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Research article

Investigation of Nano Cutting Oil Effects on Hard Milling Under Minimum Quantity Lubrication

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A B S T R A C T

The presented work aims to investigate minimum quantity lubrication (MQL) using cutting oil with/without Al2O3 nanoparticles for hard milling of 60Si2Mn steel (50-52 HRC) using carbide inserts. The effects of three different types of based cutting oils including emulsion, soybean oil and rapeseed oil on surface roughness Ra, Rz and tool life were studied and investigated. The experimental results show that the use of Al2O3 nano cutting oil has improved lubrication capability compared to base cutting oil, contributing to improve machined surface quality and tool life. Al2O3 emulsion-based nanofluid exhibited the best performance among the three surveyed oils, followed by rapeseed oil and finally soybean oil. Furthermore, the cutting speed of the carbide inserts was improved and the tool life was significantly increased with the help of nano cutting oil due to the improvement in lubrication effects in the cutting zone, thereby helping to reduce cutting forces and cutting heat.

1. INTRODUCTION

In the metal cutting field, machined surface quality is one of the most important factors to evaluate the product quality as well as greatly affects the working performance of machined parts [1]. In the traditional machining technology, there have been many studies on the influence of cutting parameters on surface quality and optimization of these parameters.

However, in recent years, hard machining technology has been developed and applied more and more widely to replace or support the grinding operation [2]. Direct cutting of hardened steel has become easier due to advances in materials technology and machine tools [3]. High cutting heat and cutting force are still the major problems in hard machining technology, so the use of cutting fluids is still the most effective solution [4].

Flood coolant is a traditional solution widely used in machining practice, but this technology has difficulty being applied for machining hard materials where the cutting process is not continuous like hard milling. Minimum quantity lubrication (MQL) technology has shown the suitability for hard milling [5].

Up to now, a lot of studies have been carried out to prove the effectiveness and optimize the technological parameters for MQL. In recent years, MQL technology parameters such as the type of cutting oil, oil flow rate, air pressure, nozzle position, spray angle, number of nozzles, and so on have been studied [6]. Some commonly used cutting oils include emulsion, vegetable oil, and ester. The researches on MQL using emulsion-based oil in machining are presented in the literature [7,8].

Among commonly used cutting oils, vegetable oils have suitable lubricating properties due to their higher molecular weight compared to conventional mineral oils, which helps vegetable oils have superior lubricating properties. In addition, these oils are derived from plants so they are naturally biodegradable, non-toxic to users and do not pollute the environment [9]. Therefore, vegetable oils are very suitable for MQL technology because they not only ensure proper lubrication and cooling properties but also maintain environmentally friendly properties, suitable for the trend of sustainable production today. Therefore, this research topic has gained a lot of attention from researchers and manufacturers.

Synthetic ether is also suitable for application in MQL technology due to its low viscosity, relatively high ignition temperature, thermal stability and low evaporation rate. Furthermore, viscosity can be controlled by mixing, thereby expanding application possibilities for each specific cutting condition. With slow evaporation properties, it contributes to the formation of an oil film in the cutting zone to help reduce friction [8]. The application of vegetable oil in MQL has shown positive effects in machining unheat-treated materials or alloys with low hardness [10], but the results are not really clear when applied in machining of hard materials, like hard milling [9].

Therefore, the additives of nanoparticles into vegetable oil to form nano cutting oil is becoming a new technological solution, which is easily deployed in production practices and still ensures the environmental friendliness of MQL. Each type of vegetable oil and nanoparticles has different lubrication and cooling properties, so it will create different lubrication and cooling mechanisms in the cutting zone [11,12]. Besides, the quality of machined surface is also greatly influenced by nano cutting oil; however, the studies on this direction are still limited. Accordingly, the authors aim to make an investiagtion of the influence of different nano cutting oils on surface roughness in hard milling of 60Si2Mn hardened steel (50-52 HRC) under minimum quantity lubrication.

2. METHODOLOGY

The set up of experimental devices is shown in Figure 1. The experiment trials were performed on Maximart VMC 85S CNC milling machine. APMT 1604 PDTR LT30 coated carbide inserts were used. The MQL system consists of NOGA MQL nozzle and a number of accompanying equipment including: air compressor, pressure regulating valve, air flow regulating valve, emulsion oil, soybean oil, rapeseed oil, Al_2O_3 nanoparticles. Mitutoyo's SJ-210 roughness meter is used to measure surface roughness values. Roughness values R_a and R_z are measured 3 times after each cut and the average value is taken. The experimental workpiece is tempered 60Si2Mn steel to achieve hardness HRC=50-52 with the chemical composition shown in table 1. The cutting mode is fixed at cutting speed V=110 m/min; depth of cut t=0.2 mm and feed rate S=0.12 mm/tooth. For each type of cutting oil investigated, the milling process was carried out until the tool reached the end of its durability, assessed through the backside wear standard of 0.3mm [3].

Table 1. Chemical composition in wt% of 60Si2Mn steel.

C	Si	Mn	P	S	Cr	Ni	Fe
0.56-0.64	1.50-2.00	0.60-0.90	≤0.035	≤0.035	0.35max	0.35max	Rest

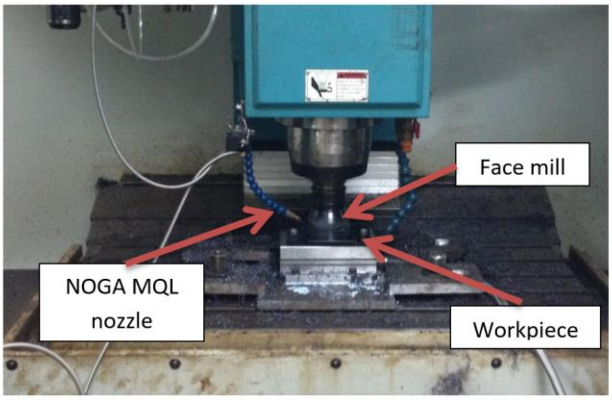


Fig. 1. The experimental set up.

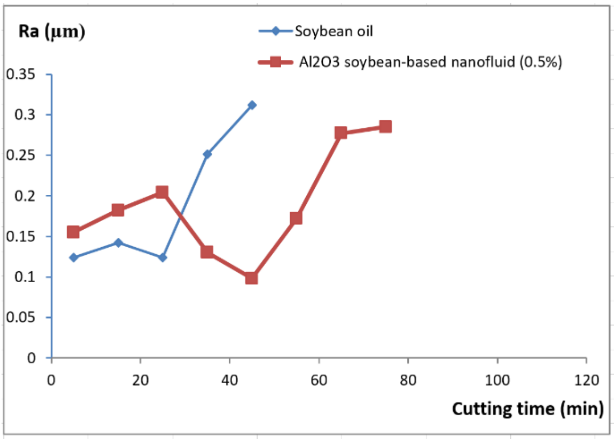
Fig. 2. The 3000868 - Ultrasons-HD (JP SELECTA in SPAIN) used for formulating Al_2O_3 nanofluids.

The preparation of Al_2O_3 nanofluids was done by using 3000868 - Ultrasons-HD (JP SELECTA in SPAIN) shown in Figure 2 for 50 minutes. The obtained nanofluids were immediately used for the experiments. The concentration of the nanofluids was calculated with the following equation and expressed in weight percent concentration (wt%).

$$\text{Weight percent concentration (wt\%)} = \frac{\text{Weight of solute (g)}}{\text{Weight of solution (g)}} \times 100\%$$

3. RESULTS AND DISCUSSION

Figure 3 presents the results of surface roughness R_a, R_z with cutting time in hard milling under MQL condition using pure soybean oil and soybean oil with Al_2O_3 nanoparticles of 0.5wt%. From Figure 3a, it can be seen that after the first 25 minutes of cutting, the surface roughness R_a in the case of using pure soybean oil is lower and shows stability compared to soybean oil having Al_2O_3 nanoparticles.



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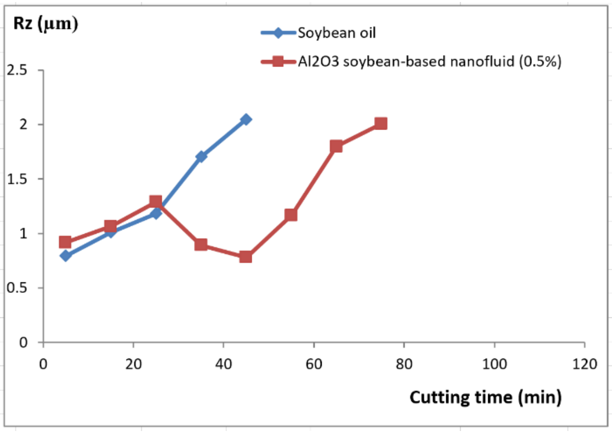

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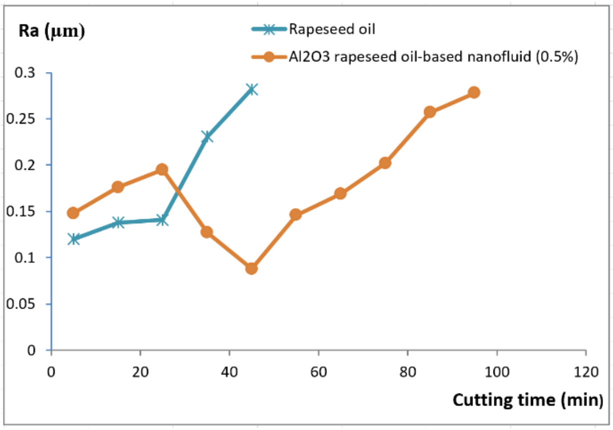
Fig. 3. Surface roughness R_a, R_z in MQL hard milling using pure soybean oil and Al_2O_3 soybean-based nanofluid (0.5%).

At the same time, in Figure 3b, it is seen that there is no significant difference in the values and changing trend of R_z. However, from the cutting time of 25 minutes to 45 minutes, a strong increasing trend was recorded with MQL using pure soybean oil, which is opposite to a strong decreasing trend in roughness values R_a, R_z. This can be explained that at the initial time, because the cutting edge was fresh, the flank wear land had not yet appeared, so the use of cutting oil with nanoparticles with high hardness and near-spherical morphology like Al_2O_3 nanoparticles is not effective but has a negative impact on surface quality.

The penetration process of Al_2O_3 nanoparticles into the contact area but the flank wear has not yet appeared and was not large enough, making the creation of the "ball roller" mechanism unfavorable and causing impedance and compression [13,14]. As a result, it led to uneven lubrication and caused the scratches on the machined surface, increasing surface roughness values. Interestingly, after the first 25 minutes, due to the large cutting force and cutting heat generated from the hard milling process, wear appeared on the cutting edge, especially on the flank face, so at this time, Al_2O_3 nanoparticles in the cutting oil created a "ball roller" lubrication mechanism, thereby significantly reducing friction in the cutting zone, which contributed to reduce cutting force, cutting heat and improving the machined surface quality [15].

In the case of using pure soybean oil, it shows that the roughness value increases rapidly and the tool life ended at 45 minutes. The reason lying in here is that because the good lubricating ability of soybean oil is rapidly degraded due to the impact of high heat generated in the cutting zone, which also caused burning of the cutting oil. The tool life is significantly improved and reaches 75 minutes in the case of MQL using Al_2O_3 soybean-based nanofluid, much higher than 45 minutes when using pure soybean oil.



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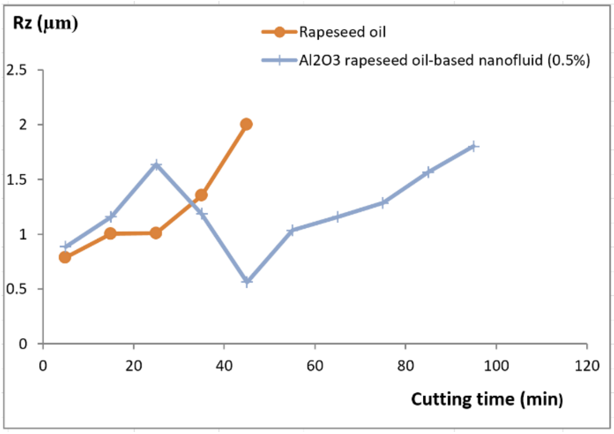

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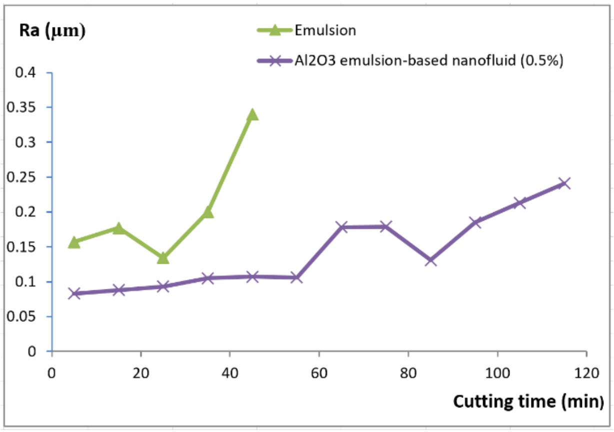
Fig. 4. Surface roughness R_a, R_z in MQL hard milling using rapeseed oil and Al_2O_3 rapeseed oil-based nanofluid (0.5%).

Figure 4 shows the surface roughness R_a, R_z with cutting time in hard milling with MQL using rapeseed oil with/without Al_2O_3 nanoparticles with 0.5wt%. It can be seen that after the first 25 minutes of cutting, the surface roughness R_a and R_z also have a similar trend as in the case of using soybean oil and then there is a decrease in value in the case of using rapeseed oil with Al_2O_3 nanoparticles. The difference here is that the tool life under MQL using Al_2O_3 rapeseed-based nanofluid increased to 95 minutes. This is because the viscosity of rapeseed oil is higher than that of soybean oil [16,17], so it has better lubricating capability.



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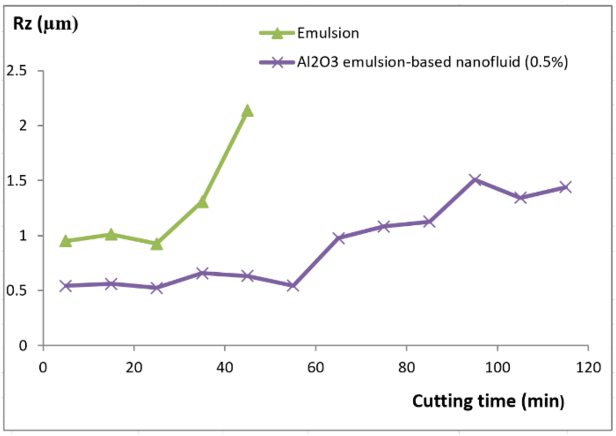

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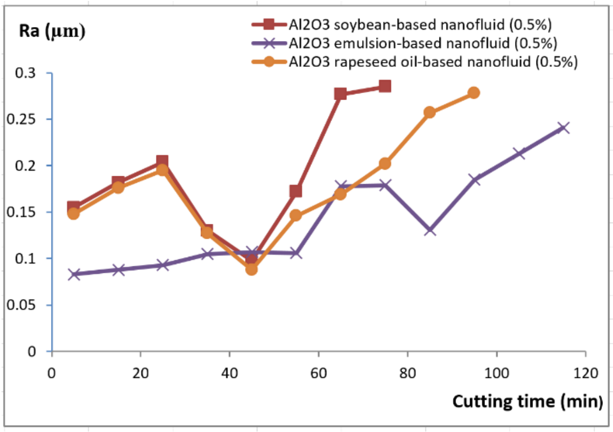
Fig. 5. Surface roughness R_a, R_z in MQL hard milling using pure emulsion and Al_2O_3 emulsion-based nanofluid (0.5%).

Surface roughness R_a, R_z with cutting time in hard milling with MQL using emulsion oil with/without Al_2O_3 nanoparticles with 0.5wt% was shown in Figure 5. In Figure 5a, it can be seen that after the first 25 minutes of cutting, the surface roughness R_a and R_z with MQL using emulsion with Al_2O_3 nanoparticles is lower than using emulsion oil without nanoparticles. After this period of time, the roughness values R_a and R_z increased rapidly in the case of using emulsion oil without nanoparticles and the tool life ended at 45 minutes. Under MQL using emulsion oil without nanoparticles, the roughness values R_a and R_z show stability and a slower growing rate compared to the case of using vegetable oils. This is because emulsion oils have better lubricating and especially cooling properties than vegetable oils. In addition, emulsion oil with a higher ignition temperature combined with the "ball roller" mechanism from Al_2O_3 nanoparticles has significantly improved the lubricating ability of this oil, so tool life improved and reached to 115 minutes.



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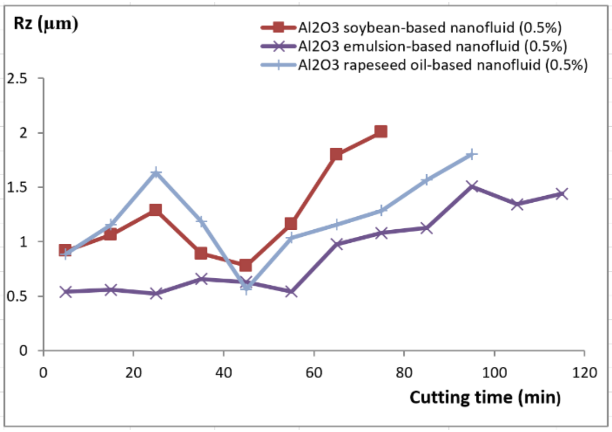

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Fig. 6. Surface roughness R_a, R_z in MQL hard milling using different Al_2O_3 nanofluids .

Figure 6 exhibits the surface roughness R_a, R_z with cutting time in hard milling under MQL environment using three different types of Al_2O_3 nano cutting oils with the same nano concentration of 0.5wt%. From the graph, it can be seen that two types of vegetable oils, including soybean oil and rapeseed oil, both show similar trends in surface roughness values, while emulsion oil gives the lowest and most stable surface roughness values. However, when considering the environmental friendliness factor, emulsion cutting oil is derived from mineral oil so it cannot biodegrade naturally like vegetable oil. Therefore, the results have great scientific and practical significance in proving the effectiveness and expanding the applicability of vegetable oils in the hard milling process.

4. CONCLUSION

In this article, MQL technique using different based cutting oils with/without Al_2O_3 nanoparticles was successfully applied for the hard milling process of 60Si2Mn steel (50-52 HRC). The effects of three types of cutting oils including emulsion, soybean oil and rapeseed oil on surface roughness R_a, R_z and tool life were studied and evaluated. Experimental results show that using Al_2O_3 nano cutting oil has improved machined surface quality and tool life due to the improvement in lubrication capability compared to the based cutting oil. Among the investigated cutting oils, it can be seen that Al_2O_3 emulsion-based nanofluid exhibited the best results in terms of surface roughness and tool life, followed by rapeseed oil and finally soybean oil. However, the extent of the applicability of vegetable oils for the hard milling process by adding Al_2O_3 nanoparticles has opened up sustainable technology solutions to meet the trend of environmentally friendly development. Furthermore, the machinability of coated carbide inserts is improved and their tool life is significantly increased with the superior lubrication performance of nano cutting oils in the cutting zone, thereby contributing to reduce cutting force and cutting temperature.

Acknowledgments

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