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Optimizing the Minimum Quantity Lubrication Parameters Using Nano AL2O3 Particles in Hard Milling of SKD11 Alloy Steel

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Abstract
The successful implementation of Minimum Quantity Lubrication (MQL) using nano-sized particles in metal cutting processes, as an alternative to traditional coolant-based lubrication methods, has been observed. The careful selection of lubrication process parameters plays a pivotal role in enhancing machining quality. In this research, the impact of MQL parameters employing nano particles-comprising nano particle concentration, compressed air pressure, and cool lubricant flow rate on surface roughness has been thoroughly investigated. The nano particles introduced into the cutting fluid consist of Al2O3 nano particles. Experimental process design and data analysis were conducted using the Taguchi optimization method. Signal-to-noise ratio (S/N) and analysis of variance (ANOVA) were utilized to pinpoint the optimal MQL conditions for achieving the most favorable surface roughness. The results further underscore the significant influence of nano particle concentration on the surface roughness of the machining process.

Keywords: Hard Milling, Taguchi Method, Nanofluid MQL, Roughness, SKD 11

Introduction

In the process of metal cutting, the coolant serves three primary functions: heat transmission to mitigate cutting heat, lubrication to minimize friction and surface scratching, and the removal of metal chips from the cutting zone to prevent chip accumulation [1, 2]. In conventional machining, a substantial amount of coolant is introduced into the cutting area through the flood cooling method. However, this traditional cooling and lubrication process has notable drawbacks, including increased costs associated with coolant usage, cleaning, and significant environmental and health hazards [3, 4].

Presently, there are successful alternatives proposed and implemented to replace traditional methods, such as dry machining and Minimum Quantity Lubrication machining. Dry machining relies on advancements in materials science, where cutting tool materials can withstand high temperatures and exhibit good wear resistance. This approach completely eliminates the use of cutting fluid, making it an environmentally friendly machining method. Additionally, it offers cost savings by reducing expenses related to cooling and cleaning [5, 6]. Nevertheless, drawbacks include a reduced tool lifespan and higher surface roughness due to elevated cutting temperatures [7, 8].

A recent solution that combines the benefits of both traditional and dry machining is Minimum Quantity Lubrication with coolant spray. MQL machining involves the use of a minimal amount of cutting fluid (typically less than 50ml/h) [9, 10]. The effectiveness of MQL in improving surface finish, increasing tool durability, reducing cutting heat, and lowering machining costs has been demonstrated in various studies [11, 12, 13, 14].

A current trend involves the incorporation of nanosized solid particles into the cutting fluid in MQL machining. This method proves highly effective in machining by enhancing surface finish, reducing cutting forces and temperatures, extending tool life, and minimizing tool wear [15, 16, 17].

In the realm of machining, the assessment of product quality often revolves around the critical parameter of surface roughness. The intricacies of the lubrication system play a pivotal role in determining the surface roughness, making it imperative to carefully choose suitable cutting and cooling conditions to minimize roughness. Understanding the profound effects of machining parameters and cooling conditions on surface roughness is a significant concern, aiming to achieve the optimum surface finish.

This study employs the Taguchi optimization method to scrutinize the impact of parameters in MQL conditions that incorporate nano particles. These parameters encompass nano particle concentration, compressed air pressure, and fluid flow rate—all crucial factors influencing surface roughness. The identification of optimal MQL conditions for minimizing roughness relies on the signal-to-noise ratio (S/N). Furthermore, through variance analysis, the study pinpoints the MQL parameters exerting the most substantial influence on surface roughness.

Experiment Setup

In this research, we employed the Taguchi experimental design to structure our experiments. We focused on three crucial parameters associated with Minimum Quantity Lubrication incorporating nano particles - specifically, nano particle concentration, compressed air pressure, and fluid flow rate. Each of these parameters was examined across three different levels. Hence, the L9 orthogonal array from Taguchi was selected as a suitable arrangement for conducting the experiments. For a detailed overview of the MQL parameters and their corresponding levels in the study, please refer to Table 1.

Table 1: Input parameters

Parameters	Levels		
	1	2	3
Nano particle concentration *c* (w%)	0	2	4
Fluid flow rate *f* (ml/h)	50	75	100
Compressed air pressure *p* (KG/cm^2)	3	4	5

All experiments were carried out on a CNC milling center, employing consistent milling parameters including a cutting speed of 70m/minute, a feed rate of 0.01mm/tooth, and a cutting depth of 0.2mm [8]. These milling conditions were kept constant throughout the entire experimental process. The workpiece, made of SKD 11 steel, measured 120 × 80 × 50mm and underwent heat treatment to achieve a hardness of 50 HRC.

Nano-sized Al2O3 particles, with a purity of 99.9% and a particle size of 20nm, were introduced into the emulsion cutting fluid. The cutting fluid used was an emulsion of ZP-600 oil mixed with water in a 1:20 ratio. A stirring device was utilized to ensure a thorough and uniform mixture of the nano particles in the cutting fluid.

For the cutting tool, a TiAlN-coated φ10 end mill was employed. Surface roughness measurements were conducted using a Mitutoyo SJ-201 device. To enhance accuracy and reliability, each experiment was replicated three times to account for potential random errors.

Results and Discussions

The outcomes of the hard-milling process on SKD 11 steel, along with the corresponding Signal-to-Noise (S/N) ratios, are outlined in Table 2. The input parameters for the MQL condition encompass the nano particle concentration in the cutting fluid (c), fluid flow rate (f), and compressed air pressure (p). The primary objective of this study is to optimize the MQL condition parameters with the goal of minimizing surface roughness (Ra). Thus, when employing the Taguchi method, the S/N ratio with the criterion "the smaller, the better" was selected and defined in the equation (1) as follows:

$$S/_N = -10log\frac{1}{n}(\sum_{i=1}^{n} y_i^2) \qquad (1)$$

Where: yi represents the observed data, and n is the number of repeated experiments.

As per Table 2, the surface roughness values fall within the range of 0.162 μm to 0.338 μm. The highest roughness value, 0.338 μm, is observed in Experiment 1, while the lowest, 0.162 μm, is recorded in Experiment 9. The Minitab V17 software was utilized to generate results for the S/N ratio and conduct variance analysis.

Table 3 displays the average S/N response values for surface roughness. Following the analysis, the top-ranking for each parameter level is the third level of nano particle concentration, the third level of fluid flow rate, and the first level of compressed air pressure. Consequently, the optimal experimental condition is identified as (3-3-1). This ranking signifies that nano particle concentration has the most significant impact on surface roughness, followed by compressed air pressure.

Table 2: Experimental result

TT	c (wt%)	f (ml/h)	p (KG/cm^2)	Ra (μm)	S/N
1	0	50	3	0.338	9.421666
2	0	75	4	0.335	9.499104
3	0	100	5	0.328	9.682523
4	2	50	4	0.319	9.924186
5	2	75	5	0.333	9.551115
6	2	100	3	0.187	14.56317
7	4	50	5	0.284	10.93363
8	4	75	3	0.171	15.34008
9	4	100	4	0.162	15.8097

Table 3: Response for the S/N ratio

Level	c	f	p
1	9.534	10.093	**13.108**
2	11.346	11.463	11.744
3	**14.028**	**13.352**	10.056
Delta	4.493	3.259	3.053
Rank	1	2	3

The Response S/N analysis is shown in Fig 1. Based on The Response S/N analysis, the optimal MQL conditions for achieving the best surface roughness include a nano particle concentration of 4%, a fluid flow rate of 100 ml/h, and a pressure of 3 KG/cm^2.

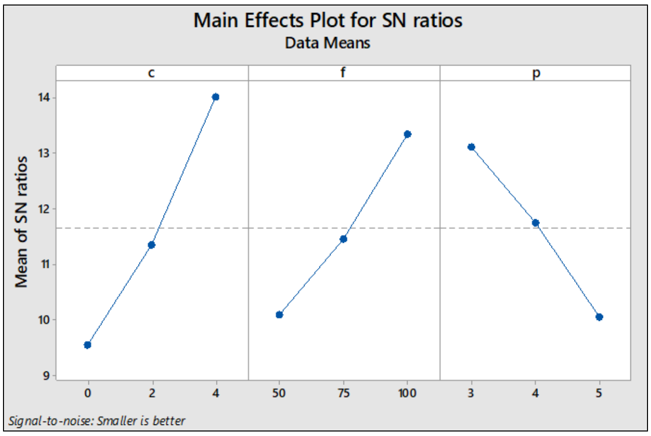

Fig 1: The S/N ratio plot

Bảng 4: The ANOVA table

Source	DF	Adj-SS	Adj-MS	F-Value	P-Value	C%
c	2	0.024776	0.012388	203.08	0.005	52.65
f	2	0.011816	0.005908	96.85	0.010	25.11
p	2	0.010338	0.005169	84.74	0.012	21.97
Error	2	0.000122	0.000061	-	-	-
Total	8	0.047052	-	-	-	-
R-sq = 99.74%						

Table 4 summarizes the results of the variance analysis. According to the ANOVA table, the concentration of nano particles in the solution emerges as the most influential factor, followed by flow rate, contributing 52.65% and 25.11%, respectively, to the overall impact. Compressed air pressure is identified as a significant factor influencing surface roughness, contributing 21.97%. P-values below 0.05 for the input factors indicate their statistically significant influence. With an R-Sq of 99.74%, 99.74% of the variation in surface roughness is explained by the input factors. The concentration of nano particles stands out as having the most substantial impact on surface roughness, suggesting that adding nano particles to the cutting fluid effectively reduces machining roughness.

For optimal surface roughness, the applied Minimum Quantity Lubrication conditions involve a higher concentration, increased liquid flow rate, and reduced compressed air pressure. Notably, incorporating a larger quantity of nano particles into the cutting fluid improves the thermal and lubrication properties of the fluid. In essence, the exceptional effectiveness of adding nano particles to the cutting fluid is demonstrated when compared to conventional MQL. A higher liquid flow rate delivers a more substantial amount of cutting fluid to the cutting zone, resulting in enhanced lubrication and cooling efficiency. Appropriate compressed air pressure is crucial in the cooling lubrication process, as excessive pressure can push out a significant amount of cutting fluid from the contact area between the cutting tool and the workpiece surface, diminishing lubrication and cooling efficiency.

The optimal MQL conditions include a nano particle concentration of 4w%, a liquid flow rate of 100ml/h, and a pressure of 3 KG/cm2. However, these specific processing conditions are not reflected in Table 2, indicating the need for a verification experiment to validate the reliability of the study. The verification experiment is conducted with the aforementioned optimal MQL conditions, following a similar cutting regime as the entire experiment.

Table 5 provides a comparative analysis of surface roughness values between two experiments: Experiment 9 (featuring the lowest surface roughness value in Table 2) and the verification experiment. Variables such as cutting speed (v), feed rate (fr), cutting depth (d), and MQL parameters (c, f, and p) are considered in Table 5.

Table 5: comparing surface roughness values

Test	Cutting parameters			MQL condition			Roughness
	v m/min	*fr* mm/tooth	*d* mm	*c* w%	*f* ml/h	*p* KG/cm^2	*Ra* µm
No. 9	70	0,01	0,2	4	100	4	0.162
The verification test	70	0,01	0,2	4	100	3	0,156

Table 5 clearly shows that the surface roughness obtained in the verification experiment is 0,156 µm, demonstrating a reduction compared to the surface roughness value of Experiment 9. This provides strong evidence for the credibility and reliability of the study's findings.

Conclusion

In this research, the Taguchi method was applied to optimize Minimum Quantity Lubrication (MQL) conditions using Al2O3 nano particles in order to minimize surface roughness during the hard milling of SKD 11 steel. Key findings can be summarized as follows:

The optimal MQL conditions were identified as a 4% nano particle concentration, a liquid flow rate of 100 ml/h, and a compressed air pressure of 3 KG/cm2, resulting in the lowest achievable surface roughness.

Nano particle concentration emerged as the most significant factor influencing surface roughness, contributing 52.65% to the overall impact. Liquid flow rate and compressed air pressure followed closely, contributing 25.11% and 21.97%, respectively, to the cumulative effect on surface roughness.

The study provided clear evidence of the efficacy of incorporating nano particles into the cutting fluid, with a higher concentration of nano particles proving optimal for minimizing surface roughness.

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