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EFFICIENCY OF NANOPARTICLE COOLING AND LUBRICATION SYSTEMS IN MECHANICAL PROCESSING OF METALS

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Abstract
In this article we investigated the effectiveness of cooling and lubrication systems based on nano-hydroxide alloys in the process of friezing. The study was conducted on AISI 1045 steel and MQL systems using CuO, Al_2O_3 and ZnO nanoparticles were compared and analyzed. Results showed that by using nanoparticle coolants, surface slippage was improved by more than 60%, shear zone temperature decreased by 25–32%, and instrument peel reduced by about 50%. Notably, the 0.5% CuO nanofluide based on neem oil gave the most effective results. SEM and EDS analyses proved that nanoparticles can form a tribochemical layer and shield the metal surface. This approach is promising for production industries where high precision and thermal stability are required.

Keywords: Milling process, nanoparticle cooling and lubrication system, Minimum Quantity Lubrication (MQL), CuO, Al_2O_3, ZnO, soybean oil, surface smoothness, thermal stability, tool eating, shear forces, tribochemical layer, heat dissipation.

Introduction

In modern metalworking technologies, particularly in the frieze process, the control of critical factors such as heat generation, tool wear and surface quality remains one of the pressing challenges. One of the main causes of these problems is the occurrence of high temperatures in the shear zone and an increase in frictional forces that have direct influence on the surface morphology, tool service life, and shear forces [1].

Conventional cutting fluids (water, mineral oils) are environmentally friendly, and their cooling and lubrication efficiency is poor. Therefore, nanoparticle cooling and lubrication systems — especially liquids made based on nano-alkaline alloys — are widely used in Minimum Quantity Lubrication (MQL) environments. With these systems, the temperature in the freeze-drying process can be reduced by up to 25–35%, tool consumption by up to 30–50%, and shear forces by up to 15–30% [2], [3].

When nanoparticles such as Al_2O_3, CuO, ZnO are applied together with vegetable oils (e.g. neem, soy, palm), the thermal conductivity increases to 20–60% and the surface quality is maintained at 0.35–0.5µm ≈ Ra [4]. Also, bio-based nanofluides reduce the flanking size of the instrument by up to 0.18 mm compared to dry or conventional MQL [5]. These approaches have been successfully tested, especially in complex machining materials such as Inconel 625, AISI 1045, and Ti–6Al–4V [6].

However, most existing scientific work has focused on turning, drilling or micromilling processes and namely in frising the effects on thermal stability and surface quality of refrigeration and lubrication systems based on nano-hydroxide alloys is not adequately studied. Therefore, in this study heat dissipation, chip formation, surface finish condition and tool wear properties inherent to the freeze process against the background of nano lubrication systems are investigated in depth.

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Methodology

In this scientific study, experimental method was used to determine the relationship between thermal stability and surface quality of cooling and lubrication systems based on nano-alkaline alloys during the freeze-grinding process. AISI 1045 steel, which is used in a wide range of industries, was chosen as the material to be processed. The thermal and mechanical stability of this material, but the thermal deformation and abrasive properties that occur when exposed to high temperatures during machining make it a relevant object for further research. The friezing process was performed on a modern three-axis CNC machine. During the cutting process, carbide cutters with TiAlN coating were used, four-beam, carbide cutters with a diameter of 10 mm.

During the study, cutting speeds from 60 to 120 m/min were selected as processing parameters, feeding rates from 0.1 to 0.2 mm/thread and cutting depth from 0.5 to 1.0mm. The cooling and lubrication system was performed by the MQL (Minimum Quantity Lubrication) method. In this system, a coolant of 50 mL/hr was sprayed into the cutting zone during each test. This system has been selected to improve cooling efficiency and to reduce the negative environmental impact.

Various nano-alkaline alloy-based nanofluides have been prepared as cooling and lubricants. Herein, 0.5% CuO were added to neem oil, 0.75% Al_2O_3 to soybean oil and 1.0% ZnO nanoparticles to the trimethylpropane trioleate-based liquid. The nanoparticles were stirred for 30 min using an ultrasonic disperser to form a stable suspension. This process was performed in order to increase the temperature tolerance of liquids and to improve heat dissipation.

The experiments were mainly evaluated by identifying three main outcome indicators: surface smoothness, thermal stability (i.e., maximum temperature), and flank wear of the tool. Surface smoothness was measured using the Mitutoyo SJ-210 profilometer and the mean value was calculated by taking measurements from each sample at three points. The temperature in the freezing zone was directly measured using an infrared pyrometer, while the temperature value was recorded at the maximum point. Instrument eating was observed microscopically after a working length of 30 meters, and the flank eating values were clarified.

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Based on experimental data, shear forces were evaluated using empirical expression based on the following formula:

$$F_c = K_c * a_p * a_e * f_z * z$$

Here:

F_c — kesish kuchi,

K_c — force coefficient depending on the material,

a_p — depth of shear,

a_e — cutting width,

f_z — the amount of feeding,

z — Number of tool teeth.

Also, to evaluate the cooling efficiency, a special thermal efficiency formula was used:

$$n_T = (\frac{T_{dry} - T_{nano}}{T_{dry}}) * 100$$

here

n_T — cooling efficiency,

T_{dry} — maximum temperature in dry working,

T_{nano} — Maximum temperature in nanofluide processing.

With the help of this indicator, it was determined to what degree each coolant reduces heat.

The data obtained were statistically analyzed via ANOVA (dispersion analysis). Experiments were constructed based on the L9 design using the Taguchi method and the effect of each parameter on the variable results was assessed via the signal/noise coefficient. This approach made it possible to determine what advantage each of the parameters is, as well as to achieve optimal results.

Results

The results of the study also show that in the process of frising application of cooling and lubrication systems made on nano-hydroxide alloys has a significant positive influence on surface quality, thermal stability and instrument wear. Results obtained under dry processing, normal MQL and nanoparticle MQL conditions during all tests were cross-analyzed. Notably, a cooling system prepared on a neem oil basis and containing 0.5% CuO nanoparticles showed the most efficient results. In cases where this system was applied during the freeze process, surface smoothness was reduced to 0.48 micrometers, which represents an almost 65 percent improvement compared to 1.35 micrometers in dry processing. Soybean oil-based treatment with 0.75% Al_2O_3 resulted in a surface slippage of 0.52 micrometers and 0.57 micrometers in ZnO-based system. These figures prove that nanoparticles have a surface relief grinding effect by forming microprecipitation.

The maximum temperature occurring in the shear zone was also significantly varied with CuO nanofluuide compared to the temperature of 186°C recorded during dry processing when compared to 126°C with CuO nanoflucide. whereas with Al_2O_3 and ZnO nanofluides, maximum temperatures of 132°C and 138°C were observed, respectively. These results made it possible to determine the effectiveness of temperature reduction by the following formula:

$$n_T = (\frac{T_{dry} - T_{nano}}{T_{dry}}) * 100$$

Calculated on this basis, the heat reduction efficiency in the CuO-based system was 32.26%, 29.03% in Al_2O_3 and 25.81% in ZnO. These indicators indicate the high activity of the nanoparticles in the dissipation, absorption and dissipation of heat.

Flange wear, an important parameter that determines the service life of the instrument, was also significantly reduced. In dry machining, microscopic analysis revealed that flank wear was 0.28 mm, while with CuO this figure was reduced to 0.14 mm. A flank depletion of 0.17 mm was recorded in Al_2O_3 and 0.19 mm in ZnO. These results are the result of coolants creating a protective layer on the surface of the tool by reducing friction.

During the experiment, the shear forces that occur during the freezing process were also directly calculated. The empirical equation used in this is:

$$F_c = K_c * a_p * a_e * f_z * z$$

In Fig. 1045, the cutting force coefficient for AISI 1045 steel was taken as 2100 N/mm^2, with a cutting depth of 1 mm, a cutting width of 0.4 mm, a feeding amount of 0.15 mm, and a total cutting force of 504 N. We observed a 15 to 25 % reduction in these forces as a result of using nanoparticle MQL systems. This means, on the one hand, a reduced degree of cut resistance of the material and on

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the other hand, a decrease in friction due to the thin and slipping layers formed on the tool surface.

Analysis

The analysis of the impact of nanoparticle cooling and lubrication systems in the process of frising shows that such systems have a significant positive influence on key technological parameters such as temperature, surface deformation, tool wear and tear in the working zone. This effect is especially evident over different particle types due to the specific thermal conductivity, coating properties and surface interaction degrees.

When the maximum shear temperature detected in the dry freeze is T = 186°C, this value decreases to 126°C when treated with CuO particles. This means that the rate of heat decline is 32.26%. At the same time, Al_2O_3-based nanofluctuide showed a temperature of 132°C, which showed a thermal reduction efficiency of 29.03%. whereas in ZnO-based fluids the maximum temperature was 138°C with an efficiency of 25.81%. These values indicate that CuO nanoparticles are the most efficient component in dissipating heat and directing heat to the near-pherherical zone.

In terms of surface smoothness, the Ra value in dry working was kept around 1.35 µm, whereas with neem + CuO nanofluide this figure decreased to 0.48 µm. Values of Ra were 0.52 µm in the combination of soybean oil and Al_2O_3 and 0.57 µm in the combination of ZnO + TMP trioleate. This means an improvement in surface quality of more than 64% over Ra. Such a sharp difference means that it helps to facilitate the microheating and chatter effects that occur in the shear zone of the nanoparticles.

Analysis of the instrument flank feed (VB) shows that using CuO, the figure was 0.14 mm, 0.17 mm in Al_2O_3, and 0.19 mm in ZnO. In dry machining, flank feed reaches 0.28 mm. This gives an indication of the nanoparticles' activity in providing surface adhesion and maintaining a smooth contact surface. Also, SEM (Scanning Electron Microscopy) analyses revealed that on surfaces involved by CuO particles, tribochemical layers with a thickness of 20–25 nm are formed. These layers protect the surface from corrosion, oxidation and microscopic abrasion.

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The chip shape and disruption rate observed during the freeze-breaking process also point to the efficiency of the nanoparticles. In dry working, the chips were observed in a long, multi-twisted form, while when the CuO nanofluide was applied, the chips were in a short, spiral, and rapidly dissociating state. This proves that the nanoparticles cause a directed heat absorption within the shear zone and thereby local narrowing of the plasticity zone.
In nanoparticle cooling systems, this power is recorded at around 420–440 N, with a power drop of 12–18% being achieved. This serves to reduce cutting force and prevent tool overheating, especially during long cycle machining.
Unlike other analyses, this study also analyzed the level of residual density of the coolant on the processing surface. According to the results of Energy Dispersion Spectroscopy (EDS), the mass fraction of the element Cu on surfaces treated with CuO nanoparticles was detected in the range of 0.93–1.11%, which proves the capability of non-liquid nanoparticles to make chemical traces on the surface.

Conclusion

The experimental studies conducted have shown that the use of nanoparticle cooling and lubrication systems in the milling process has significant effects on processing quality, thermal control, and tool stability. In particular key parameters such as surface slippage, cutting zone temperature and tool wear are optimized via MQL (Minimum Quantity Lubrication) systems prepared on nano-alkaline alloys.
As a result of experiments, a 0.5% CuO nanoparticle cooling system based on neem oil gave the most efficient results. Compared to dry machining, surface slippage was improved by 64% (Ra = 0.48 µm), maximum shear temperature decreased by 32.26% (T = 126°C), and tool flange wear was reduced by 50% (VB = 0.14mm). Although results obtained with other nanofluids (Al_2O_3, ZnO) were also effective, CuO provided the most stable and all-round superior performance. The fact that through SEM and EDS analysis the nanoparticles formed tribochemical layers about 20–25 nm thick on the processing surface and also revealed a residual trace of the element Cu around 1.1%, it was proved that these particles also serve as a surface activating protective layer. These layers limit the

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direct contact between metal and metal, reducing the coefficient of friction by up to 60% ($\mu \approx 0.09–0.12$).

It was also observed that shear forces involving nanoparticles were also reduced by 15–18%, which resulted in reduced energy consumption, tool heating, and reduced vibrational forces. Those phenomena have occurred respectively of the nanocoatings that form in the frictional zone between the metal and the metal, the high thermal conductivity of the coolant, and the dispersion stability of the nanoparticles.

At the same time, improvements in surface relief and chip shape as well as a decrease in temperature gradient at the shear zone (45°C in dry working, 25°C in CuO) showed that the nanoparticles were active in heat conduction. This provides an important scientific basis for industrial sectors where high precision and thermal stability are required.

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