PERFORMANCE EVALUATION OF DIFFERENT TYPES OF CUTTING FLUID IN THE MACHINING OF AISI 01 HARDENED STEEL USING PULSED JET MINIMAL QUANTITY LUBRICATION SYSTEM

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Abstract

This paper presents the performance evaluation of three different cutting fluids used in a minimal quantity lubrication (MQL) system. The MQL system, developed in-house at the University of Malaya, was capable of delivering high velocity cutting fluid in narrow pulsed jet forms at a rate of 2 ml/min and a pressure of 20 MPa. The three cutting fluids chosen were neat oil, soluble oil and semi-synthetic cutting fluids. The experiments were designed to evaluate the performance of the fluids at various cutting velocities of 20,40 and 60 m/min and feed rates of 0.05,0.06 and 0.07 mm/tooth. The results were measured in terms of the average surface roughness of the machined workpiece, the cutting forces and the maximum flank wear. In addition, the resultant chip formations were also observed. Analysis of the results has shown that in general, neat oil had performed the best in low cutting velocities and feed rates. On the other hand, 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 most appropriate for general machining usage. With suitable machining parameter selection, water-mixed cutting fluids (soluble oil and semisynthetics) performed comparatively well to deliver low surface roughness results. Therefore, this can be an economical choice for use in industrial production processes.

Keywords: Chip formation, Cutting fluids, Force, MQL, Wear

Introduction

The primary function of the cutting fluids in metal machining operations is to serve as a coolant as well as a lubricant. It is generally agreed that the application of cutting fluids can improve the tool life and results in good surface finish by reducing thermal distortion and flushing away of machined chips. The goal in all conventional metal-removal operations is to raise productivity and reduce costs by machining at the highest practical speed along with long tool life, fewest rejects, and minimum downtime, and with the production of surfaces of satisfactory accuracy and finish [1]. Selecting the right cutting fluid is as important as choosing the suitable machine tools, tooling, speed and feed because it can always affect the output parameters. In addition, the ability of the cutting fluid to penetrate into the cutting zone is a critical issue; otherwise, the function of cutting fluid becomes useless [2]. The use of cutting fluid permits higher cutting speeds, higher feed rates, greater depths of cut, lengthened tool life, decreased surface roughness, increased dimensional accuracy, and reduced power consumption.

Cutting fluids can be applied using various methods. The flooding method is the most commonly used in which a high volume flow is applied and floods the entire machining area, effectively removing the heat generated from the machining process [3].

However, improved production efficiency and revised regulations in the machining industry favours the reduction of cutting fluid usage. It was reported that operators who are frequently exposed to cutting fluids are susceptible to costly cases of occupational dermatitis and other skin diseases such as sensitization to specific irritants, oil acne, and hyperpigmentation [4, 5]. In addition, improper disposal of used cutting fluids may cause serious impact to the environment through contamination of the soil, water and air. Furthermore, cutting fluid usage can account for 7-17% of the total production costs through its procurement, storage, maintenance and disposal [6].

Minimal quantity lubrication (MQL) encompasses various techniques in which the cutting fluid is applied in very small quantities during machining. An example of an MQL technique is the mist coolant application. In this method, very small droplets of the cutting fluid are dispersed in a gas medium, generally air, and applied at the cutting zone [3]. Past researchers such as M.Rahman et al. [7] have evaluated oil mist generators and have concluded that MQL systems can significantly reduce the usage of cutting fluids while maintaining the machining performance. Evaluations of MQL systems had measured their performance in terms of tool wear, cutting forces and surface roughness [8,9]. In those studies, it was shown that MQL systems had comparable machining performance with flooding applications in turning and drilling processes.

Application of the cutting fluid in the form of narrow pulsed jet streams was proposed by A. S. Vadarajan et. al [10]. Usage of such an MQL system in the turning of hardened tool steels had shown better machining performance in terms of cutting force, tool life and surface finish as compared to flooding and dry machining. T. Thepsonthi [11] adapted this technique for the milling of hardened steel with carbide mills by applying high velocity and narrow pulsed jet at the rate of 2 ml/min. Similar results favouring the MQL technique over both flooding and dry machining was obtained showing comparable machining performance.

Previous studies have concentrated on the comparison between the various types of cutting fluid delivery systems and have concluded that MQL systems are suitable replacements for existing flooding techniques. Subsequently, there is a need to focus on the optimisation of the MQL system. One significant area is the selection of cutting fluids, a topic which is yet to be fully addressed. Thus, this research will focus on the evaluation of cutting fluids used in the pulsed jet MQL system.

Methodology

Apparatus

Pulsed Jet MQL System

The pulsed jet MQL system, schematically shown in Figure 1, was developed in-house at the University of Malaya. It consists of a variable speed control drive which regulates an injection pump to deliver cutting fluid in the form of a high pressure pulsed jet stream.

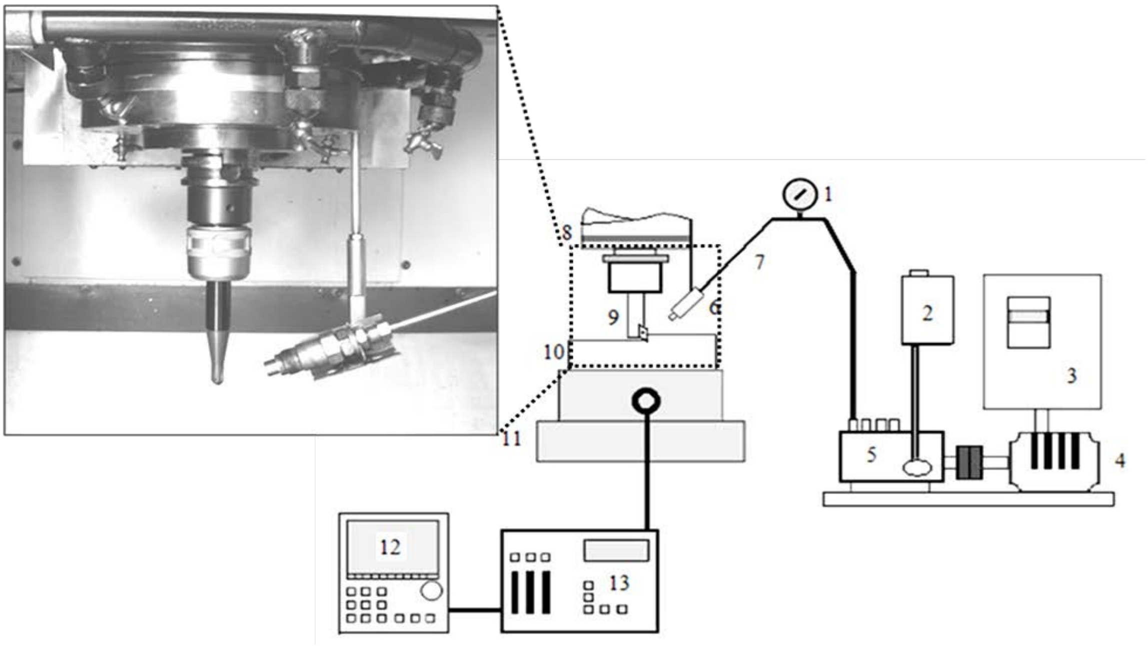

Figure 1: Schematic diagram of pulsed jet MQL system: 1- pressure gauge; 2- fluid tank; 3- variable speed control drive; 4- electric motor; 5- injection pump; 6- nozzle; 7- steel pipe; 8- spindle; 9- insert tool holder; 10- workpiece; 11- dynamometer 12-charge amplifier;,13-oscilloscope

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.

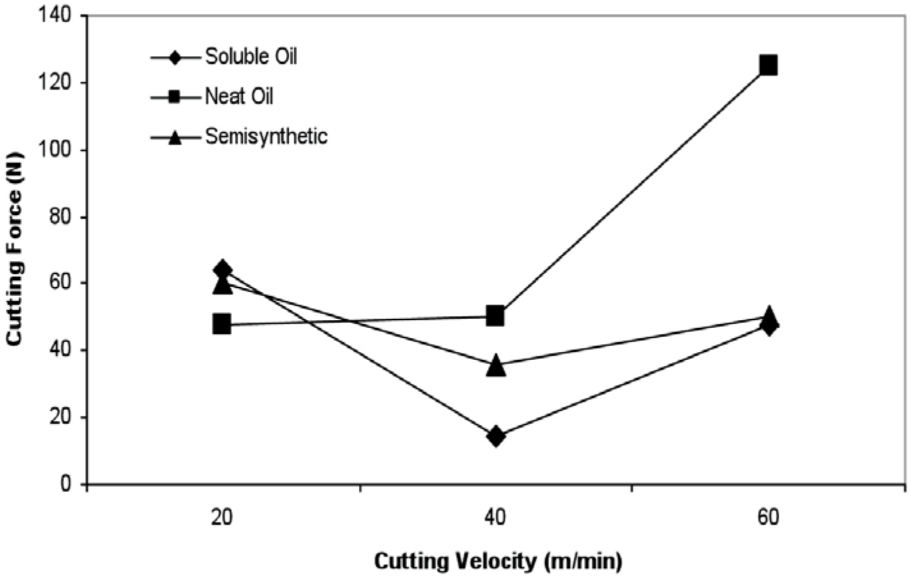

Figure 2. Effect of cutting velocity on cutting force (feed rate 0.01 mm/tooth)

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.

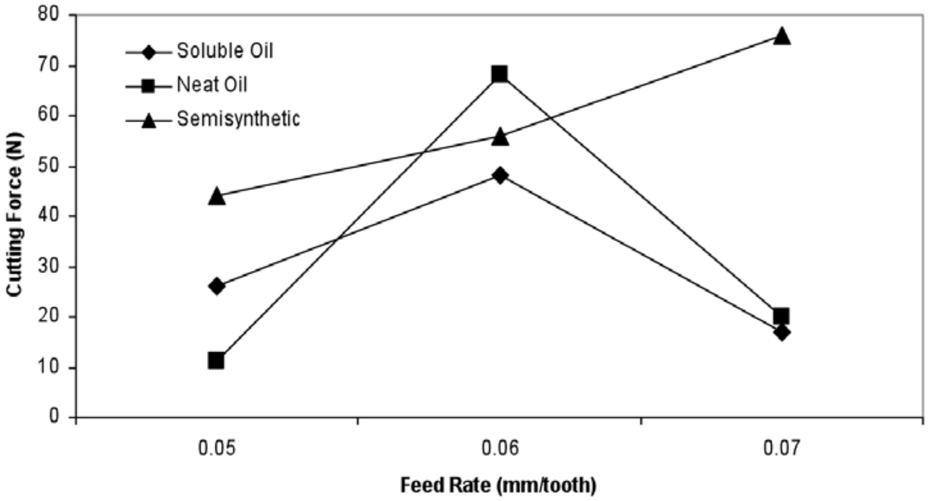

Figure 3. Effect of feed rate on cutting force (cutting velocity 30 m/min)

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.

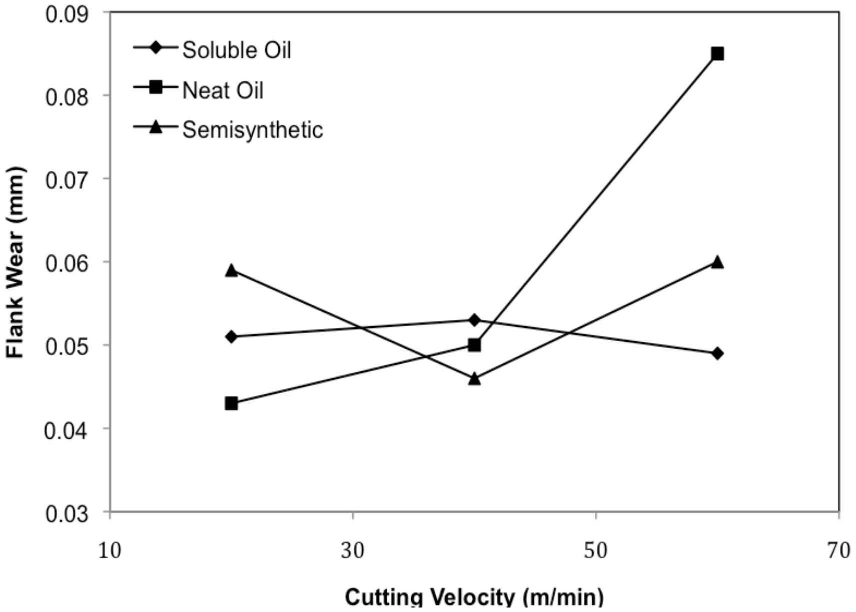

Figure 4. Effect of cutting velocity on flank wear (feed rate 0.01 mm/tooth)

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.

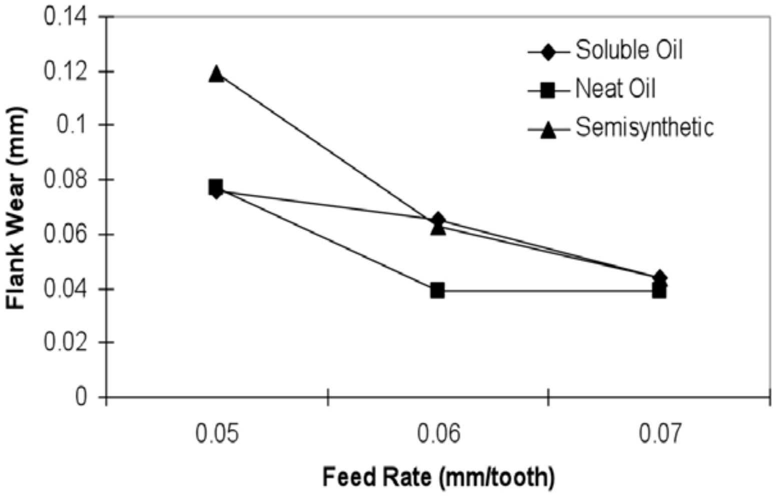

Figure 5. Effect of feed rate on flank wear (cutting velocity 30 m/min)

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.

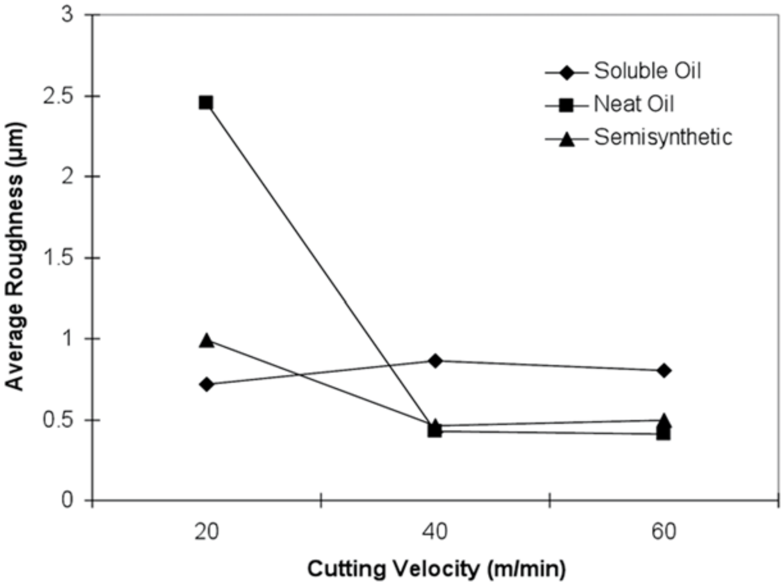

Figure 6. Effect of cutting velocity on surface roughness (feed rate 0.01 mm/tooth)

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.

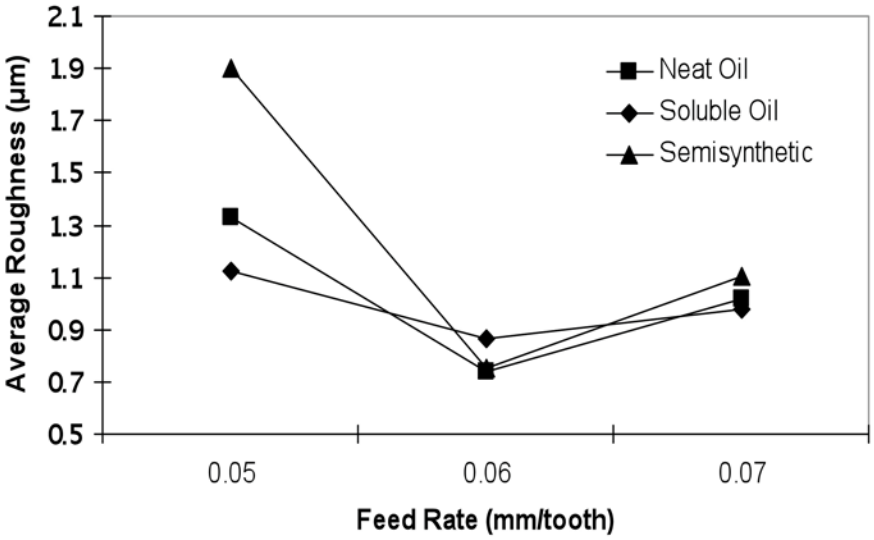

Figure 7. Effect of feed rate on surface roughness (cutting velocity 30 m/min)

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.

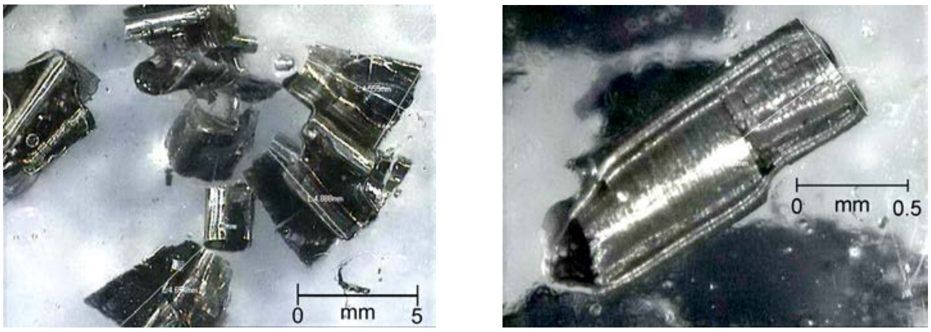

Figure 8(a) Figure 8(b)

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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