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Investigation on the Effect of Process Parameters on Surface Roughness in Hard Milling of SKD61 Steel using Taguchi Method and ANOVA

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Abstract
Surface roughness is a key indicator of the quality in metal cutting processes. This study utilizes the Taguchi method to determine the optimal machining parameters for minimizing surface roughness when machining hard steel SKD61. The investigation focuses on three primary parameters: Cutting speed, cutting depth, and feed rate, each of which is tested at three levels: Low, medium, and high. An L9 orthogonal array is used for the experimental design. ANOVA reveal that the feed rate is the most significant factor affecting surface roughness, followed by cutting depth and cutting speed. Based on the results, an optimal set of machining parameters is recommended to achieve the lowest surface roughness.

Keywords: Hard Milling, SKD61 Alloy Steel, Taguchi Method, Surface Roughness, ANOVA

Introduction
The SKD61 steel chosen for this study is a widely used workpiece material, particularly valued in manufacturing for high-pressure die-casting, extrusion molding, cutting blades, and hot dies due to its excellent toughness and abrasion resistance [1, 2, 3].
Hard machining has become extensively utilized in mechanical processing due to its numerous advantages. These benefits include improved geometric accuracy, superior surface quality of finished products, reduced labor costs, minimized burr formation, more efficient chip disposal, increased stability, simplified tooling, and greater flexibility in process design [4, 5, 6, 7]. Today, hard machining is commonly employed in various production methods such as turning, milling, and drilling [8, 9, 10, 11, 12].
Surface roughness is a critical measure for evaluating the quality of mechanical products [13]. Several factors influence surface roughness, including cutting tool properties (such as material, shape, run-out error, and nose radius), workpiece characteristics (such as diameter, hardness, and length), cutting phenomena (including acceleration, vibrations, chip formation, friction in the cutting zone, and cutting force variation), and machining parameters (such as process kinematics, cooling fluid, step over, tool angle, depth-of-cut, feed rate, and cutting speed) [10, 14, 15, 16, 17]. Selecting appropriate cutting parameters tailored to the material of the workpieces is a pivotal step in ensuring manufacturing quality in any machining operation.
The Taguchi technique, which employs designed experiments, is widely used for optimizing cutting parameters and predicting surface roughness. Extensive research has been conducted to explore the impact of cutting parameters on surface roughness, leveraging the Taguchi method to derive insights and optimizations [18, 19, 20, 21].
In the present study, the Taguchi method and ANOVA were applied to optimize cutting parameters for surface roughness in the hard milling of SKD61 steel. The optimal cutting parameters, including cutting speed, feed rate, and depth of cut, were identified to achieve improved surface roughness.

Experimental procedure
In this study, a sophisticated Design of Experiments (DOE) methodology was employed to pinpoint the key variables influencing surface roughness. By leveraging the Taguchi method and Analysis of Variance (ANOVA), the cutting parameters were meticulously optimized to achieve minimal surface roughness. The experimental framework was structured using the L9 orthogonal array, a hallmark of Taguchi's experimental design technique. The primary factors examined included cutting speed, feed rate, and depth of cut, each scrutinized across three distinct levels: Low, medium, and high.
The experiments were conducted using a DMU50 5-axis milling machine. The workpiece material was SKD61 steel,

measuring 50 mm in width, 100 mm in length, and 100 mm in height, with a hardness rating of 50 HRC. TiAlN-coated end mill tools with a diameter of 10 mm (ø10) were employed for the machining process. The machining process was performed without the use of coolant, adhering to dry machining principles. Surface roughness measurements were taken at three different positions on the workpiece and averaged to ensure accurate analysis.

Results and discussions

The experimental results are detailed in Table 1, with surface roughness values spanning from 0.165 µm (Experiment 8) to 0.239µm (Experiment 5). Statistical analysis was conducted using Minitab V17 software. Table 1 also includes the Signal-to-Noise (S/N) ratio values, providing a comprehensive overview of the data.

Table 1: Table of experiment results

S. No	*v* (m/min)	*d* (mm)	*f* (mm/tooth)	Ra (µm)	S/N
1	60	0.2	0.01	0.176	15.08975
2	60	0.4	0.02	0.202	13.89297
3	60	0.6	0.03	0.229	12.80329
4	80	0.2	0.02	0.189	14.47076
5	80	0.4	0.03	0.239	12.43204
6	80	0.6	0.01	0.177	15.04053
7	100	0.2	0.03	0.208	13.63873
8	100	0.4	0.01	0.165	15.65032
9	100	0.6	0.02	0.197	14.11068

The response values for each level of the input factors are summarized in Table 2. The variation between the minimum and maximum values for each level of the input factors illustrates their impact on the output response, specifically surface roughness.

Notably, the difference in levels for feed rate (Delta = 2.30) is the most pronounced, signifying that feed rate is the most influential factor on surface roughness.

This is followed in significance by cutting speed and depth of cut.

Table 2: Response table for signal to noise ratios

Level	*v*	*d*	*f*
1	13.93	14.40	15.26
2	13.98	13.99	14.16
3	14.47	13.98	12.96
Delta	0.54	0.41	2.30
Rank	2	3	1

The Response S/N analysis, depicted in Fig 1, reveals that the optimal conditions for achieving the lowest surface roughness are the highest cutting speed, the lowest depth of cut, and the lowest feed rate.

The analysis highlights that the difference between the maximum and minimum points of the feed rate is the largest, underscoring that the feed rate exerts the greatest influence on surface roughness.

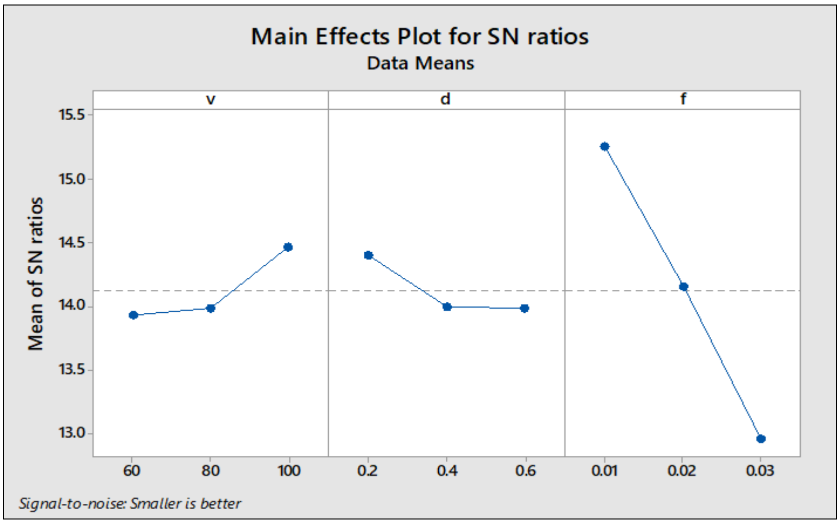

Fig 1: The S/N ratio plot for Ra

Table 3: Analysis of Variance table

Source	DF	Adj-SS	Adj-MS	F-Value	P-Value	C%
v	2	0.000289	0.000144	1.75	0.363	5.95
d	2	0.000222	0.000111	1.35	0.426	4.57
f	2	0.004179	0.002089	25.38	0.038	86.09
Error	2	0.000165	0.000082	-	-	-
Total	8	0.004854	-	-	-	-
R-sq = 96.61%						

The analysis of variance results are detailed in Table 3. This analysis confirms that feed rate is the most significant factor affecting machining roughness, followed by cutting speed and depth of cut. Feed rate accounts for 86.09% of the total influence. All parameter p-values are below 0.05, indicating that the effects of the selected parameters are statistically significant. Additionally, Table 3 provides the coefficient of determination (R-squared) values. With an R^2 value of 96.61%, it is evident that 96.61% of the variation in surface roughness can be attributed to the input factors selected in this study.

A mathematical regression model for predicting surface roughness was developed using Minitab software. The model is expressed as follows:

$$Ra = 0.1600 - 0.000308*v + 0.0250*d + 2.633*f \quad (1)$$

Where: Ra is the surface roughness, v is the cutting speed, d is the depth of cut, f is the feed rate.

Conclusion

This study aimed to optimize cutting parameters to minimize surface roughness in the hard milling of SKD61 alloy steel under dry cutting conditions. The research focused on three key parameters: Cutting speed, feed rate, and depth of cut. Analysis using the Taguchi method and ANOVA yielded the following conclusions:

- The optimal machining conditions for achieving the lowest surface roughness are the highest cutting speed, the lowest feed rate, and the minimum depth of cut.
- Feed rate has the most significant impact on surface roughness, followed by cutting speed and depth of cut.
- An effective mathematical regression model was established to predict surface roughness with high accuracy.

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