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Experimental Study and Modeling of Machining with Dry Compressed Air, Flood and Minimum Quantity Cutting Fluid Cooling Techniques

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Abstract

In the present work, the effect of dry air cooling (DAC), flood cooling (FC) and cooling with minimum quantity cutting fluid (MQCF) on average surface roughness (R_a), chip thickness and tool flank wear were studied. For MQCF, a specially designed and fabricated mist application system was developed. In MQCF, the cutting fluid and pressurized air are mixed externally to form homogenous mist at the exit of twin holed nozzle, which is delivered to cutting zone. Preliminary experiments were carried out to find the optimum air pressure (cutting fluid discharge) for minimum R_a and tool wear. Later complete experiments were planned according to central rotatable composite design technique. It was found from the experimental results that MQCF was effective in substantially bringing down the R_a (22% & 15.5%), chip thickness (9.5% & 5.0%), and flank wear (15.5% & 6.0%), compared to DAC and FC respectively. In MQCF, due to negligible consumption of cutting fluid, both emissions during machining and cutting fluid cost are negligible. Hence the product cost is reduced greatly in MQCF. Thus MQCF enhances safety standards, environmental cleanliness and reduces the manufacturing cost of the product

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Keywords: Minimum quantity cutting fluid; tool surface morphology; surface roughness; flank wear

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1. Introduction

In machining processes, cutting fluids are commonly used for cooling, lubrication, and chip evacuation purposes. In order to reduce the average surface roughness (R_a) and minimize tool wear, the chip-tool interface temperature should be controlled. The best way for controlling the chip-tool interface temperature is by using cutting fluids. Control of the chip-tool interface temperature leads to development of different types of cutting fluids and different cutting fluid application techniques such as, dry compressed air cooling, flood cooling (FC) [1], high-pressure jet cooling [2] and ultra high pressure cooling [3]. Such attempts brought forth better tool life, better R_a, low cutting force and better chip formation. Furthermore, application of cutting fluid is unable to prevent high temperatures at the tool-chip interface completely, particularly at higher cutting speeds, due to the fact that it cannot access the cutting zone where a considerable amount of heat is generated. But these cutting fluids adversely affect shop floor environment by releasing unwanted emissions and residual materials. Depending on the mode of disposal, it also results in ground, water and air pollution. So the ecological aspects must now be accorded serious consideration [4]. Machining cost is another relevant aspect to be considered and the costs associated with the cutting fluid use in FC represent approximately 15%-20% of the machined product cost. Other associated problems include raising cost for waste disposal, cutting fluid losses during machining process, further cleaning of the workpiece etc. Due to multiple negative effects of cutting fluids on mankind and environment, an increasing attention has been paid towards environment-friendly machining processes in modern machining i.e., clean machining technology [5]. Hence, the latest trend of research in the field of machining is towards the concept of economic and eco-friendly machining with maximum efficiency.

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Liquid cutting fluid of FC has high convection coefficient but it cannot access interior zones of cutting region due to its high density. Compressed air/gas of DAC possess low convective heat transfer coefficient but it can easily penetrate into intricate regions of cutting zones. To get advantages from both processes (DAC and FC), these two processes are combined. This gives rise to the concept of machining with minimum quantity cutting fluid (MQCF) (Figure 1) or minimum quantity lubrication [6] in which it takes the advantages of both DAC and FC (i.e., the properties of air easy penetration into interior of cutting zones and high convective heat transfer co-efficient of cutting fluid respectively).

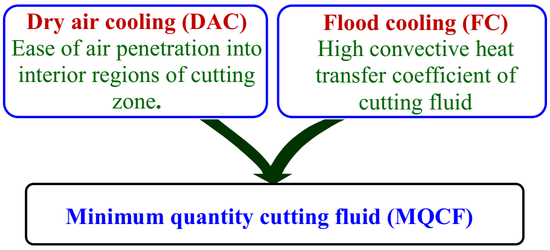


Fig. 1. Minimum quantity cutting fluid system

In the present work, preliminary experimentation was conducted to test the cutting fluid discharge with various air pressures and optimum cutting fluid discharge for minimum R_a on workpiece and tool wear. Later complete comparative experimental study among DAC, FC and MQCF was planned using central composite rotatable design and modelling was done using response surface methodology (RSM) to compare workpiece R_a, chip thickness and tool's flank wear.

2. Preliminary Experimentation and its Observations

In order to compare the performance among DAC, FC and MQCF, an experimental set-up was developed on "Hindustan machine tools" lathe for machining of "micro alloyed steel (Elemental composition is given in Table 1)" with "carbide insert (TPUN 16-03-08)". In TPUN 16-03-08, T = Insert Shape (Triangular), P = Insert clearance angle (11^0), U = Tolerance on inscribe circle of triangular insert, N = Insert type (Normal i.e., Plane type), 16 = Cutting edge length or Insert size = 16mm, 03 = Insert thickness = 3mm, 08 = Nose Radius = 0.8mm.

Table 1. Elemental composition of micro alloyed steel

Element name	Quantity (wt %)
C	0.38
Si	0.68
Mn	1.50
P	0.02
S	0.06
V	0.11
N	0.01
Cr	0.18
Fe	97.06

The close-up of machining zone and atomized fine mist formation in MQCF was shown in Figure 2. Because of limited availability of micro alloyed steel and its homogenous nature, experiments are conducted only one time. So, in the present case the error bars are not added. For few cases, replicates were carried and it was observed that there is good repeatability. Hence, it was decided to carry all experiments once, considering limitation on the availability of the workpiece material

In the present experimental study, emulsion type mineral oil based cutting fluid with additives like biocide (prevents bacterial growth in the emulsion), deodorizing agent, evaporator, emulsifier and rust inhibitors (impart anti-rust and anti corrosion properties) was used. In MQCF, air was supplied from the compressor and cutting fluid was supplied from the graduated cutting fluid tank which was kept at a certain height from lathe bed. Pressurized air mixes with cutting fluid externally at the twin-holed nozzle (Figure 3) exits due to pressure difference to form uniform atomized cutting fluid mist.

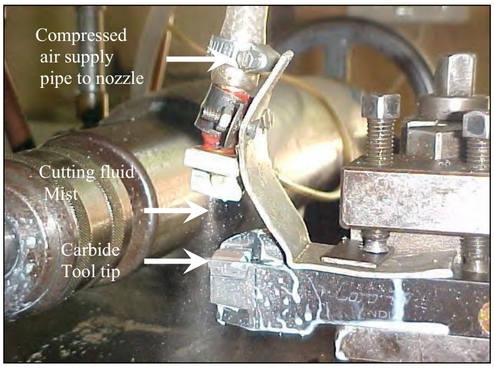


Figure 2: Overview of experimental set-up showing machining region and mist generation.

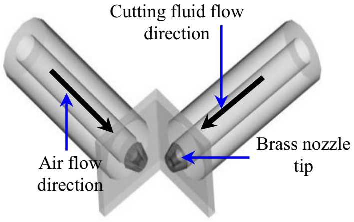


Figure 3: Twin holed nozzle for MQCF system

First preliminary experiments were conducted to calibrate the cutting fluid flow rate for different air pressures in MQCF process. The cutting fluid flows by the virtue of gravity as well as pressure difference. At low air pressure, the flow rate of the cutting fluid is high due to gravity as well as partial sucking of low pressure air. As the compressed air pressure increases, the atomization of cutting fluid increases. However, gradual increase in air pressure also starts gradually pushing back the cutting fluid in its nozzle. So, the cutting fluid flow rate gradually decreases with increase in air pressure (Figure 4). So after 1.0 MPa, cutting fluid consumption was not noticed much and mist is dominated completely by compressed air. So, in the current work, air pressures considered till 1.0 MPa but not beyond. Later, preliminary experiments were also conducted to determine the optimum air pressure (cutting fluid flow rate) for minimum R_a and tool flank wear (Figure 5).

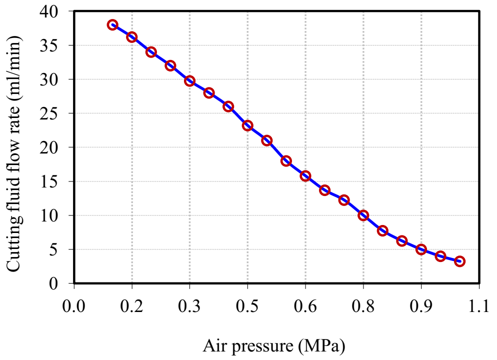


Figure 4: Calibration curve of cutting fluid discharge the variation with air pressure

As discussed above, at low air pressure in MQCF, the cutting fluid mist was dominated by liquid cutting fluid, which cannot penetrate into the seizure zones of machining region. So, dominated liquid phase of the cutting fluid mist might not efficiently take out the heat generated in machining region. Thus both R_a and tool flank wear were high at low air pressures (Figure 5). With the increase in air pressure, a fine mist formation starts wherein the cutting fluid particle/drop size gradually decreases facilitating the easy penetration of mist into the machining zone.

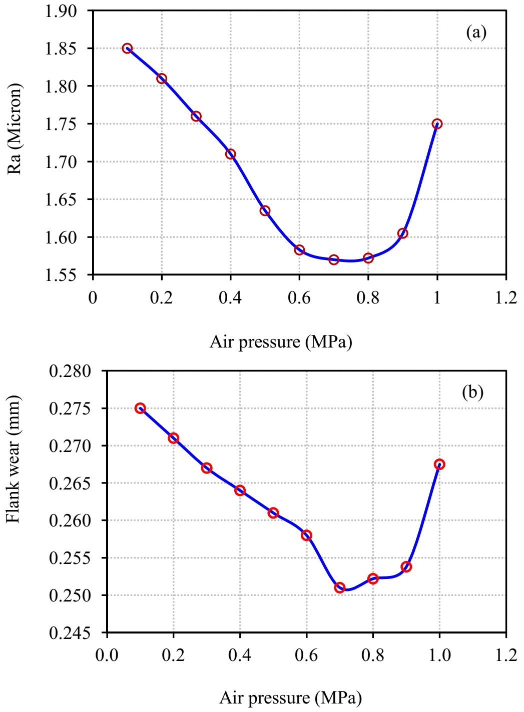


Figure 5: The effect of air pressure in machining with MQCF on (a) average surface roughness and (b) flank wear

This atomized homogenous cutting fluid mist possesses better convective heat transfer coefficient compared to dry air and because of its impinging at high velocity, it extracts more amount of heat from machining region by forced convection. Thus, better heat conduction and convection occur in the machining region. Hence, the R_a (Figure 5(a)) as well as flank wear (Figure 5(b)) reduces greatly in the region of 0.6 – 0.8 MPa of air pressure. Beyond 0.8 MPa, air comes out of nozzle with high pressure and restricts the cutting fluid coming out of its exit in twin hole nozzle. So dominating air possess low convective heat transfer coefficient compared to fine cutting fluid mist. So, it leads to increase in R_a and flank wear in the 0.8-1.0 MPa region.

Thus, in the present work for the MQCF study, 0.7 MPa (10 ml/min) is chosen as optimum value of air pressure to compare MQCF performance advantage over DAC as well as FC. Based on the observations of preliminary experimental results and machine input ranges, the common ranges of various machining input parameters were selected using central composite rotatatable design (CCRD) technique (Table.2). Complete comparative experiments were carried out among DAC, FC and MQCF (cutting fluid discharge10 ml/min).

Table 2. CCRD coded and actual values of input parameters for machining process (Depth of cut = 1.00 mm (radially), Air pressure = 0.70 MPa, Cutting fluid discharge = 10.00 ml/min))

CCRD Code values	Cutting speed (m/min)	Feed rate (mm/rev)
-1.414	200	0.100
-1.000	225	0.125
0.000	290	0.175
1.000	355	0.225
1.414	380	0.250

3. Results and Discussion

3.1. Average flank wear

In the present work, response surface methodology (RSM) method was used to model the flank wear empirically. Taking the non-linearity of the output responses into consideration, a second-order model was developed. Complete experimentation on flank wear was conducted to evaluate its growth with feed rate and cutting speed. The second-order empirical model equations were obtained (Eq.(1)-Eq.(3)) and analysis of variance (Table 3) for average flank wear is carried out. R^2 and adj R^2 of the models (Eq.(1) Eq.(3)) is found to be more than 95%. This implies that the models are significant.

Table.3. Analysis of variance (ANOVA) for average flank wear

Source	F Value	p-value Prob > F	Percentage Contribution
Model	22.92	0.0003	
A-Cutting speed	41.94	0.0003	36.086
B-Feed	60.67	0.0001	52.203
AB	0.41	0.5409	0.352
A^2	8.27	0.0238	7.115
B^2	4.93	0.0618	4.242

$$FW\ (DAC) = 0.5 - 2.440E\text{-}003V - 0.125F - 2.308E\text{-}004VF + 5.997E\text{-}006V^2 + 4.164F^2 \quad \textbf{... (1)}$$

$$FW\ (FC) = 0.773 - 0.004V - 1.562F + 0.002VF + 7.443E\text{-}006V^2 + 6.820F^2 \quad \textbf{... (2)}$$

$$FW\ (MQCF) = 0.708 - 3.192E\text{-}003V - 1.929F + 2.308E\text{-}003VF + 6.239E\text{-}006V^2 + 7.164F^2 \quad \textbf{... (3)}$$

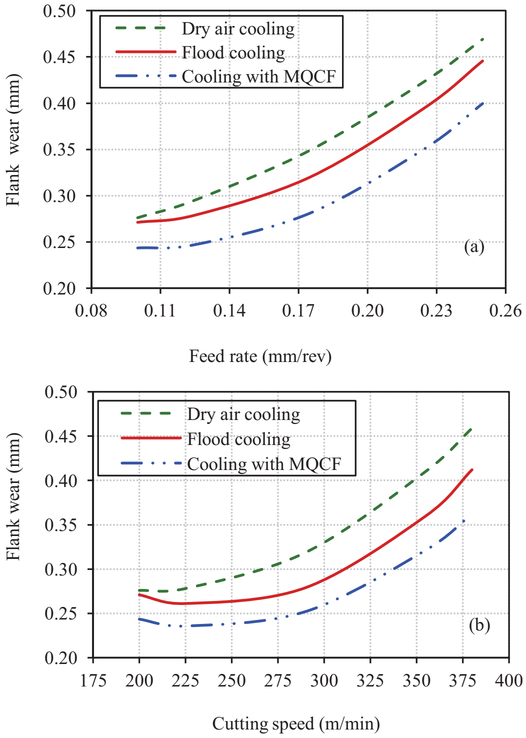


Figure 6: Variation of flank wear with (a) feed rate and (b) cutting speed for DAC, FC, MQCF

As the feed rate increases, material removal for unit time increases indicating that more machined material come in contact and rub the flank face. So, abrading area with flank face increases with increase in feed rate irrespective of cooling type (Figure 6(a)). The cutting fluid that can reach the interior regions of the machining can only lubricate the tool-workpiece region. In MQCF, the probability of better lubricating and cooling of tool-workpiece region is maintained. So the flank wear is 16% and 11% less compared to DAC and FC.

As cutting speed increases more heat is developed in the tool-workpiece region. Because of better cooling due to forced convection nature of MQCF, most of the heat generated in machining zone is carried away. Thus, tool wear is 18.2% less compared to DAC and 10.5% less compared to FC in MQCF (Figure 6). Scanning electron micrographs showing the tool flank wear topography of in DAC (Figure. 7(a)), FC (Figure. 7(b)) and MQCF (Figure. 7(c)) are in accordance with the Figure 6.

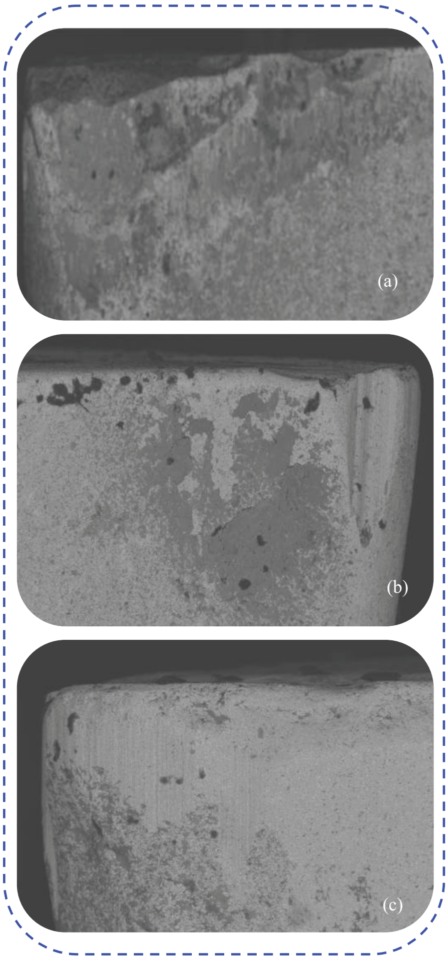


Figure 7: Cutting tool flank wear topography for three type of cooling techniques (a) DAC, (b) flood cooling and (c) MQCF.

3.2. Average surface roughness (R_a)

Empirical models of R_a for DAC, FC and MQCF were obtained as shown in Eq.(4)-Eq.(6). The ANOVA for R_a is carried out. R^2 and adj R^2 of the models (Eq.(4) Eq.(6)) is found to be more than 95%. This implies that the models are significant.

$$R_a\ (DAC) = 8.905 - 0.0187V - 59.443F - 6.115E\text{-}003VF + 3.243E\text{-}005V^2 + 242.513F^2 \quad \textbf{... (4)}$$

$$R_a\ (FC) = 6.724 - 0.012V - 49.548F - 0.028VF + 2.695E\text{-}005V^2 + 226.550F^2 \quad \textbf{... (5)}$$

$$R_a\ (MQCF) = 5.102 - 0.013V - 29.570F - 0.014VF + 2.439E\text{-}005V^2 + 139.715F^2 \quad \textbf{... (6)}$$

Figure 8 (a) shows the variation in R_a with feed rate under DAC, FC and MQCF conditions. Normally cutting speed and feed rate play an important role on R_a [7]. Surface roughness is primarily the feed marks left by the tool tip on the workpiece surface. As the feed rate increases, the feed mark size increases, so the R_a increases irrespective of type of cooling technique.

Higher feed rate causes increased thrust forces. Due to poor cooling and lubrication, in DAC, the auxiliary flank wear is maximum. So, workpiece R_a obtained is high. In FC, liquid cutting fluid with low pressure cannot penetrate into chip-tool interface area. The pressurized MQCF jet is capable of creating a hydraulic wedge between the tool and the workpiece to penetrate into the interface deeply. So, MQCF not only provides adequate cooling at the tool-workpiece interface but also provides an effective flushing of chips from the cutting region. So, MQCF can lower the R_a by 20% with respect to DAC and 14% with respect to FC respectively (Figure 8(a)).

Since R_a is directly proportional to feed rate, the variation of R_a with cutting speed were plotted with minimum feed rate. The R_a has a tendency to decrease with increase in cutting speed but at higher speeds it rises slightly irrespective of cutting fluid application technique due to higher tool wear (Figure 8(b)).

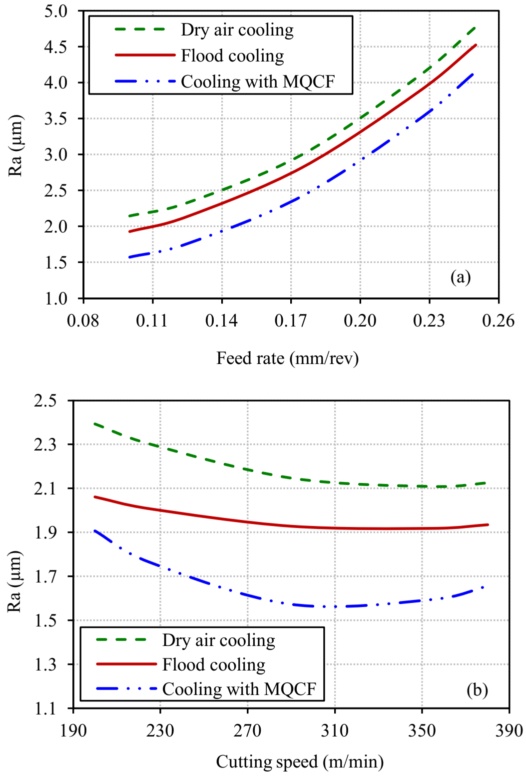


Figure 8: Effect of (a) feed rate and (b) cutting speed on average surface roughness in DAC, FC as well as MQCF.

In DAC, the air has limited cooling ability so, minimal R_a. At low feed rate and cutting speeds, where temperature generation is low, FC technique (cutting fluid is applied conventionally into the machining zone) can control tool temperatures. But at high speeds, (where temperature is about 1,000°C), cutting fluid starts evaporating. This leads to formation of a pressurized vapor zone that effectively prevents the flow of incoming low-pressure cutting fluid to reach the cutter edge. Thus FC cannot cool and lubricate the interior regions of machining zone properly but it provides lower R_a compared to DAC. In MQCF, pressurized cutting fluid mist jet, impinged into the machining zone, can create MQCF wedge between the tool-chip interfaces forcing the chip to bend upwards giving it a curl. The cutting fluid mist wedge created at the tool-chip interface reduces tool-chip contact length and also lowers the coefficient of friction. Thus, MQCF appeared to be effective in reducing R_a by 23.5% and 14% with DAC and FC respectively (Figure 8(b)).

3.3. Chip thickness (t_2)

In machining, maximum heat is generated at chip-tool interface due to secondary deformation, which influences the chip formation and tool wear. Chip thickness mainly depends on feed rate, cutting speed and the type of cutting fluid application.

Taking into consideration the non-linearity of the chip thickness with input parameters, second-order empirical models for DAC, FC and MQCF were obtained (Eq.(7)-Eq.(9)). The ANOVA for average surface roughness is carried out. R^2 and adj R^2 of the models (Eq.(7) Eq.(9)) is found to be more than 95%. This implies that the models are significant.

$$t_2\ (DAC) = -0.157 + 4.219E\text{-}004V + 2.867F - 4.615E\text{-}004VF - 7.988E\text{-}007V^2 - 3.85F^2 \quad \textbf{... (7)}$$

$$t_2\ (FC) = -0.149 + 3.612\ E\text{-}004V + 2.837F - 7.462\ E\text{-}004VF - 6.021E\text{-}007\ V^2 - 3.618F^2 \quad \textbf{... (8)}$$

$$t_2\ (MQCF) = -0.150 + 3.731E\text{-}004V + 2.729F - 1.108E\text{-}003VF - 4.94083E\text{-}007V^2 - 3.115F^2 \quad \textbf{... (9)}$$

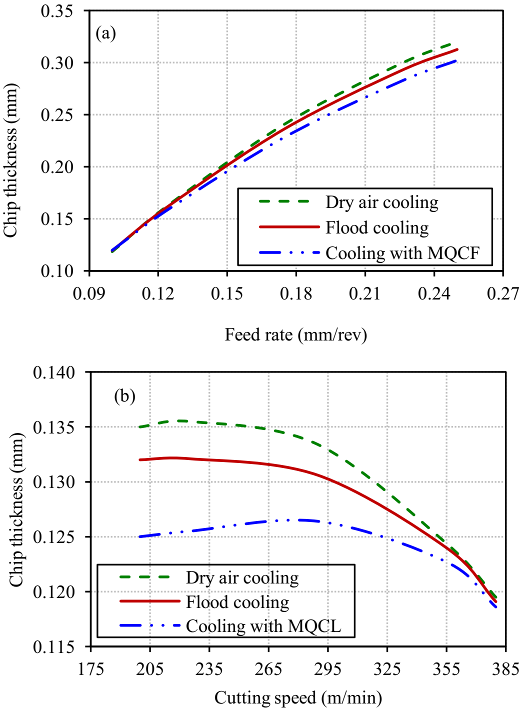
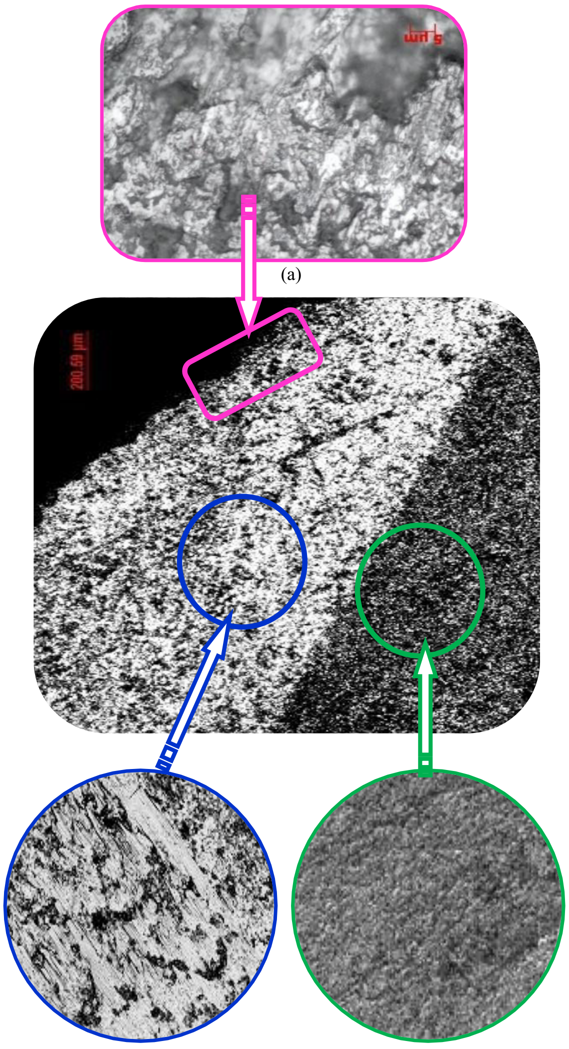


Figure 9: Variation of chip thickness with (a) feed rate and (b) cutting speed for DAC, FC, as well as MQCF

As the feed rate increases, the chip thickness increases irrespective of the type of cooling method (Figure 9(a)). But there is slight variation in chip thickness for different cutting fluid application techniques. In DAC, the cooling and lubrication is poor so sticking/welding of top most layers of tool surface (built up edge) is more, so the chip thickness is more. In FC, cutting fluid cannot enter into interior zones of machining region due to pressurized vapour zone that effectively prevents the inflow of low-pressure cutting fluid to reach the cutter edge. So the partially the adhesion of top layers of tool surface occurs reducing the chip thickness slightly with respect to DAC. But MQCF jet can penetrate in this pressurized vapour zone and effectively cool as well as lubricate the region, keeping the chip thickness relatively low (Figure 9(a)).



(a)

(b)

(c)

Figure 10: Topography of tool rake surface after machining due to chip flow (a) Sticking region, (b) sliding region and (c) un-sheared tool surface region

Chip thickness decreases as the cutting speed increases irrespective of cutting fluid application technique. At low cutting speeds, the chip curl radius is low so the chip tool contact length is more. Due to high temperature in shear region and more chip tool contact length, chip tries to stick the tool rake face around cutting edge region. This causes the sticking region (Figure 10(a)) and because of continuous sliding of chip over the tool rake face, it causes sliding region (Figure 10(b)). Wear is severe in sticking region, followed by sliding region compared to normal/original tool surface (Figure 10(c)). As the cutting speed increases, chip curl radius increases gradually so the plastic and elastic contact region between the chip and the tool rake face decreases gradually. Thus, at low cutting speeds, built-up edge (BUE) formation is common and retaining of BUE fragments increases the chip thickness. At high cutting speeds due to more heat generation near tool tip region, the BUE is partially eliminated leading to lower chip thickness (Figure 9(b)).

In DAC, because of no proper cooling and lubrication, regular BUE formation occurs. In FC, due to inability of cutting fluid penetration (improper cooling and lubrication) into the seizure zone of machining doesn't affect much of the BUE formation. But in machining with MQCF, cutting fluid mist wedge created at the tool-chip interface reduces tool-chip contact length and lowers the coefficient of friction. This wedge forces the cutting fluid mist into the plastic contact region by capillary action. Thus, the chip thickness in MQCF is 4.5% less compared to DAC and 3.0% less compared to FC technique (Figure 9(b)).

4. Conclusion

In the present study, preliminary experimentation was carried out to find variation of cutting fluid flow rate with air pressure and it was observed that, as the air pressure increases, the cutting fluid flow rate decreases. Later the optimum air pressure in MQCF for minimum R_a and tool flank wear was found as 0.7 MPa. Complete experimental study and modelling was carried out on DAC, FC and MQCF to compare its performances in terms of R_a, chip thickness and tool flank wear. All output responses shows that MQCF is one of viable economic and eco-friendly alternative machining to FC and DAC.

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