system combines the advantages of the cryogenic air and MQL systems.

In our study, a milling process-lubrication method was examined that employs cooling system-assisted minimum quantity lubrication (CSMQL) using a thermoelectric cooler system. Four different coolant strategies including CSMQL, dry, MQL, and wet methods were compared in processing mill die steel (SKD11), which is widely used in industry. Different aspects of the milling performance (e.g. surface roughness, morphology, milling temperature, and milling forces) were investigated using these coolant strategies. A thermoelectric cooler was selected because it is clean, cheap, and contains liquid nitrogen, a nontoxic fluid that has no environmental contamination issues.

2. Experimental procedure

2.1. Cooling system setup

The cooling system used in the milling experiments is shown in Figure 1(a) (schematic) and (b) (photo). The system includes a computer temperature controller, temperature sensor, thermoelectric cooler, and heat sink. The computer temperature controller used in the experiments was a DEI-635, produced by the DEI Company, Taiwan. The design temperature range is -40 to 40 °C with 1 °C resolution. The thermoelectric cooler used was a

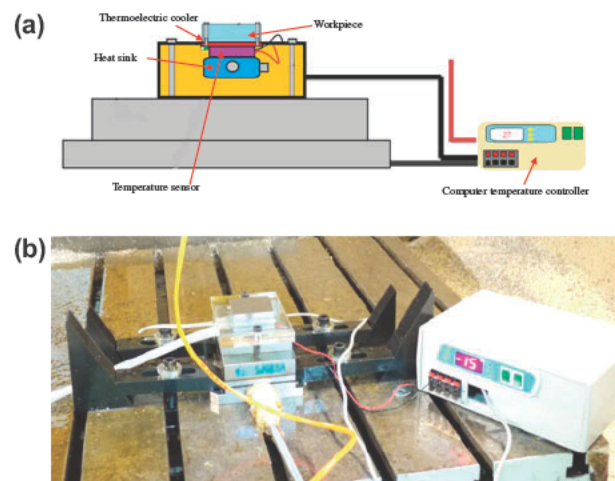


Figure 1. Cooling system: (a) schematic and (b) photo.

TECI12712, produced by the Centenary Materials Company, Ltd., Hsin Chu, Taiwan. The maximum temperature differential was 68 °C. The size of the thermoelectric cooler was approximately 50 mm square by 5 mm in height. The principle of a thermoelectric cooler is that heat will be moved through the module from one side to the other. One module face, therefore, will be cooled while the opposite face is simultaneously heated. It is important to note that this phenomenon may be reversed, whereby a change in the polarity of the applied DC voltage will cause heat to be moved in the opposite direction. Consequently, a thermoelectric cooler may be used for both heating and cooling, thereby making it highly suitable for cooling a workpiece in the milling process. The many advantages of a thermoelectric cooler include no moving parts, freedom from maintenance, heating and cooling capabilities with the same module (including temperature cycling), environmental friendliness, cooling to very low temperature, and low price.

2.2. Experimental apparatus

The experiments were conducted on a CNC machine center, produced by the Quick Jet Machine Co., Ltd., Taichung City, Taiwan, as shown in Figure 2. The workpiece is secured on a thermoelectric cooler attached to the worktable of the machine, as shown in Figure 3(a). The temperature of the cool side of the thermoelectric cooler is controlled at a constant value of -10°C . The material used in these tests was die steel (SKD11) with the chemical composition of C 1.4–1.6%, Si 0.15–0.35%, Mn 0.3–0.6%, Cr 0.11–1.3%, Mo 0.8–1.2%, V 0.2–0.5%, P 0.025%, and S 0.01%. The steel was prepared in $60 \times 60 \times 10 \text{ mm}^3$ blocks. The cutting tool was a milling cutter made by Safety Company with positive rectangular inserts (RT 100308 R-81- Grade 5050). The insert had a cemented carbide substrate with an outer coated layer of titanium nitride, TiN. Before machining,

the materials were pre-machined with a 1-mm cut to remove any possible surface irregularities, and to ensure similar surface properties for all the specimens. The tests were conducted to evaluate the performance of four different coolant strategies using the CNC machine center. All the experiments were conducted thrice and the average value was taken as the response value.

The four coolant strategies were also evaluated with respect to the tools and workpiece performances. Milling conditions are as shown in Table 1. The following cooling and lubricant techniques and their designations were used in the experiments: dry, without any cooling or lubrication; MQL, minimum quantity lubrication milling using pure water fed into the milling contact zone; wet, with lots of coolant; and CSMQL, cooling system-assisted MQL, which combines the advantages of the thermoelectric cooler and MQL. The control unit of the MQL equipment was fixed to the miller at the location where the lubricant dosage and airflow rate adjustments are carried out. Figure 3(b) shows details of the MQL equipment, with its parts enumerated for easy understanding of their descriptions and functioning. The MQL system consisted of a compressor, a pressure regulator, a rotameter, a doser, and a spray nozzle. The nozzle was placed at a distance of about 30 mm from the cutting tool–workpiece interface.

After the workpiece was machined, its surface roughness was measured by the Hommel Tester T1000 (Hommelwerke GmbH, VS-Schwenningen, Germany) with a cut-off length of 0.8 mm. At the end of each test, the R_a across the cutting direction was measured at five different points on the machined surface. A scanning electron microscope (SEM) was used to analyze possible damage to the surface morphology caused by thermal and mechanical forces on the tool and the material surface. The milling forces were recorded using a piezoelectric transducer-based dynamometer (Type9257B, Kistler, Winterthur, Switzerland) positioned under the workpiece clamping device. The dynamometer was connected to an

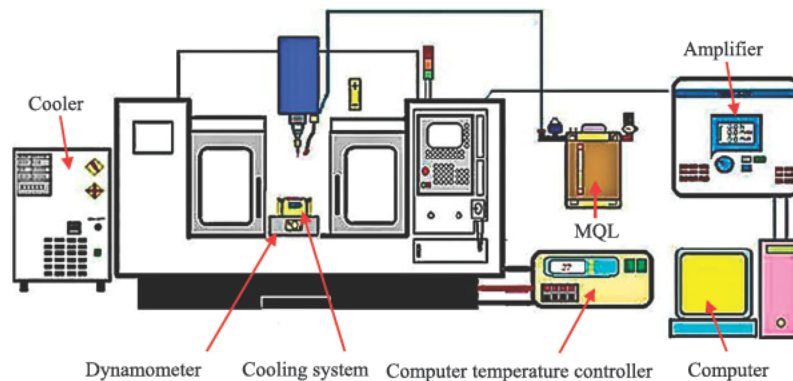


Figure 2. Experimental system configuration and setup.

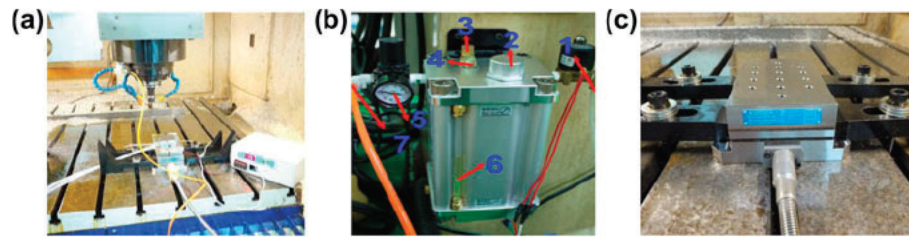


Figure 3. (a) Photo of experimental setup; (b) details of MQL equipment [1 export of pure water mist, 2 filler, 3 knob for lubricant flow rate adjustment, 4 window for viewing droplets, 5 manometer (0 150 psi or 0 10.2 kgf/cm²), 6 water meter, 7 air inlet]; and (c) dynamometer setup.

Table 1. Milling conditions.

Machine tool	Depo speed CNC milling machine, Taiwan
Workpiece material	SKD11 alloys, $HRC = 60 \pm 2$, $60 \times 60 \times 10$ mm ³ block
Cutting tool	Coated cemented carbide insert, outer coated layer of TiN, Diameter = 6.35 mm, Grade 5050
Milling conditions	Cutting speed: 75 m/min; feed rate: 150 mm/min; depth of cut: 0.5 mm
Environments	(1) Dry machining (2) Wet machining (3) MQL with pure water milling, flow rate: 180 mL/h; air pressure: 4 kg/cm ² (4) Cooling system (10 °C) assisted MQL

amplifier and a computer equipped for online monitoring and recording of the cutting force, as shown in Figure 3(c).

3. Results and discussion

3.1. Cutting force and chip formation

Cutting forces are important parameters by which performance of any cutting process can be evaluated. The relative contribution of different factors to the cutting force depends on the type of work material, the tool material, and the presence of cutting fluid or other lubricants. The cutting force component determines the power requirement of the process. The intensity of heat generation depends upon this force, and it is of primary importance as far as the machining temperature and surface quality of the products are concerned (Suresh Kumar Reddy and Venkateswara Rao 2006). To account for the influence of cooling environments, the values of the cutting forces were measured with fresh tools. Representative examples for all four cutting environments of resultant cutting force (R) data measured by dynamometer after 10 min of cutting are presented in Figure 4. Figure 5 shows the variation in the resultant cutting forces for SKD11 with different cooling environments. The cutting force was measured thrice after separate cuts. The results show that the highest cutting force was obtained with a dry cutting

environment. This may be attributed to the higher coefficient of friction at the chip–tool interface due to the lack of lubrication and cooling. The lower cutting force obtained with CSMQL had a value that was almost the same as with the wet environment. This may be due to the effectiveness of the lubricant and cooling in minimizing the frictional effects at the tool–workpiece interface, relative to the cutting forces seen for dry and MQL machining.

The chip formation and breaking aspect play an important role in cutting process optimization, surface finish, workpiece accuracy, and tool life (Bhuiyan, Choudhury, and Nukman 2012). Furthermore, chip formation is generally dependent on the mechanical properties of the work materials, tool geometry (particularly rake angle), cutting parameters, nature of the chip–tool interaction, and the cutting environment. The machining chips were collected during all of the cutting tests to study the nature of chip formation (shape and color) under different machining environments, as seen in Figure 6. Knowledge of the temperature in the chip formation zone is crucial to explain the phenomena occurring during machining. Since it is impossible to measure the temperature in the formation zone itself, one can only determine the temperature of regions near the zone where the chips are generated. The situation is more complicated in milling, because the cutter is rotating

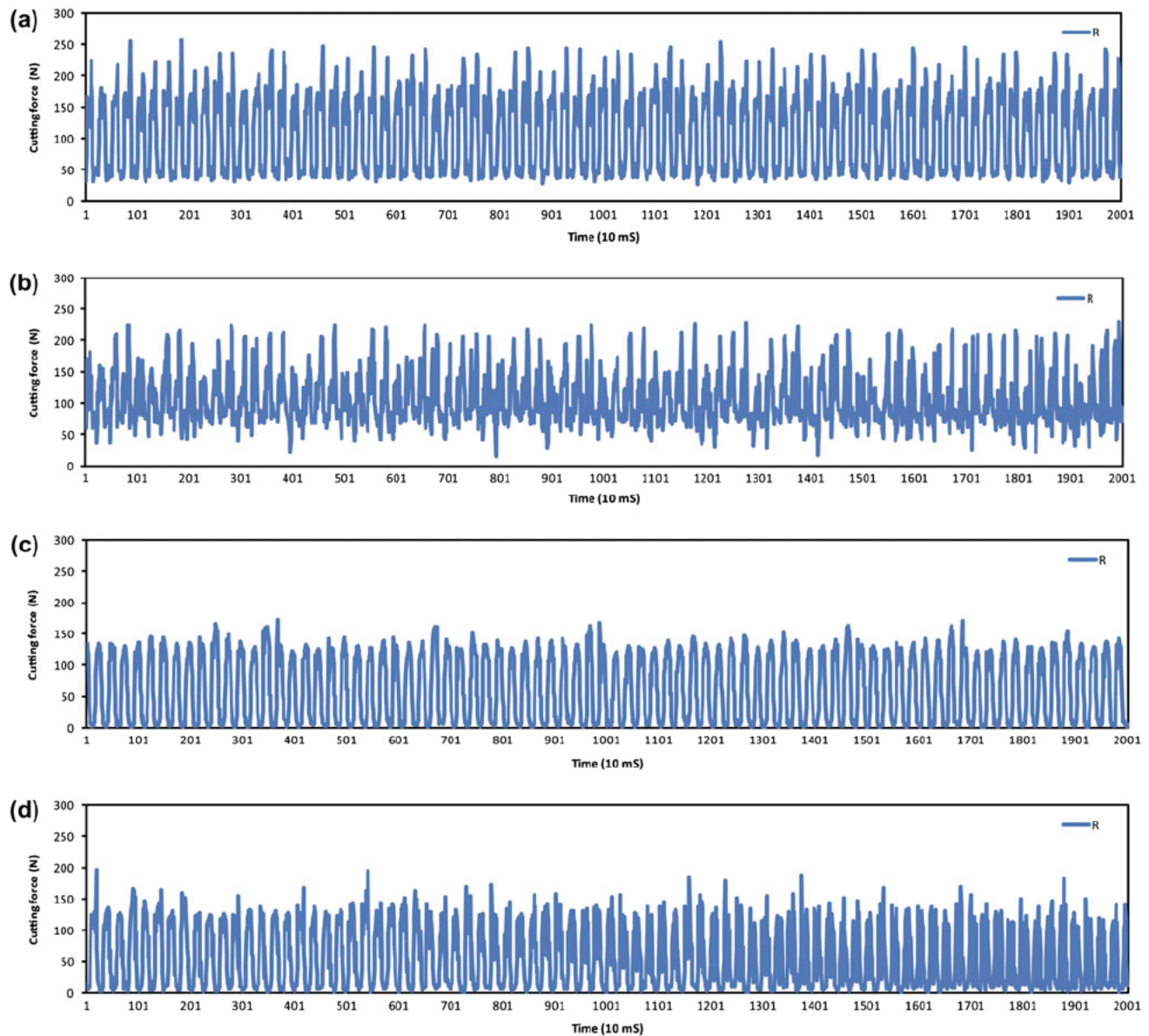


Figure 4. Cutting force signal captured from (a) dry machining; (b) MQL; (c) CSMQL; and (d) wet machining.

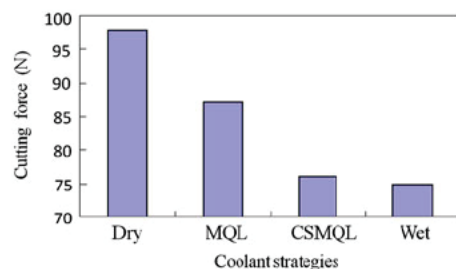


Figure 5. Variation in cutting force for SKD11 in different cutting environments.

while traveling in the feed direction; therefore, in this study the temperature was determined by examining the color of the chips (Ning, Rahman, and Wong 2001). It is clear that the stability of the cutting process, also more or less, indicates the temperature. Zhang (1983) was the first to present the chip temperature versus color chart shown in Table 2. For different chip colors, the chip temperature is different, and thus the cutting temperature is also different. Based on Zhang's findings, the temperature of the tool face is about 1.5 times that of the chip temperature. In Figure 6, the color of a chip from dry machining is blue, which means that the temperature of the chip was about 300 °C, based on Table 2. The chip

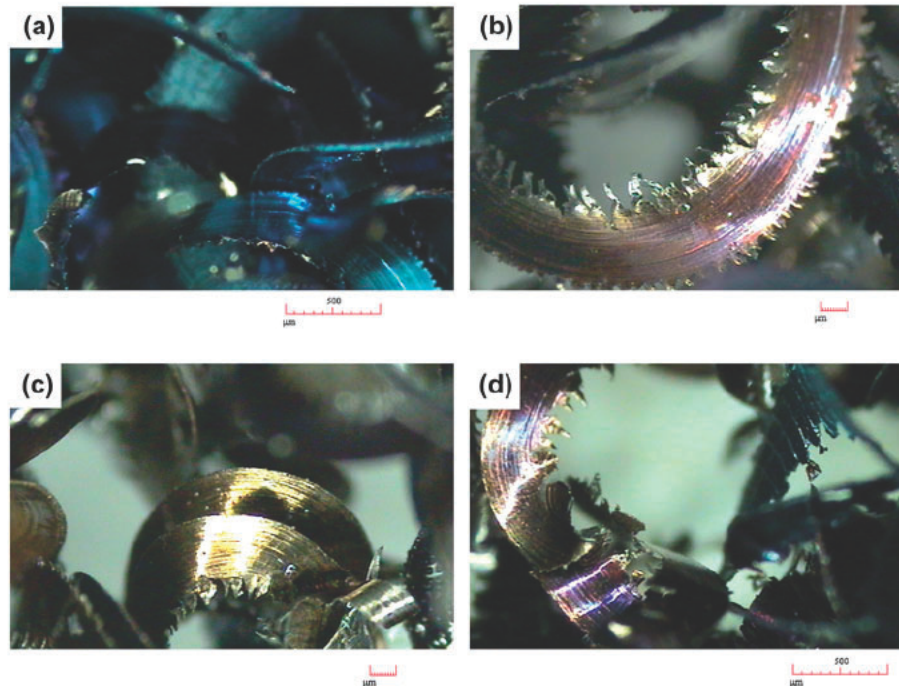


Figure 6. Chip morphology (shape) and color difference after machining 10 min under (a) dry; (b) MQL; (c) CSMQL; and (d) wet conditions.

colors from MQL and CSMQL machining are purple and yellow, which indicate that the chip temperatures were about 260 and 220 °C, respectively. After wet machining, the chip colors are both purple and yellow, which mean that the temperature of the chip was about 220–260 °C. Based on the above result, it was observed that the CSMQL method resulted in reductions in the average cutting temperature by about 27 and 15%, respectively, over the dry and MQL methods. The combined effect of the thermoelectric cooler and the MQL techniques is the cause of the reduced milling temperature. Decreases in milling temperature lead to weaker adhesion and better surface roughness, as discussed later.

3.2. Tool wear

Tool wear is one of the important parameters for evaluating the machining cost and quality of a workpiece.

Table 2. Chip color vs. chip temperature.

Chip color	Chip temperature (°C)
Yellow	220
Purple	260
Blue	300
Gray	400
Dark green	600

Several methods for evaluation of cutting tool wear have been developed that take into account the qualitative and quantitative effect of their causes. Wear of the cutting tool edges takes place in the complex conditions caused by, among others, the mutual interaction of mechanical and fatigue wear, and plastic strain, as well as phenomena connected with adhesion, and thermal and diffusion oxidation. Figure 7 shows tool wear after 5 and 10 min of machining under all cutting environments. In the figure, the tool wear is very sensitive to the increase in cutting time, as expected. It is evident that the dry machining condition leads to a built-up edge and flank wear after 10 min of machining, due to the high cutting zone temperature and increased friction force between the tool and workpiece. The flank wear occurred due to rubbing of the work materials by the cutting edges, which led to adhesion or welding of the work material onto the flank face, causing a strong bond at the tool–workpiece interface. The MQL method caused obvious reduction in the built-up edge, but some microchips are found on the cutting edge after 10 min of machining. As expected, a significant benefit achieved by the CSMQL is the absence of a built-up edge after 10 min of machining. This is due to the combined effect of the cooling system in reducing the tool–workpiece interface temperature. In addition, in the process of tool disengagement, the oil mists sprayed on the cutting tool when the tool is engaged in cutting are evaporated, leaving the

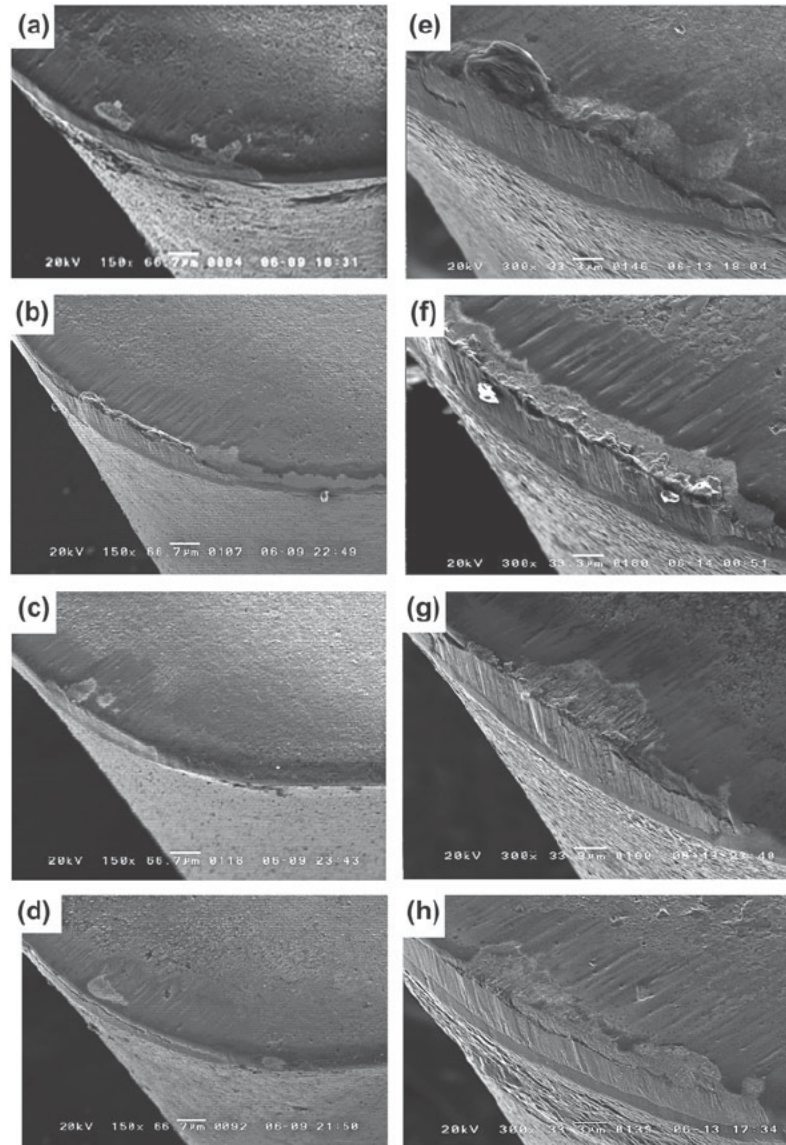


Figure 7. SEM view of insert after machining 5 min under (a) dry; (b) MQL; (c) CSMQL; and (d) wet conditions, and after machining for 10 min under (e) dry; (f) MQL; (g) CSMQL; and (h) wet conditions.

oil particles on the tool face. The oil particles adhered to the tool face in the presence of abundant oxygen then provide sufficient oxygen to activate the formation of an oxide layer on the chip-tool interface (Liao and Lin 2007). The CSMQL method can also reduce flank wear compared with dry machining, because the heat generated in the cutting zone will be removed effectively and the tool life will be prolonged. In wet cutting, a flood of cutting fluid improves the built-up edge after 10 min of machining. However, flaking also occurs on the flank wear face, mainly because the cutting fluid fails to penetrate the interface and cannot remove heat effectively.

3.3. Surface roughness and surface topography

It is well known that the surface finish can significantly affect the mechanical strength of components subjected to fatigue cycles. The surface roughness also plays a broader role in the performance of a product. Poor surfaces may cause poor performance and make the product fail well before the end of its expected lifetime (Tsai and Jian 2012). Figure 8 compares the mean values of R_a parameters in different coolant environments. As shown in Figure 8, the mean values of R_a for the CSMQL method are markedly lower than those for the dry and MQL methods due to the reduction in cutting force and tool wear, and the lowering of the cutting temperature.

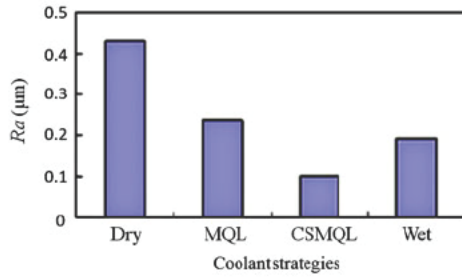


Figure 8. Variation in surface roughness for SKD11 with dry, MQL, CSMQL, and wet machining.

These findings are consistent with those of Leppert (2011). This behavior of CSMQL is mainly because better lubrication and greater cooling effect provide lower friction at the chip-tool and tool-workpiece interfaces and that a decrease in cutting temperature leads to less adhesion. The roughest workpiece surfaces are obtained

with the dry machining process, when compared with the other cooling strategies, mainly because of more intensive temperatures and friction between the tool flank and the workpiece, as well as the built-up edge. To understand the variable surface roughness results that were measured, the surface topography of the workpiece after milling under all cutting environments was also studied. Figure 9(a) shows the cross-sectional SEM images of the workpiece surface after dry machining. As shown in the figure, surface chatter and roughness were formed due to a lack of lubrication leading to a high temperature for the workpiece surface and built-up edge. A careful observation of these figures (see Figure 9(b) and (d)) reveals some fine tool marks on the workpiece surface that contributed to a poor surface roughness. Figure 9(c) shows slight tool marks on the workpiece surface after milling, which again proves that CSMQL can provide better lubrication and cooling at the tool-chip and tool-workpiece interfaces.

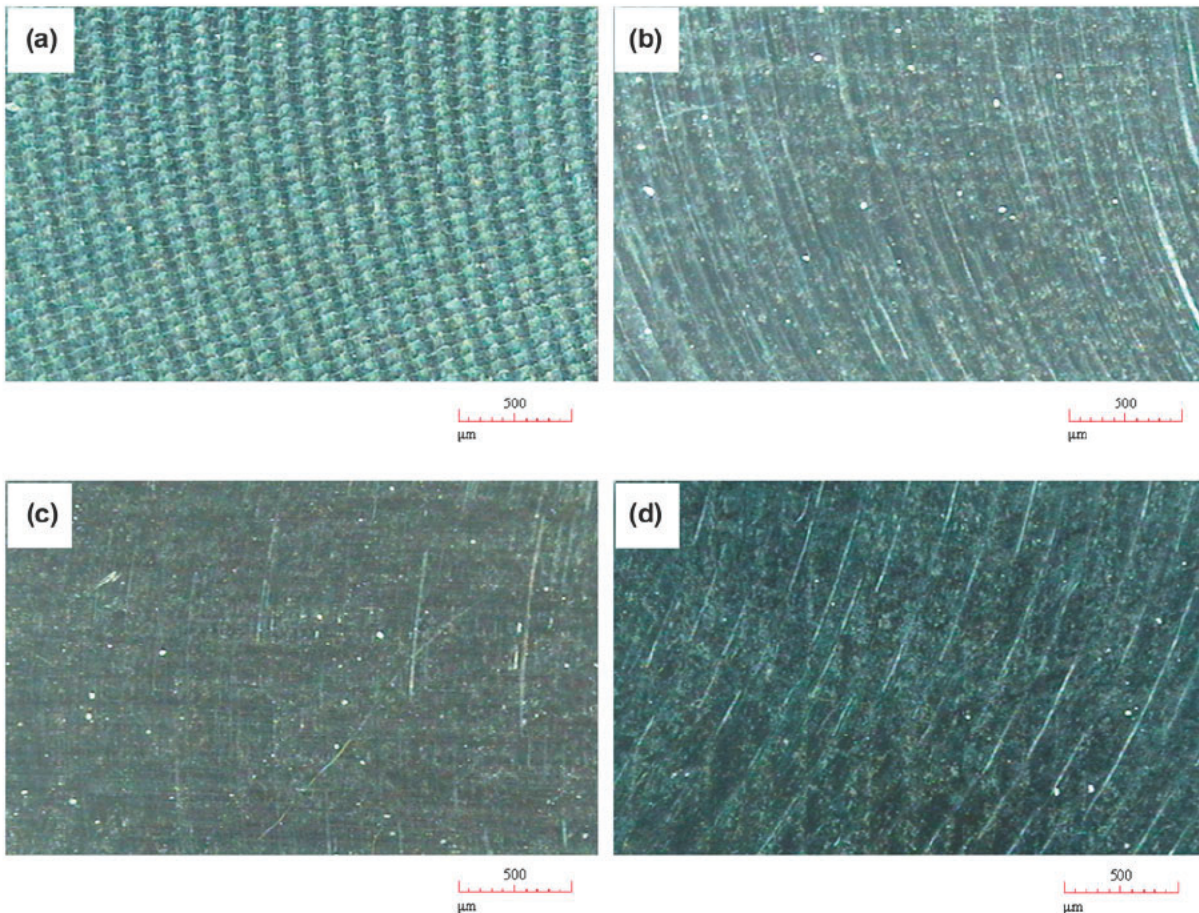


Figure 9. Cross sectional SEM images of workpiece surface with (a) dry; (b) MQL; (c) CSMQL; and (d) wet machining.

4. Conclusions

This paper presents a newly designed CSMQL method to lubricate and cool the milling site. Milling performance parameters such as surface roughness, morphology, chip formation, and cutting forces were investigated under dry, wet, MQL, and CSMQL conditions. The experimental results show that the surface roughness of material milled using CSMQL is not only smoother than that of the same material milled with other methods, but there are also fewer tool marks on the workpiece surface. In addition, it was found from observations of chip color that the cutting temperature using CSMQL was reduced by 27% compared with the dry method, and the cutting force was reduced by 22%. In summary, the use of CSMQL can not only improve the surface roughness and reduce the cutting force and cutting temperature, but also promote the processing quality and reduce tool wear, which prolongs tool lifetime. This study helps advance the understanding of lubricant techniques and further develops an application method that eliminates the use of any oils or toxic organic lubricants in the milling process.

Acknowledgment

The authors thank the National Science Council of the Republic of China, Taiwan, and the Chung Shan Institute of Science and Technology, for financially supporting this research under Contract Nos. NSC 101 2221 E 167 006, 101 2622 E 167 001 CC3, and CSIST 010V302.

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