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Effectiveness of alumina nanofluid on slotting end milling performance of SKD 11 tool steel

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Abstract

SKD 11 tool steel is among the most popular metals in mold industries for making different kinds of cold work molds and dies with high accuracy and long service life. The demand for higher quality, lower manufacturing costs, particularly the environmentally friendly characteristics, have provided the stimuli for manufacturers and researchers to find alternative solutions. An excellent media is formed in the cutting zone by using MQL nanofluids in order to enhance the thermal conductivity and tribological characteristics; therefore, improving the machining performance. The formation of the lubricating film as well as the rolling action of nanoparticles in contact zones has gained much attention in the machining field. In this research work, the application of MQL Al_2O_3 nanofluids with vegetable oils and emulsion 5% is developed for slotting end milling of SKD 11 steel using normal HSS tool. The cutting forces, tool wear, tool life, and surface roughness are investigated to evaluate the effectiveness of MQL nanofluid on cutting performance. The experimental results reveal that the cutting forces and cutting temperature decrease and the surface quality and tool life enhance. Furthermore, the improvement of the thermal conductivity of nanofluids is proven when compared to pure fluids. Due to the rise of viscosity and thermal conductivity, the soybean oil-based nanofluid, which is almost inherently nontoxic, gives superior lubricating and cooling properties suitable for MQL application compared to emulsion-based nanofluids. The novel environmental friendly technology definitely brings out many technological and economic benefits in machining practice.

1. Introduction

SKD 11 tool steel has a high carbon and chromium (12%) with extremely high wear-resistant properties. It also possesses good hardenability (heat treatable to 60-62HRC), high oxidation resistance, good corrosion resistance after quenching and polishing, and small deformation after heat treatment. Therefore, it is widely used in industries, especially for different kinds of cold work molds and dies with high accuracy and long service life due to its toughness, strength, and hardness maintained up to high temperature [1, 2]. However, SKD 11 steel is grouped under difficult-to-cut materials because of their metallurgical and material characteristics, and it is extremely difficult and expensive to be machined using conventional

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machining processes. Grinding is the most popular conventional process for finishing SKD 11 hardened steel parts; however, low productivity, heat deterioration, and high cost are among the main drawbacks [1]. Along with the technological development, the utilization of various advanced machining processes such as hard machining and electric-discharge machining, etc. [1]. Along with the technological development as well as the utilization of various advanced machining processes such as hard machining, electric-discharge machining, and so on, thermally assisted machining techniques have been proposed and investigated by various researchers. P.K. Wright et al. [3] pointed out that the surface temperature has to be evaluated below its recrystallization temperature in order to reduce the shear strength in the cutting zone. The problems caused by low cutting speeds, feed rate, and heavy loads would be eliminated, and this makes the machining process easier. Laser assisted machining is an advanced strategy to increase the cutting performance or simply to enable a cutting process of difficult to cut materials like SKD 11 steel [4, 5].

However, the high additional price for laser head and its fixture is the main drawback for the applications, and this technique only uses for hardened steels. Thus, hard machining processes have been proven to be alternative solution for high metal removal rate, significant reduction of cutting fluids, and low machine tool investment. However, high cutting forces and enormous cutting temperature will be generated from hard machining, so the higher performance is required for cutting tools [6].

High surface hardness, low friction factor, and low thermal conductivity are some of the outstanding physical and mechanical properties of coated carbide inserts [7]. Moreover, compared to the ceramic and CBN tools, lower tool cost, as well as a wide range of hard machining application, is some of the advantages. C.Y. Wang et al. [8] studied wear and breakage of TiAlN- and TiSiN-coated carbide tools in high-speed end milling of hardened steel (SKD11/ 51 HRC, S136/ 62 HRC) to explore the tool failure mechanisms. The experimental results indicated that the flank wear, rack face wear, breakage, and micro-chipping were the dominant wear patterns. The breakage modes were coat peeling, chipping, and tip breakage. They also pointed out that the life of tools coated with TiSiN was approximately four times longer than that of the tools coated with TiAlN.

The failure of HSS tools is commonly caused by abrasion, thermal softening, plastic deformation, adhesion, and build-up edge [9]. When the temperature rises above 540°C, their hot hardness rapidly decreases [10]. For the cutting speeds that generate the amount of heat larger than this level, rapid abrasive wear and plastic deformation occur. Hence, the usable cutting speeds of HSS tools are limited to roughly 30-35 m/min for soft steels [10, 11]. Even before heat treatment, the hardness of SKD 11 steel is relatively high (about 200~255 HB), and together with high chromium, this makes it difficult for rough machining using normal cutting tools like HSS end mills under dry and flood conditions [12]. On the other hand, SKD 11 tool steel is among the most common steels for making a permanent mold. With partial faces, grooves, pockets, and so on, the end mills are commonly utilized for making mold cavity. Mold makers and researchers are paying attention to reduce or eliminate the use of cutting fluids in metal cutting, which gives out less negative effects on the environment and economic benefits. It has been reported that compared to dry and flood cutting, the application of minimal quantity lubrication (MQL) technique in end milling provides additional benefits, such as tool wear reduction, surface quality improvement, and tool life enhancement [13, 14]. In MQL, the lubricant is directly sprayed to the cutting zone in form of oil mist, which significantly improves the machining performance to reach higher cutting speeds and feed rates due to the formation of oil film for improving the lubricating condition [15-18]. Recently, nanoparticles (NPs) suspended in MQL fluids have created an attractive and innovative solution for finish machining, especially for difficult-to-cut materials [19, 25]. The oil film including Al_2O_3 nanoparticles is formed in the cutting zone and plays an important role in creating "roller effect". So the sliding friction is changed to rolling one in contact faces [19, 26-30]. However, the literature suggests that there are almost no studies to investigate the effectiveness of MQL nanofluid for rough end milling of steel before heat treatment. Therefore, in this paper, the authors are motivated to make the study of rough end milling of SKD 11 steel, grouped in difficult-to-cut materials, using the novel cooling and lubricating technique, MQL nanofluid. Furthermore, the normal HSS end mills are still utilized in rough milling with a speed of 30 m/min and bring out the technological and economic benefits. The surface quality of machined grooves is improved, and the cutting forces significantly reduce when the cutting speed is increased. The MQL nanofluid with soybean oil exhibits the better performance compared to that with emulsion 5%. In this study, the wear modes on HSS tool and the effect of MQL nanofluids (NFs) on tool life are also investigated. The experimental results show the very promising solutions for enhancing the machining performance of difficult-to-cut steels before heat treatment with the environmentally friendly technique as well as economical HSS tools, which help to reduce machining costs.

2. Materials and methods

2.1. Experimental design

The VMC 85S milling center is used to conduct the experiments. The SWT end mill cutters 10 × 10 × 22 × 72 HSS AL are used. The Kistler quartz three-component dynamometer (9257BA) connected to A/D DQA N16210 (made by National instruments, USA), linked to a computer having DASYlab 10.0 software, is used for directly measuring cutting forces during machining processes. KEYENCE VHX-6000 digital microscope is used to study the tool wear. To measure the surface roughness (R_a, R_z), the Mitutoyo SJ-210 (made by Japan) is used (Fig. 1). The DV2T™ viscometer (Brookfield Engineering Laboratories, Inc., USA, Fig. 2) and Linseis THB 500 (Germany, Fig. 3) are utilized for measuring the viscosity and thermal conductivity of nanofluids, respectively. The MQL system used in the present study includes NOGA nozzles, pressure stabilization device, soybean oil, and Al_2O_3 nanofluids 0.5%.

Fig. 1. The portable surface profilometer Mitutoyo SJ-210 used for the roughness measurement.

Fig. 2. DV2T™ viscometer for measuring the viscosity of nanofluids.

Fig. 3. Linseis THB 500 for measuring the thermal conductivity of nanofluids.

Alumina nanoparticles made by Soochow Hengqiu Graphene Technology Co., Ltd have the size of 30nm (average) (Fig. 4), and other technical specifications are given in Ref. [19].

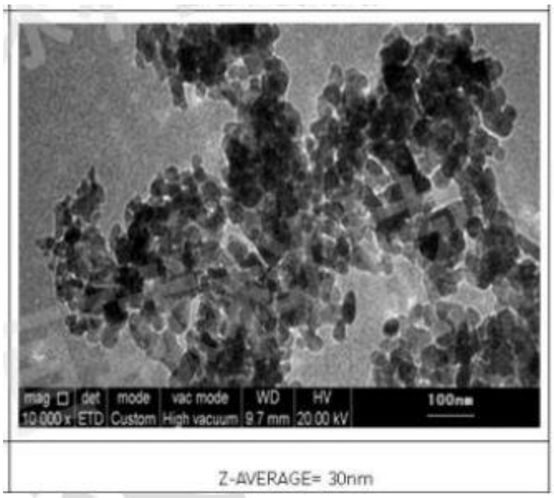

Fig. 4. SEM image of Al_2O_3 nanoparticles [13].

The 3000868 - Ultrasons-HD (JP SELECTA in SPAIN) (Fig. 5) is used to generate the ultrasonic vibration in order to create the homogenous mixture of nanofluids for 25 min [19]; otherwise they will sink to the bottom, cause the waste and bring out very little effectiveness. Cubic workpiece samples of SKD 11 tool steel (250-255 HB) with dimensions of 100 × 80 × 50 mm are utilized. Fig. 6 shows the experimental set-up.

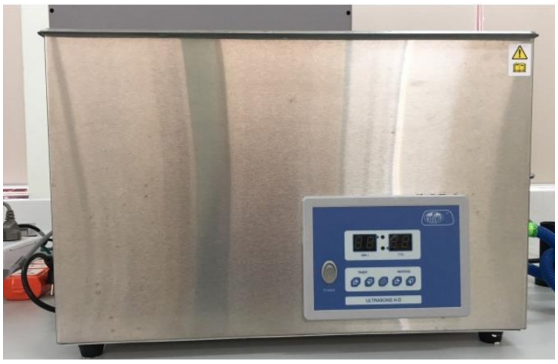

Fig. 5. The 3000868 - Ultrasons-HD for the preparation of nanofluids

2.2 Cutting condition

Table 1 provides the cutting conditons for the slot-milling test. Fig. 7 displays the cutting parameters of slot milling. The MQL nozzle is positioned to the flank face of end mills. The cutting speeds for emulsion nanofluid 0.5% vary from 18 to 30 m/min.

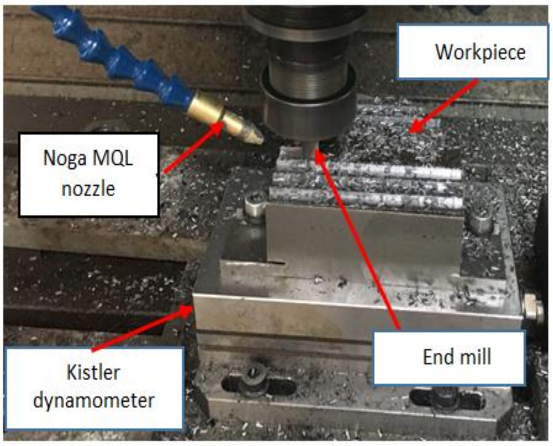

Fig. 6. Experimental set-up.

At the cutting speed of 30 m/min, the comparative experiment for Al_2O_3 nanofluid 0.5% of soybean oil is carried out to evaluate the effect of cutting fluids on the cooling and lubricating characteristics of cutting processes. For each trial, the cutting force components F_x, F_y, F_z are directly measured, and the surface roughness (R_a, R_z) is measured after every six trials.

Table 1. Cutting condition.

Cutting parameters	**Value**
Cutting speed (m/min)	18; 24; 30
Feed rate (f_z)	0.01 mm/tooth
Axial depth of cut (a_a)	3 mm
Radial depth of cut (a_r)	10 mm
Air pressure	6 bar
Flow rate	0.23-0.25 ml/min
Al_2O_3 nano concentration (wt.%)	0.5
Cutting fluid	Emulsion; soybean oil

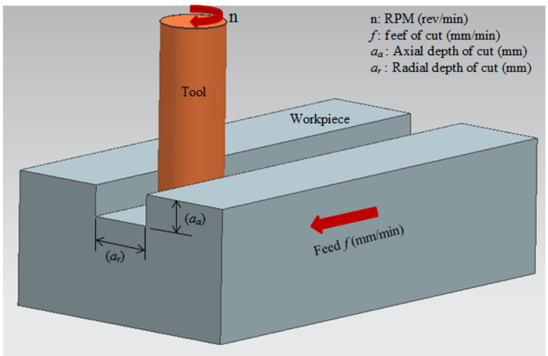

Fig. 7. Cutting parameters of slot milling.

3. Results and discussion

The relation of cutting speed and nano-cutting fluids to the cutting force components F_z, F_y, F_x is given by Figs. 8-10.

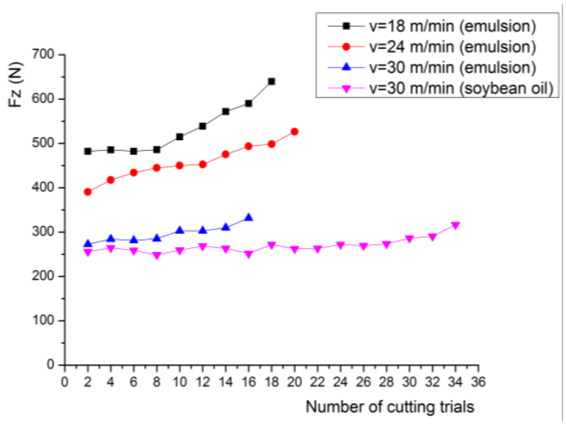

Fig. 8. The relation of cutting speeds and nanofluids to the cutting force F_z

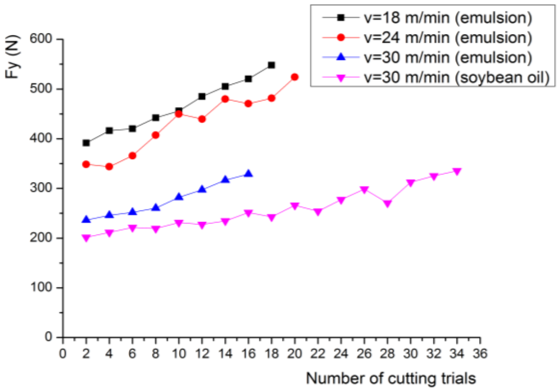

Fig. 9. The relation of cutting speeds and nanofluids to the cutting force F_y

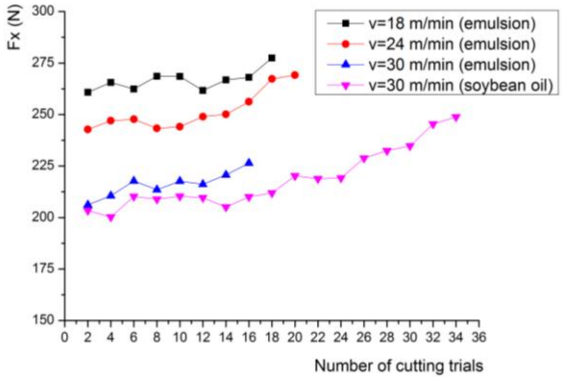

Fig. 10. The relation of cutting speeds and nanofluids to the cutting force F_x

The tool life of end mills is determined at the time when the severe wear period is observed from the cutting forces as well as surface roughness. The cutting process will be stopped to measure end mills. The critical value of the flank wear is 0.3 mm [6, 11]. The tool life is determined by:

$$T_c = t\,.n \text{ (min)}$$

where T_c is tool life (min), n is the number of vutinh cutting trials, and t is the cutting time for one trial. The tool life is given in Table 2. Fig. 11 illustrates the tool life, depending on the type of nanofluids and cutting speed.

Table 2. Tool life depending on nanofluid types and cutting speeds.

Cutting speed *v* (m/min)	Nanofluid with emulsion 5%			Nanofluid with soybean oil
	18	24	30	30
n	18	20	16	34
t (min)	4.5	3.5	2.5	2.5
T_c *(min)*	81	70	40	85

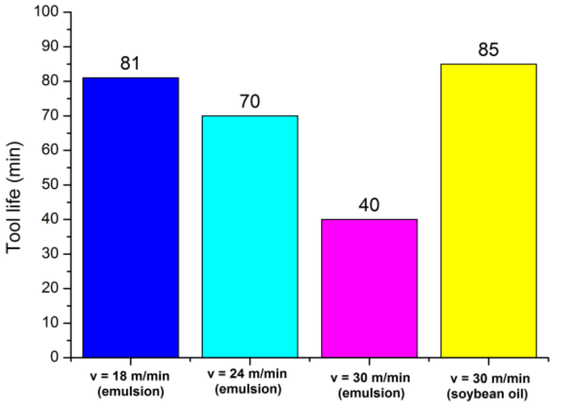

Fig. 11. The relation of cutting speeds and nano-cutting fluids to the tool life

The wear along the cutting edge, flank wear and notch wear are shown in Fig. 12. The uniform flank wear and notch wear related to cutting speeds and the types of nanofluids are shown in Figs. 12-15. Figs. 16-17 show the surface roughness R_a, R_z (cut-off length: 1.25mm) related to cutting speeds and the types of nanofluids.

Fig. 12. Notch wear and uniform flank wear (v=18 m/min, nanofluid with emulsion 5%)

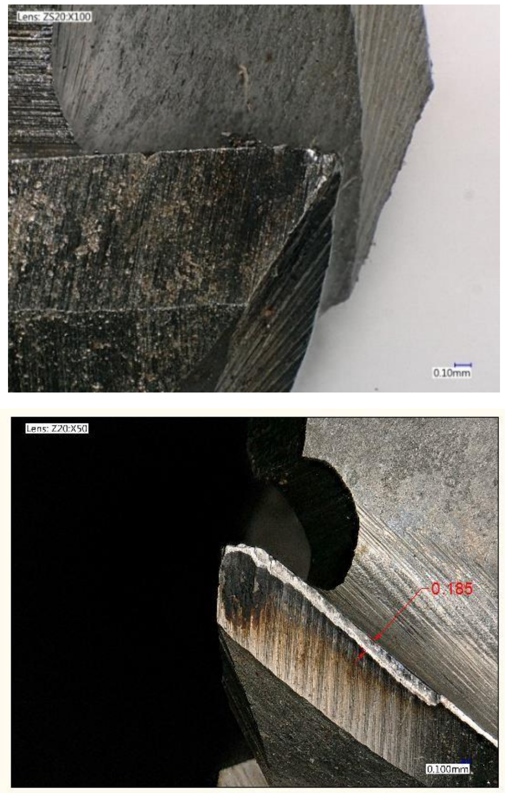

Fig. 13. Notch wear and uniform flank wear (v=24 m/min, nanofluid with emulsion 5%)

Fig. 14. Notch wear and uniform flank wear (v=30 m/min, nanofluid with emulsion 5%) at 40 minutes

Fig. 15. Notch wear and uniform flank wear (v=30 m/min, nanofluid with soybean oil) at 85 mintues

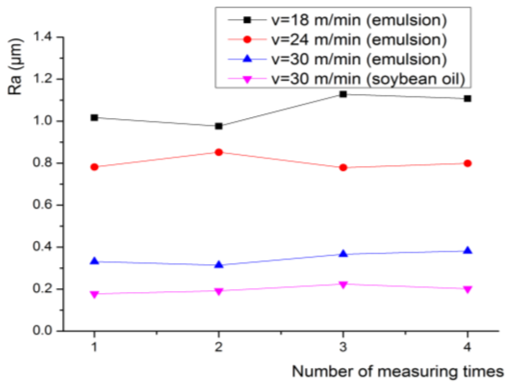

Fig. 16. Relation of surface roughness R_a with cutting speeds and nanofluid types

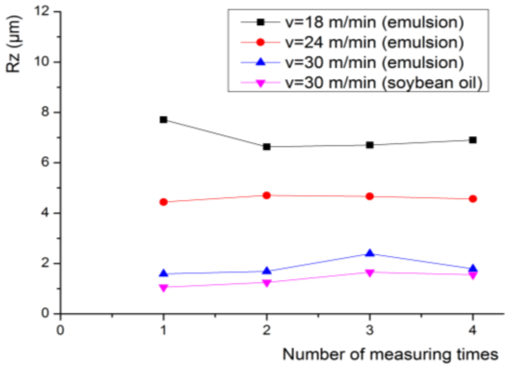

Fig. 17. Relation of surface roughness R_z with cutting speeds and nanofluid types

3.1. The effects of nanofluids on end milling

From the obtained results, the tribological characteristics of nanofluids are proven to improve by using Al_2O_3 nanomaterial. From Table 3, the viscosity of soybean oil-based NFs increases slightly due to the presence of nanoparticles. The thermal conductivity of NFs increases when compared to pure fluids. Hence, soybean oil-based NF can easily form the oil mist and gives out the superior lubricating effects on the cutting zone. In this case, the milling process is carried out on the no heat-treated steel with low hardness, so the cutting forces and heat generated from the cutting zone are much lower than hard milling. That is the reason why the soybean oil with higher viscosity is better in this situation. Furthermore, the nanoparticles suspended in oil as “the rollers” play an important role in cooling and lubricating effects [19 and 22]. In addition, slotting end milling is the semi-closed cutting, and the oil having higher viscosity brings out more effectively machining performance.

Table 3. The measured viscosities and thermal conductivity of the different types of fluids (at room temperature of 20°C)

No.	Type of fluid	Viscosity (cP)	Thermal conductivity (W/(m.K))
1	Emulsion 5%	-	0.339
2	Emulsion 5% with Al_2O_3 0.5 wt%	-	0.483
3	Soybean oil	130.0	0.194
4	Soybean oil with Al_2O_3 0.5 wt%	130.8	0.210

(Note: The viscosity of emulsion 5% and emulsion-based nanofluid is too small to measure)

3.2. Milling with emulsion-based nanofluid

From Figs. 8-10, the cutting force components F_x, F_y, F_z reduce when the cutting speed increases from 18 m/min to 30 m/min. The experiment results are suitable with the previous studies [19, 20].

The flank wear and radial wear are investigated and measured on the flank face of cutting edge (Fig. 12). The wear mode is uniform flank wear and the amount of tool wear rises (seen in Figs. 12-14) when increasing the cutting speeds. At the cutting speed of 18m/min, the wear mode is abrasive on flank face and tool notch, and the heat deterioration phenomena do not appear (Fig. 12). The occurrence of heat deterioration phenomena on the flank face can be easily observed at the cutting speed of 24 m/min, but the abrasive wear reduces (Fig. 13). The flank face is significantly deteriorated by the generated heat at v=30m/min. The wear land is mainly concentrated along the cutting edge of the end mill (Fig. 14). It can be explained that the generated heat goes up when increasing the cutting speed, and this amount of heat causes thermal softening. Accordingly, rapid abrasive wear and plastic deformation occur. At the low cutting speed of v=18 m/min, the amount of cutting temperature is low, so the end mill is not affected by thermal softening. Hence, the wear mode is mainly abrasive on the flank face [9, 10], which is appropriate to the investigation of cutting forces, as shown in Figs. 8-10. For the critical value of flank, flank wear is 0.3 mm, and the tool life strongly reduces from 81 min to 40 min with increasing the cutting speed. Furthermore, it can be explained that due to the low viscosity of emulsion-based nanofluids, they do not provide the proper lubrication for cutting zone. However, Figs. 16-17 show the relation of the surface roughness R_a, R_z to cutting speeds and the types of nanofluids, which reveals that the better surface quality is obtained by increasing the cutting speed. This result is suitable for the other previous studies [6, 19, 20]. Moreover, the values of surface roughness are low (R_a = 0.2– 0.4 µm; R_z = 1.0– 2.0 µm) due to the presence of NPs in MQL fluids. According to ISO 8688-2:1989 (en) [11], the recommended cutting speed of normal HSS mill is 30-35 m/min for soft steels, so the much lower cutting speed (about 14-18 m/min) is chosen for machining the steel with hardness of 200-250 HB [13]. Using MQL nanofluids, the normal HSS end mills can be effectively used for cutting the difficult-to-machine SKD 11 steel (hardness of 200-255 HB) at higher cutting speeds (18 m/min, 24 m/min and 30 m/min). Especially in the case of MQL soybean-based nanofluid, good tool life is reached even at v=30 m/min. Therefore, the experimental results exhibit the effectiveness of Al_2O_3 nanofluid in MQL end milling of the difficult-to-cut material. The formation of oil film (lubricating film) including Al_2O_3 nanoparticles in cutting zone plays such an important role in reducing the friction coefficient, which leads to decrease the cutting forces, cutting temperature, and improve the surface quality and tool life.

3.3. Milling with soybean oil-based nanofluid

The cutting forces in case of emulsion-based nanofluid are about 10% lower than those of soybean oil-based nanofluid. For the cutting speed of v=30m/min at 40 min, the wear mode on the flank face is abrasive, and the heat deterioration does not occur (as seen in Fig. 15). The life of tool, in this case, ends at 85 min (about 2.13 times longer than that with emulsion) with the flank wear of 0.140 mm (reducing about 45.5% compared to MQL with emulsion). The amount of notch wear with emulsion 5% at 40 min is also larger than that of soybean oil at 85 min (as seen in Figs.14 and 15). The reason is that the viscosity of soybean oil is higher than that of emulsion 5%, so the lubricating property is better. The NPs in the soybean oil help to convert the sliding friction to rolling friction. Accordingly, the friction coefficient in cutting zone reduces leading to the decreased cutting forces, cutting temperature, and tool wear, so the generated heat does not exceed the ignition temperature of soybean oil (about 360ºC). For that reason, the tool life significantly enhances. From the obtained results, the surface roughness (R_a, R_z) is lower than that of MQL nanofluids with emulsion due to the better lubricating property of soybean oil. From that, the MQL nanofluid with soybean oil performs better in slot milling of SKD 11 steel than that with emulsion 5%. The soybean oil is vegetable oil, which definitely reduces environmental loads and manufacturing cost in machining practice.

4. Conclusions

In this investigation, the effects of Al_2O_3 nanoparticles suspended in MQL fluids (emulsion 5% and soybean oil) on slot milling of SKD 11 steel using normal HSS tools are studied in terms of cutting forces, tool wear, tool life, and surface roughness. The nanolubricants are prepared by suspending Al_2O_3 nanoparticles (30 nm) of 0.5 wt% concentration in emulsion 5% and soybean oil. The Noga MQL system is adopted to directly supply the nanofluids in the form of oil mist to the cutting zone, which helps to reduce cutting fluid consumption. The cutting experiments were carried out on SKD 11 tool steel. The presence of Al_2O_3 nanoparticles in the tool-workpiece interfaces improves cutting performance of HSS mills due to the formation of an oil mist and rolling action of NPs. The reduction of cutting forces is observed when increasing the cutting speed with MQL emulsion-based nanofluids, and the surface roughness improves. The wear mode on the flank face is abrasive and uniform. The heat deterioration phenomena are also observed at higher cutting speed (v=24 - 30 m/min) and cause thermal softening. Hence, the tool life strongly reduces from 81 min at v=18m/min to 40 min at v=30m/min. The comparative experiment using MQL nanofluid with soybean oil is carried out with v=30m/min to improve the cutting performance due to the better lubricating property of vegetable oil. The results obtained exhibit that the reduction of flank wear as well as the better tool life and surface roughness could be achieved. Finally, it can be concluded that Al_2O_3 MQL nanofluids is an excellent alternative for the conventional cutting fluids to achieve the better machining ability of difficult-to-cut materials because of the improvement in thermal conductivity of NFs when compared to pure fluids. The most outstanding is that the normal HSS end mills with economical characteristic still present the effectiveness on cutting SKD 11 steel at appropriate cutting speed (v=30m/min), which ensures the productivity and reduces the manufacturing costs. Moreover, the MQL nanofluid with soybean oil gives superior lubricating performance due to the higher viscosity when compared to the emulsion 5%. Therefore, the vegetable oil should be recommended to the end milling of the steel before heat treatments, which is considered a step toward the sustainable machining. For future work, the research should be extended to investigate the parameters of MQL systems and nanofluids to improve this novel technique in order to use in machining practice.

Acknowledgements

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