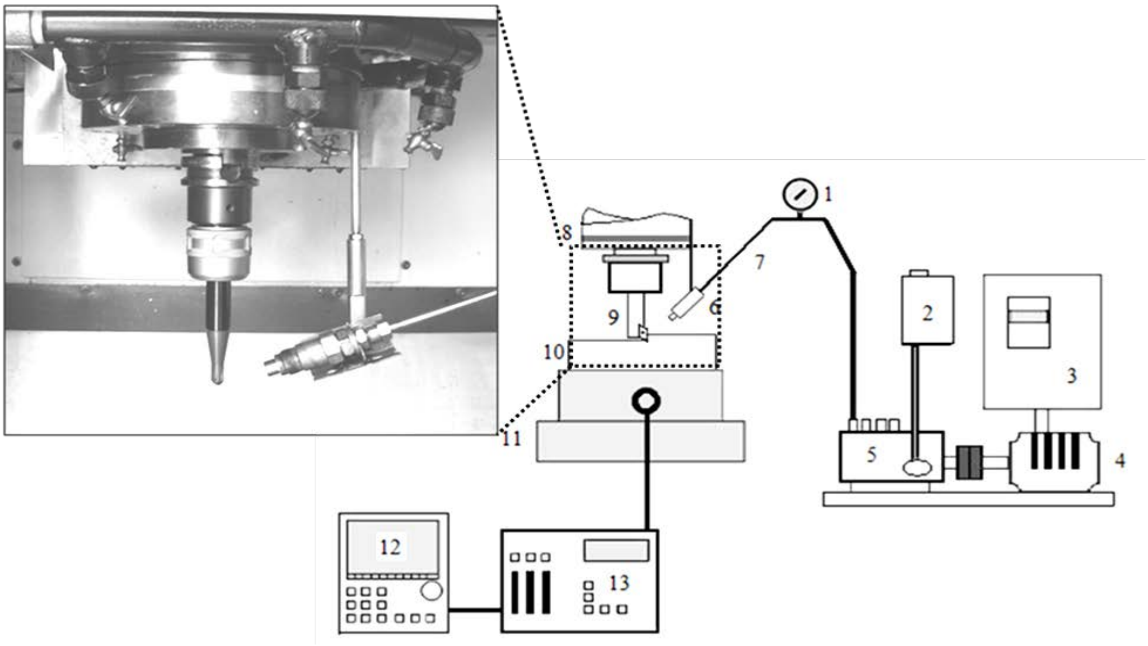

Figure 1: Schematic diagram of pulsed jet MQL system: 1- pressure gauge; 2- fluid tank; 3- variable speed control drive; 4- electric motor; 5- injection pump; 6- nozzle; 7- steel pipe; 8- spindle; 9- insert tool holder; 10- workpiece; 11- dynamometer 12-charge amplifier;,13-oscilloscope

Experiment Setup

Experiments were conducted on a high-speed vertical machining centre (Mitsui Seiki VT3A). The cutting tools selected were PVD coated carbide inserts (ACZ310, Sumitomo Electric Hardmetal, Japan). The workpiece chosen was AISI 01 compliant hardened tool steel (ASSAB DF3) having a chemical composition of 0.95% C, 0.11% Mn, 0.6% Cr, 0.6% W and 0.1% V. This tool steel type is popularly used for the fabrication of plastic injection moulds and cold worked dies. The size of the workpiece was 50 mm x 100 mm x 250 mm and its hardness after heat-treatment was 51 HRc.

Three types of cutting fluids chosen were neat oil (FUCHS SSN 321 PF), soluble oil (ECOCOOL 62101T) and semi-synthetic cutting fluid (ECOCOOL 68 CF2). Prior to usage, the soluble oil and the semi-synthetic cutting fluid were mixed with water in a volumetric concentration of 1:10, whereas the neat oil was used as received.

Design of Experiments

Table 1 shows the variable and constant parameters for the experiments. The depth of cut and pick feed were kept constant at 0.2 mm and 4 mm respectively. The MQL was set at a pulsing rate of 400 pulse/min, a pulsing pressure of 20 MPa and a delivery rate of 2 ml/min [11] with the fluid injected against the feeding direction.

Table 1. Experimental Parameters

Variables	Exp. 1	Exp. 2
V, cutting speed, m/min	20, 40, 60	30
f_z, feed rate, mm/tooth	0.05	0.05, 0.06, 0.07
D, cutter diameter, mm	25	
f_m, table feed	40, 80, 119	60, 72, 84
DOC, axial depth of cut, mm	0.2	
f_p, Pick feed, mm	4	
l, cutting length, m	1	
Pulsing rate, pulse/min	400	
Pulsing pressure, MPa	20	
Lubricant delivery rate, ml/min	2	
Pulsing direction	Against feeding direction	

Experimental Procedures

The experimental runs consisted of 4 down milling passes along the 250 mm length of the workpiece. After finishing one milling pass, the tool was shifted 4 mm inwards (pick feed) to start the next pass. The total cutting length was set at 1 m or equivalent to 4 milling passes along the workpiece. The cutting forces were measured at the initial 100 mm of the cutting lengths, to avoid the influence of tool wear on the measurements. The tool wear is taken as the maximum flank wear, which was observed under magnification. The average surface roughness was calculated from three selected points of the resultant cut parallel to the cutting direction. The physical appearances of the chips were also recorded for evaluation of chip formation.

Results and Discussion

The results obtained showed the relative performance of the three types of cutting fluids in terms of cutting forces, average surface roughness, maximum flank wear and chip formation. The following discussion will describe the influence of cutting velocities and feed rates on the measured outputs. The desirable outputs for good machining performance are low cutting forces, low surface roughness and low flank wear.

Cutting Forces

Figure 2 shows the effect of cutting velocity on the cutting force. At 20 mm/min, the cutting forces for neat oil were the lowest among the cutting fluids compared. However, as the cutting velocity increases from 40 m/min to 60 m/min, the cutting forces for neat oil drastically increase more than soluble and semi-synthetic cutting fluids. It was observed that soluble oil had achieved the lowest cutting forces amongst the three cutting fluid compared, obtained at cutting velocity of 40 m/min.

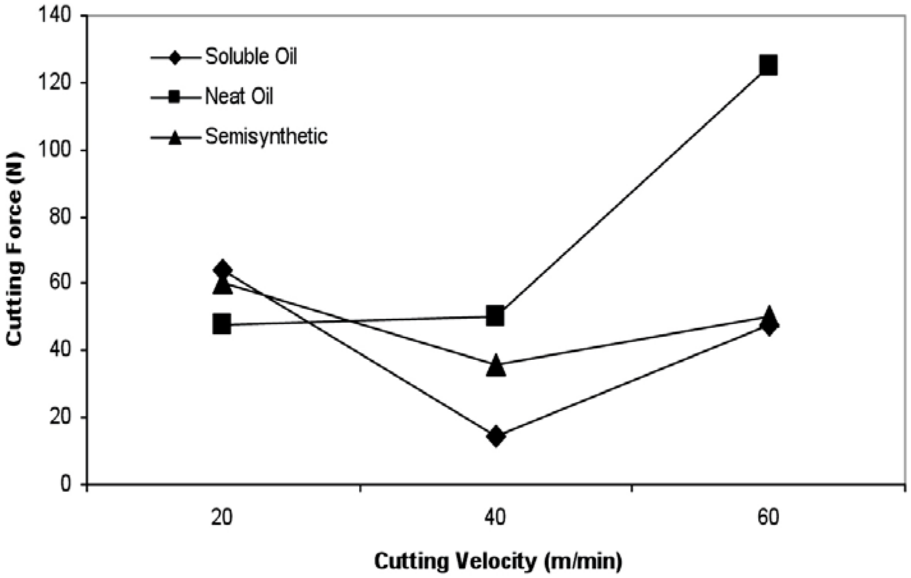

Figure 2. Effect of cutting velocity on cutting force (feed rate 0.01 mm/tooth)

Figure 3 shows the effect of feed rate on the cutting force. For neat oil, although it generates the lowest cutting force at 0.05 mm/tooth feed rate, the force increases dramatically when the feed rate is increased to 0.06 mm/tooth. For 0.07 mm/tooth feed rate, semi-synthetic cutting fluid gave the highest cutting force readings. In all cases, the soluble oil did not experience drastic changes in cutting force with the variation in feed rate.

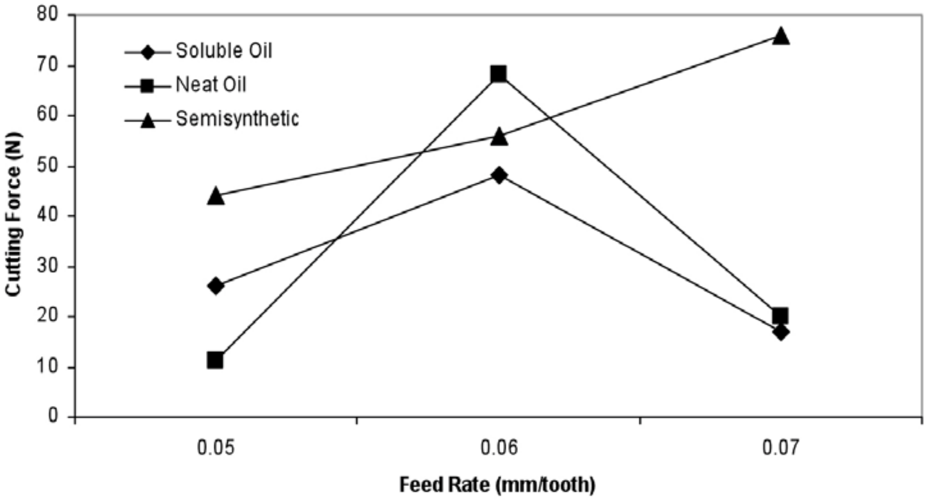

Figure 3. Effect of feed rate on cutting force (cutting velocity 30 m/min)

Maximum Flank Wears

Figure 4 shows the effect of cutting velocity on maximum flank wear. For low cutting velocity of 20 m/min, it was observed that the highest flank wear was for the semi-synthetic fluid, whereas the lowest flank wear was obtained for neat oil. However, for high velocity of 40 m/min, the semi-synthetic results in the lowest flank wear. An increasing trend of flank wear is apparent in the case of neat oil, whereas no clear trends were observable for both soluble and semisynthetic cutting fluids.

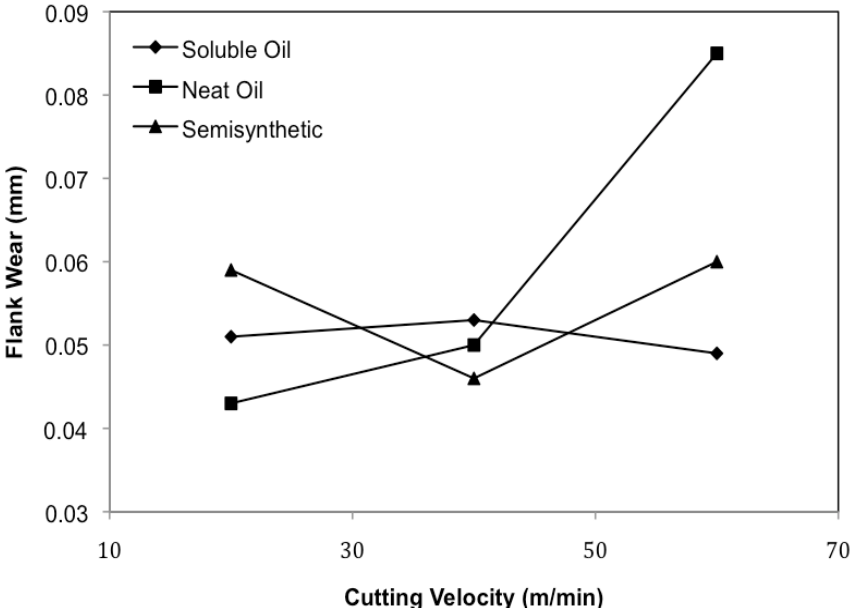

Figure 4. Effect of cutting velocity on flank wear (feed rate 0.01 mm/tooth)

The effect of feed rate on maximum flank wear is shown in Figure 5. It is observed that the maximum flank wear decreases with an increase in feed rates for all the cutting fluids. Generally, it was shown that neat oil demonstrates the best performance in reducing flank wear as compared to the other two cutting fluids.

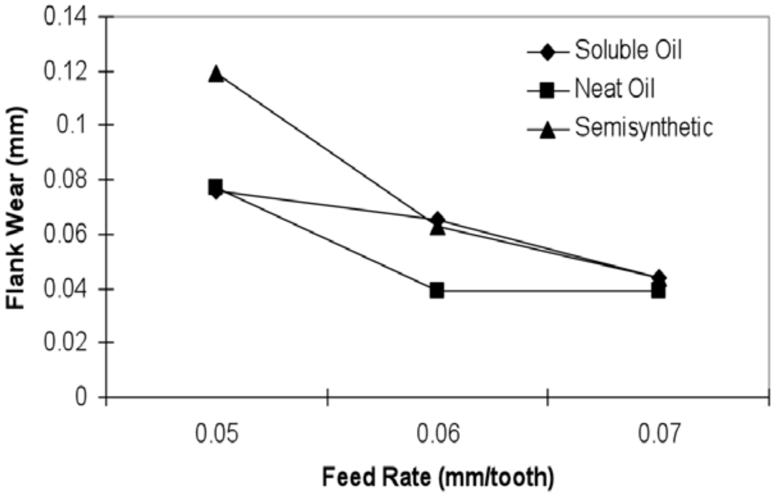

Figure 5. Effect of feed rate on flank wear (cutting velocity 30 m/min)

Average surface roughness

Figure 6 shows the effect of cutting velocity on the average surface roughness. For 0.01 mm/tooth feed, it was observed that for neat oil and semi-synthetic cutting fluid, the average surface roughness decreases with the increase in cutting velocity. However, for soluble oil, the average surface roughness increases only slightly with an increase in cutting velocity. For low cutting velocities, neat oil produces surfaces with the highest roughness although at increased velocity, the surface roughness improves dramatically.

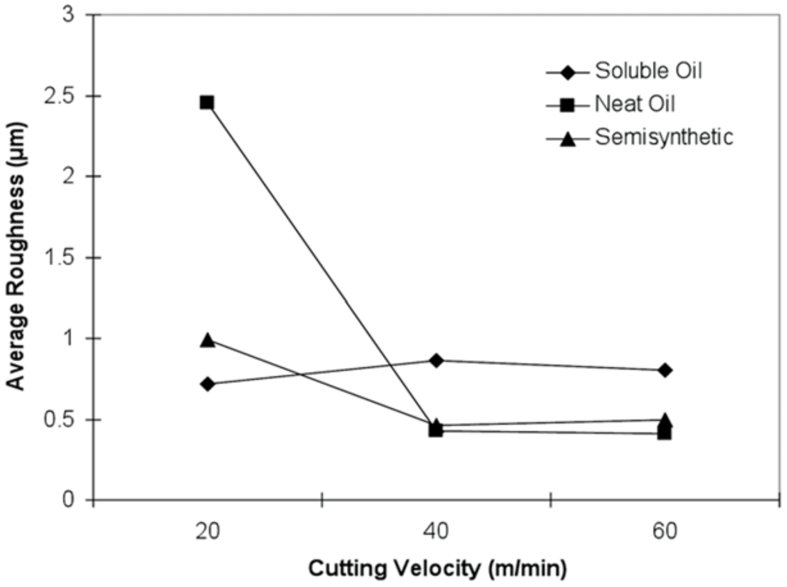

Figure 6. Effect of cutting velocity on surface roughness (feed rate 0.01 mm/tooth)

The effect of feed rate on average surface roughness is shown in Figure 7. For low feed rate of 0.05 mm/tooth, there was a significant difference in surface roughness between the three cutting fluids, with the semi-synthetic cutting fluid resulted in the highest and the soluble oil giving the lowest value. However, when the feed rates are increased, the surface roughness values for all cutting fluids were similarly close. In general, the average surface roughness decreases with an increase in feed rate.

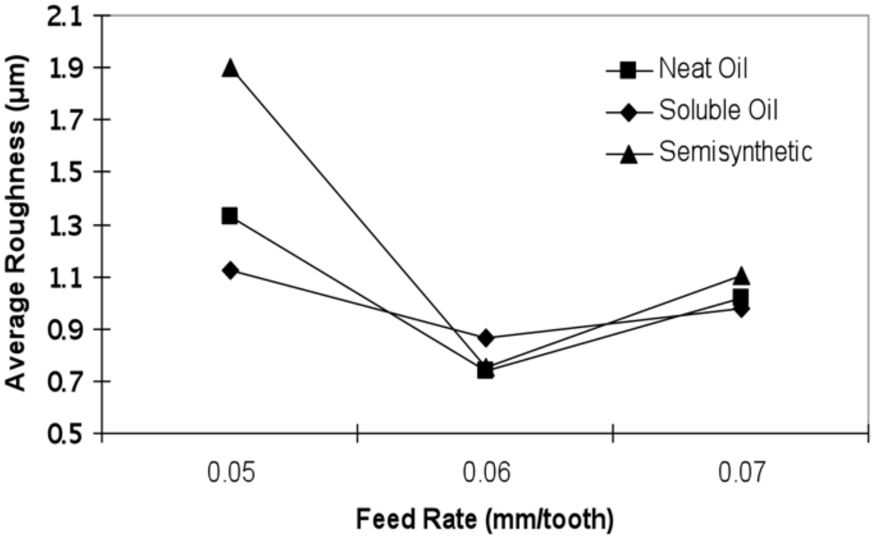

Figure 7. Effect of feed rate on surface roughness (cutting velocity 30 m/min)

Chip Formation

It was observed that cutting using neat oil produces golden brown coloured chips, as shown in Figures 8(a) and 8(b). Although generally the chips produced are cylindrical in shapes, there were occurrences of discontinuous small chips for experiments with cutting velocity 60 m/min and feed rate 0.05 mm/tooth. It was also observed that chips were accumulating on the machined surface, especially for the more viscous neat oil applications. Nevertheless, chips were not interfering in the cutting zone since they are blown away by the high pressure pulsed fluid injection.

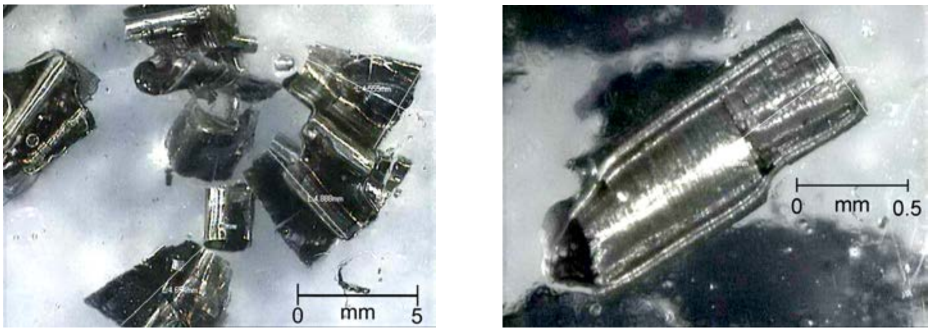

Figure 8(a) Figure 8(b)

Figures 8(a) and 8(b) showing magnified view of chips formed while cutting using neat oil, cutting velocity = 60 m/min, feed rate = 0.05 mm/tooth

Conclusions

The following conclusions can be drawn from the findings in this study:

- Neat oil gave the lowest cutting forces and flank wears at low cutting velocities and feed rates as compared to soluble oil and synthetic cutting fluid.
- Soluble oil gave the lowest cutting forces and flank wears at high cutting velocities and feed rated as compared to neat oil and synthetic cutting fluid.
- It was observed that performance of soluble oil does not drastically change with variation to the cutting velocities and feed rates. Thus, the choice of soluble oil would be appropriate for general usage.
- For specific requirements, such as the need for controlled low surface roughness, the use of neat oil or semi-synthetic cutting fluid may be more appropriate. However, the machining requirements, such as high cutting velocity and high feed rates should be observed.
- With proper machining parameter selection, water-mixed cutting fluids (soluble oil and semisynthetic) performed comparatively well to deliver low surface roughness results. Thus, this can be an economical choice in the selection process.

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