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Optimization of Minimum Quantity Lubrication with Al2O3 Nanoparticles for Improving Surface Roughness in the Hard Turning of SKD11 steel

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Abstract
This study investigates the application of Minimum Quantity Lubrication (MQL) with Al2O3 nanoparticles in hard turning of SKD11 steel to improve surface roughness, a key factor in machining hardened steel. Conventional flood cooling poses environmental and economic challenges, prompting the adoption of MQL as a more sustainable alternative. By integrating nano-sized particles into the cutting fluid, this research explores the effects of critical MQL parameters—namely, nanoparticle concentration, compressed air pressure, and lubricant flow rate—on surface quality. The experiments were designed using the Taguchi method, and the data was analyzed through Signal-to-Noise ratio (S/N) to identify the optimal conditions for minimizing surface roughness. Results reveal that nanoparticle concentration has the most significant impact, underscoring the potential of nanofluid-based MQL in enhancing machining performance in hard turning. These findings contribute valuable insights for optimizing MQL in sustainable manufacturing.

Keywords: Al2O3 Nanoparticles, MQL, Hard Turning, Taguchi Method, Surface Roughness, SKD 11 steel

Introduction

Hard turning, a process used to machine hardened steel components, presents unique challenges due to the high cutting forces and temperatures generated during machining [1], [2], [3]. Traditional flood cooling methods, often employed to mitigate these issues, are associated with high costs and environmental concerns. As an alternative, the use of Minimum Quantity Lubrication has gained traction in hard turning operations due to its ability to significantly reduce coolant consumption while still providing sufficient lubrication and cooling [4], [5], [6], [7], [8]. However, further optimization of the MQL process is necessary to enhance its effectiveness, particularly when machining hardened materials.

Recent advances in the field have demonstrated the potential of integrating nano-sized particles into MQL fluids to improve machining performance. Nanofluids, containing particles such as Al2O3, have been shown to enhance the thermal and lubricating properties of cutting fluids, leading to reduced cutting temperatures, lower friction, and improved surface quality [9], [10], [11], [12]. These characteristics are especially beneficial in hard turning, where maintaining a smooth surface finish is crucial for the functionality and durability of machined components.

SKD11 steel is a high-carbon, high-chromium tool steel widely used in manufacturing cutting tools, dies, and molds due to its excellent wear resistance, toughness, and hardness [13], [14]. It is typically heat-treated to achieve a hardness of over 60 HRC, making it ideal for applications requiring high strength and durability, such as stamping dies and plastic molding tools. SKD11 also offers good dimensional stability during heat treatment, allowing for precision machining. Its ability to maintain hardness at elevated temperatures makes it a preferred material for high-performance industrial applications.

This study focuses on investigating the effects of key MQL parameters—nano particle concentration, compressed air pressure, and lubricant flow rate—on the surface roughness during hard turning of SKD11 steel. Using Al2O3 nanoparticles as the additive, we aim to optimize the MQL process by employing the Taguchi method for experimental design and data analysis. Signal-to-noise ratio (S/N) is applied to identify the optimal conditions for achieving the best surface finish. The results of this research will contribute to a deeper understanding of the role that nanofluids play in enhancing machining quality in hard turning, offering insights for improved process control and efficiency.

Experiment setup

All experiments were conducted on an EMCO Maxxturn 45 CNC lathe, maintaining consistent machining parameters: a cutting speed of 80 m/min, a feed rate of 0.2 mm/rev, and a cutting depth of 0.2 mm. These conditions remained constant throughout the entire experimental process. The workpiece, made from SKD11 steel with an initial diameter of 35 mm, was heat-treated to a hardness of 50 HRC.

Nano-sized Al2O3 particles, with 99.9% purity and an average size of 20 nm, were incorporated into the cutting fluid, which was a ZP-600 oil emulsion mixed with water in a 1:20 ratio. A stirring device ensured the nanoparticles were evenly dispersed within the fluid to maintain a uniform mixture.

The cutting tool used was a CBN insert, known for its superior performance in hard turning. Surface roughness was measured using a Mitutoyo SJ-201 device, with each experiment repeated three times to enhance accuracy and minimize random errors.

Results and discussions

The experimental results reveal the surface roughness (Ra) measurements for hard turning SKD11 steel under varying conditions of Al2O3 nanoparticle concentration, flow rate (F), and pneumatic pressure (P). At 0% Al2O3 concentration, Ra values range from 1.108 to 1.118. When the concentration increases to 2%, Ra fluctuates between 0.997 and 1.143, indicating variability in surface quality. At 4% concentration, surface roughness improves, with Ra values between 0.972 and 1.094, demonstrating the positive effect of higher nanoparticle concentration.

Flow rate also impacts Ra, where higher flow rates generally result in lower surface roughness, leading to a smoother finish, especially when paired with higher Al2O3 concentrations. On the other hand, increasing pneumatic pressure tends to increase Ra, which means that higher pressure contributes to a rougher surface. Overall, the best surface roughness is achieved with higher concentrations of Al2O3 nanoparticles, lower pneumatic pressures, and higher flow rates.

Table 1: Experimental result

c (wt%)	f (ml/h)	p (KG/cm^2)	Ra (µm)	S/N
0	40	3	1.118	-0.96884
0	60	4	1.115	-0.9455
0	80	5	1.108	-0.8908
2	40	4	1.129	-1.05388
2	60	5	1.143	-1.16092
2	80	3	0.997	0.026097
4	40	5	1.094	-0.78035
4	60	3	0.981	0.16662
4	80	4	0.972	0.246675

The table (Table 2) presents the average S/N response values for surface roughness, with the highest delta values indicating the most influential factors. According to the analysis, the optimal parameter levels are the third level of nanoparticle concentration, the third level of fluid flow rate, and the first level of compressed air pressure, resulting in an optimal condition of (3-3-1). The ranking indicates that nanoparticle concentration has the greatest impact on surface roughness, followed by fluid flow rate, and lastly, compressed air pressure. This suggests that increasing the concentration of nanoparticles significantly enhances surface quality, while the effects of fluid flow rate and air pressure are comparatively less impactful.

Table 2: The average S/N response values for surface roughness

Level	C	F	P
1	-0.9350	-0.9344	-0.2587
2	-0.7296	-0.6466	-0.5842
3	-0.1224	-0.2060	-0.9440
Delta	0.8127	0.7283	0.6853
Rank	1	2	3

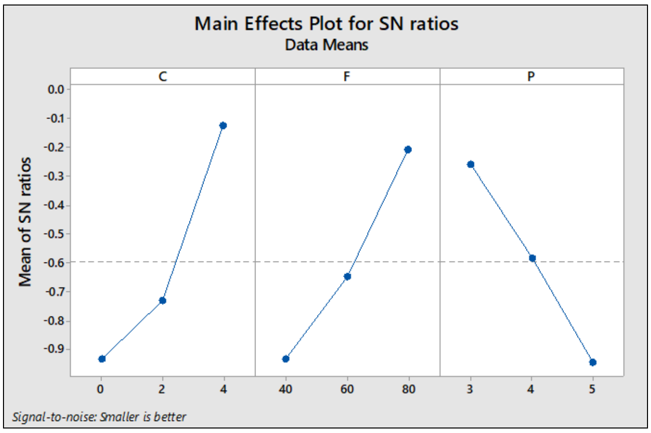

Fig 1: The S/N ratio plot

The Response S/N analysis, as illustrated in Fig 1, identifies the optimal Minimum Quantity Lubrication (MQL) conditions for achieving the best surface roughness. These conditions include a nanoparticle concentration of 4%, a high fluid flow rate of 80 ml/h, and an optimal pneumatic pressure of 3 KG/cm^2. This analysis indicates that a higher flow rate combined with the optimal air pressure and increased nanoparticle concentration significantly improves surface finish, making these conditions ideal for minimizing surface roughness in hard turning operations.

Conclusion

In this work, the study demonstrates that the application of Minimum Quantity Lubrication (MQL) with Al2O3 nanoparticles significantly improves surface roughness in the hard turning of SKD11 steel. The optimal conditions for achieving the best surface finish include a nanoparticle concentration of 4%, a high fluid flow rate of 80 ml/h, and a pneumatic pressure of 3 KG/cm^2. The analysis highlights that nanoparticle concentration is the most influential factor, followed by flow rate and air pressure. These findings provide valuable insights into optimizing MQL parameters for enhanced surface quality in precision machining.

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