Green Machining: Studying the impact of viscosity of Green Cutting fluid on surface quality in straight turning

Rahul Katna 1,2, M.Suhaib2, Narayan Agrawa1, Kanwarjeet Singh1, Swati Jain3, S.Maji1

1Delhi Institute of Tool Engineering, Okhla, New Delhi, India
2Dept of Mechanical Engineering, Jamia Millia Islamia, New Delhi, India
3Integrated Institute of Technology, Dwarka, New Delhi, India

Corresponding author: katnarahul@gmail.com

Abstract. Cutting fluids are the category of metalworking fluids which are used in metal machining operation. Application of cutting fluids eases metal removal and enhances the productivity of the industry. Cutting fluids have been used for many decades. Lately the industry is looking toward shifting to using biodegradable cutting fluids. In the last decade many researchers have found that cutting fluids derived from edible oils have a potential to be used in place of the mineral oil based products. However there has not been much reported literature on the surface chemistry of the cutting fluids and how they affect the machining outcomes. In this work experiment was done to study the way in which the viscosity of a non mineral oil based cutting fluid affects the surface roughness of the machining product and the interaction mechanism of cutting fluid with the surface is tried to be deduced from the outcome.

1. Introduction

Metalworking fluids have become the essential requirement of the modern industry. Modern industry wants to increase the productivity at any cost. Use of cutting fluid helps in achieving the desired machining results like surface roughness [1,2]. Cutting fluids play an important role in machining operations [3-5]. They help in reducing the friction occurring between the tool and the workpiece and also help in keeping the temperature rise under control [6-9]. Since almost a century mineral oil based cutting fluids have been used in the industry [10-12]. However, Cutting fluids increase the machining output without considering the environment and human impact [13, 16].

1.1 Performance and effectiveness of cutting fluids

It has been reported many times that cutting fluids and all other metalworking fluids contain chemicals and additives that are harmful and carcinogenic [4-7, 15]. The additives are blended with the fluid in order to improve their efficiency. Their overall cost increases when their life gets over because the disposal requires additional neutralization processes thereby adding up to the total cost [4-7]. Overcoming this challenge is the current demand of the industry. A cutting fluid that works at par with the mineral oil based cutting fluids needs to be developed. In order to find the feasibility of using vegetable oil based cutting fluids many researchers have formulated cutting fluids from oils like coconut oil, groundnut oil, palm oil, castor oil, sunflower oil, modified sunflower oil etc. [10-13]. It has been reported that vegetable oil based cutting fluids perform at par with the conventional mineral oil based cutting fluid. It is also discovered that these are better alternative to conventional cutting fluids.

The vegetable oils have been found to perform better in flood type delivery as well as in the MQL method of delivering cutting fluid. The MQL method uses very minimum quantity of lubricant yet it is
effective because it reaches the cutting zone due to the small size of lubricant droplets achieved. The oils derived from vegetables lubricate better than the mineral oil derived ones due to their inherent property. The reported literature gives information about only the efficacy of vegetable oil based cutting fluids over the mineral oil based cutting fluid only in terms of output data like temperature reduction, surface roughness, tool wear and cutting forces. Not much literature is reported on the interaction of the cutting fluid with the machined surface. In almost many studies, only the machining outcomes and surface quality have been reported without explaining the physical or chemical mechanism of the cutting fluid interaction.

1.2 Cutting fluid in machining

Before formulating any vegetable oil based cutting fluid, it is important to know the working mechanism and the interaction between the cutting fluid and the workpiece material [7]. Kuram et al. performed experiments with five different cutting fluids on three different materials [14]. They reported that a same cutting fluid has different effect on different material. Even the input machining parameters change the way of interaction of cutting fluid with the type of material [8]. It is hence essential to know how a cutting fluid interacts with the workpiece material. It has been reported that there is a matching problem between the cutting fluid and the materials [9].

The surface quality of the machined surface largely depends on the cutting fluid viscosity. The viscosity of a cutting fluid used is an important characteristic because it dictates the behaviour of cutting fluid near the cutting zone. In addition, the interactions between the material and the cutting fluid on the surface depend on the cutting fluid viscosity. Fluid that is more viscous will tend to create a strong layer of lubricant for the impending cutting action as compared to a fluid with lesser viscosity. However, a more viscous fluid is restrained from entering the cutting zone effectively during machining. Hence, there is a need to understand how viscosity affects the surface quality. In this study, the effect of viscosity on surface roughness was studied and other factors that come into play during machining are reported.

2. Material and Method

In order to understand the effect of viscosity on the machined surface quality and the interactions between the material and the cutting fluid, six cutting fluid formulations were prepared. Only one oil was chosen to keep the lubricating effect of oil constant. The method of preparation involved blending different concentration of surfactant with base oil. Six different concentrations of emulsifier from 5% to 30% in steps of 5% were prepared limiting the maximum amount of surfactant at 30% in the cutting fluid formulation.

2.1 Cutting fluid Sample preparation

For studying the effect of viscosity of oil in water emulsions, six different stock solutions of oil in water emulsions were prepared. For preparing samples of cutting fluids the oil and emulsifier were blended together in a magnetic stirrer at 600 rpm for 15 minutes. The concentrate was then diluted to 10% by mixing in water. The emulsions were found to be stable immediately.

The concentration of oil was maintained constant in each stock solution and viscosity level was varied by using the emulsifier in variable quantity. Samples from the stock solution contained oil 50 ml in each and surfactant 2.6 ml, 5.5 ml, 8.8 ml, 12.5 ml, 16.7 ml and 21.5 ml respectively as shown in Table 1. The stock solutions were coded as S1, S2, S3, S4, S5 and S6 respectively. Each sample was diluted with water in the ratio 1:9. Table 1 shows the formulated samples and the constituent in each sample. The viscosity of each cutting fluid was measured using Labman rotational viscometer having low viscosity adapter and least count of 0.1cSt. The results of viscosity of each sample are reported in the result and discussion section. Each sample was measured four times and average reading was taken as reference.

2.2 Machining condition

For studying the effect of viscosity on surface quality, straight turning was done AISI 1045 steel with uncoated carbide insert. A constant cutting fluid flow rate of one liter per minute was maintained by an external submersible pump. Surface roughness readings were taken by a portable surface roughness tester having least count 0.01 micrometer at regular intervals. The readings were taken at three positions by rotating the machined workpiece by 120 degrees and the average surface roughness was taken for
analysis. Constant cutting parameters, cutting speed = 90m/min, feed rate 0.1mm/rev and depth of cut 0.5 mm were used with all the cutting fluid samples. Fresh cutting edge of the insert was used for each cutting operation.

| Table 1. Formulated samples and their constituents |
|-----------------|-----------------|-----------------|-----------------|
| Sample No | Oil quantity (ml) | Emulsifier quantity (ml) | % Emulsifier in concentrate |
| S1 | 50 | 2.6 | 5% |
| S2 | 50 | 5.5 | 10% |
| S3 | 50 | 8.8 | 15% |
| S4 | 50 | 12.5 | 20% |
| S5 | 50 | 16.7 | 25% |
| S6 | 50 | 21.5 | 30% |

3. Results and Discussion
The kinematic viscosity of the samples S1, S2, S3, S4, S5 and S6 was found to be 1.12 cSt, 1.13 cSt, 1.14 cSt, 1.15 cSt, 1.17 cSt and 1.18 cSt respectively. The surface roughness was measured with every cutting fluid sample and average value was taken. The samples prepared were coded as S1, S2, S3, S4, S5, and S6. For sample S1, the variation in surface roughness was recorded throughout the machining and reported. Similarly, the surface roughness for other sample was recorded in this manner and reported. In this study we have tried to observe the relation between surface roughness, change of viscosity in sample and machining time. The surface roughness comparison chart was drawn for every cutting fluid sample for analysis.

As seen in figure 1, for sample S1, surface roughness decreases initially from 2 to 4 minute but then starts increasing gradually after 4 min as the machining time increases. Initial low values of surface roughness could be due to good adsorption of the cutting fluid on the freshly generated surface and the affinity of the work surface to the cutting fluid. After that, the surface finish starts decreasing gradually may be due to the wear of the cutting tool. From figure 2, for sample S2, it can be seen that the surface roughness decreases and then increases gradually. This could be due to increased surface interaction of the cutting fluid with the surface of workpiece.

![Surface roughness Vs Machining time with sample S1](image1)

**Figure 1.** Surface roughness with sample S1 at different machining time

![Surface roughness Vs Machining time with sample S2](image2)

**Figure 2.** Surface roughness with sample S2 at different machining time

Figure 3, for sample S3, shows that the surface roughness remains the same during half of the machining time and starts increasing afterwards as the machining progresses towards an end. This
behaviour can be explained based on the tool wear after some time. Figure 4, for sample S4, shows gradual increase of surface roughness from the beginning as against the previous cases. The increase in roughness is attributed to the increase wear of the cutting edge of the tool. However, no decrease in surface roughness during initial machining could be due to improper interaction of cutting fluid with the metal surface.

Figure 3. Surface roughness with sample S3 at different machining time  

Figure 4. Surface roughness with sample S4 at different machining time

Figure 5, for sample S5, shows that the surface roughness decreases, which is attributed to better surface adsorption of the cutting fluid on the freshly machined workpiece surface. The roughness then increased due to tool wear occurring with machining time. Figure 6, for sample S6, shows that the cutting fluid sample showed the same trend as observed in other cutting fluid samples. The roughness first decreases and then increased due to tool wear. The decrease in surface roughness at any instant is due to better surface adsorption of the cutting fluid on the surface of the workpiece.

Figure 5. Surface roughness with sample S5 at different machining time  

Figure 6. Surface roughness with sample S6 at different machining time

As seen in figure 7, sample S6 gave the least surface roughness during initial machining and the highest roughness was achieved with sample S2. Samples S3 and S4 gave almost similar roughness values. Figure 8 shows that minimum roughness was achieved with sample S6 and highest roughness was achieved with sample S4. Figure 9 shows that sample S5 gave the highest surface finish and lowest
surface roughness and sample S1 gave the highest roughness. In figure 10, minimum value of surface roughness was achieved with samples S2 and S3 whereas sample S6 gave highest roughness value. Figure 11 shows highest roughness was achieved with sample S1 and least surface roughness was achieved with sample S3. As seen from the results above, a lower viscosity does not always mean that better surface finish will be achieved and also a higher viscosity does not guarantee a good surface finish. As seen in figure 7, during the initial stages of machining, when the cutting tool edges are very sharp, finish achieved is almost same with a difference of one micron.

![Surface roughness comparison with different samples after 2 minutes](image1)

**Figure 7.** Surface roughness and viscosity of different samples after 2-minute machining time

However an interesting trend is seen in figure 8. Sample S1 having lowest viscosity gives least surface roughness followed by sample S2 having slightly higher viscosity. This could be due to formation of microcracks after sometime when the machining has taken place. After machining is done for some time, tool wear starts, and micro cracks start forming on the surface of the workpiece. These micro cracks allow the cutting fluid to penetrate inside due to capillary action. During the initial phases of machining, when the cutting edges are sharp, not much cracks are formed. So, during initial stages of machining the only factor that comes into play is the viscous effect of the cutting fluid i.e. more viscous the fluid more is the surface finish achieved.

![Surface roughness comparison with different samples after 4 minutes](image2)

**Figure 8.** Surface roughness and viscosity of different samples after 4-minute machining time

After the tool wear out more, the sample having higher viscosity again starts reaching the cutting zone effectively due to increased size of microcracks due to capillary action and thus gives better surface finish than the sample S1. Also, higher viscosity is due to higher percentage of the surfactant added in the cutting
fluid. It is also possible that there is an increased chemical interaction of the cutting fluid at the workpiece surface due to the surfactant and the workpiece material has more affinity towards the surfactant used.

In figure 9, highest roughness is achieved with lowest viscosity and almost similar surface roughness is achieved with higher viscosities. This is also in line with the trend observed for other cutting fluid samples. However, in figure 10, a strange pattern is observed. The low viscosity cutting fluid samples give less surface roughness i.e. better surface finish is observed and is almost equal to the surface roughness achieved by the highest viscosity cutting fluid. For rest of the cutting fluid samples the trend is similar. This behaviour could be due to the fact that surface cracks might have reduced and thus only the low viscosity cutting fluid sample could penetrate. Thus, of the three samples S1, S2 and S3 having low viscosity, which penetrated into the cutting zone effectively, S3 gave the least surface roughness due to combined effect of capillarity and higher viscosity.

From figure 11 it can be seen that the surface roughness for all samples increased during the final stages of machining. Here, the largest surface roughness was achieved with the least viscous cutting fluid. Samples having relatively higher viscosity gave nearly the same result. This can be due to the fact that increased tool wear caused the microcracks to reduce in size by rubbing action of tool on the workpiece surface due to welding of atoms and also due to increased chemical interaction between the cutting fluid constituent concentration (surfactant concentration) and the workpiece surface.
4. Conclusion

It was observed in this study that for all samples the roughness value is higher at the start of machining but decreases after 2 minutes of machining. The reduction in the surface roughness value may be due to better surface adsorption of the cutting fluid after 2 minutes of machining. However, increase in machining time after 4 min to 10 min the roughness increases in all samples with different viscosity. It can be inferred that multiple factors come into play to dictate the surface quality in machining. Surface quality may not be attributed wholly to the application of cutting fluid.

As seen in this study, the surface quality also depends on the machining time because with continuous machining the cutting edge wears out and this changes the behavior of cutting fluid (cutting fluid interaction) on the workpiece surface. The chemical interaction depends on the constituents of the cutting fluid. It is observed that optimum viscosity of cutting fluid gives best result, i.e. low surface roughness value. Use of cutting fluid delays the increase in surface roughness arising due to increase in tool wear with machining time.

Further, it is also seen that a high viscosity (subject to constraints) helps in minimizing the effect of tool wear on surface roughness. To maintain low surface roughness the viscosity of cutting fluid needs to be raised continuously up to an optimum value by means of adding concentrate in the stock emulsion. Regular increase in concentration should be limited to the machining time and tool wear.

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