OPTIMIZING SKD-61 STEEL MACHINING FOR MARINE COMPONENT MANUFACTURE: A GREY-TAGUCHI STUDY ON NANOFLUID MINIMUM QUANTITY LUBRICATION

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ABSTRACT

"SKD-61 steel finds extensive application in various sectors, including the marine industry where materials must withstand harsh aquatic conditions. In this study, we employ the Grey-Taguchi approach to optimize surface roughness (Ra), cutting force (Fc), and material removal rate (MRR) when hard-milling SKD-61 steel in pure minimum quantity lubrication (MQL) and nanofluid MQL environments, aligning with the demands of marine engineering. The orthogonal array method generates a set of experiments based on four input parameters: cutting speed, depth of cut, feed per tooth, and cutting condition, which are essential factors in marine component manufacturing. Our approach combines Grey relational analysis (GRA) with the Taguchi method to enhance multi-objective outcomes in machining. The results of this marine-focused study reveal that the lowest surface roughness, cutting force, and highest material removal rates are attained when the cutting conditions align with the principles of nanofluid MQL at a cutting velocity of 80 m/min, a depth of cut of 0.2 mm, and a feed per tooth of 0.01 mm/tooth."

***Keywords**: hard milling, nanofluid MQL, optimization machining parameters; Grey relational analysis; Taguchi*

I. INTRODUCTION

The high toughness, wear resistance, and strength of SKD-61 steel make it a preferred material in the industrial sector, and it is especially crucial in the maritime industry, where materials must endure harsh marine conditions. Nevertheless, machining this steel‘s extreme hardness presents major difficulties, including significant cutting pressures, slow material removal rates, and subpar surface polish [1]. These difficulties may cause severe issues in various industrial applications, including the maritime sector, where the durability of components is paramount. There is a rising need to optimize the machining parameters to improve the machining performance of SKD-61 steel in maritime applications [2].

Researchers have investigated several machining procedures to increase the hard milling performance of SKD-61 steel, aligning with the maritime industry‘s stringent requirements. Among these techniques, Minimum quantity lubrication (MQL) and nanofluid MQL have received much attention [3, 4]. MQL is a machining method that employs little lubricant to minimize friction and heat during machining, resulting in less tool wear, better surface quality, and improved machining performance suitable for maritime equipment [5]. Nanofluid MQL, on the other hand, blends MQL with nanoparticles to enhance lubrication and cooling during milling, contributing to better performance in maritime component fabrication [6]. Nanofluid MQL has been shown to improve surface quality, minimize cutting forces, and boost material removal rates in machining processes, all essential in the marine sector [7].

Researchers employed a variety of optimization approaches, including the Taguchi method, response surface methodology (RSM), and artificial neural networks (ANN), to obtain optimal machining performance in SKD-61 steel. The Taguchi method is a popular optimization methodology for reducing the tests necessary to discover the best combination of machining parameters [8]. The Grey-Taguchi approach is a Taguchi method modification that employs grey relational analysis to determine the best machining settings for various replies. The Grey-Taguchi approach is especially beneficial when numerous responses must be optimized simultaneously [9].

This study aims to improve the hard milling parameters of SKD-61 steel utilizing the Grey-Taguchi technique in pure MQL and nanofluid MQL environments. To determine the best machining parameters, we analyze three essential machining responses: surface roughness (Ra), cutting force (Fc), and material removal rate (MRR). We also use the ANOVA approach to evaluate the experimental data to determine the significant machining parameters and their interactions.

II. MATERIAL AND METHODS

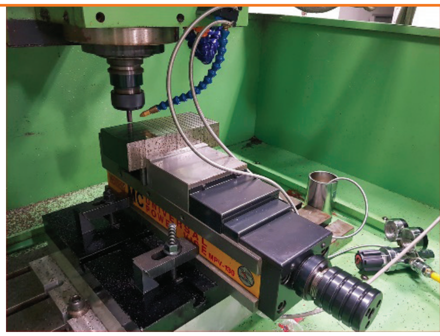
In this investigation, SKD 61 material was utilized to conduct experiments owing to its properties and appropriateness for our research objectives. The workpiece dimensions were deliberately chosen to be 180 mm in length, 100 mm in width, and 40 mm in height to ensure precision and accuracy in conducting the experiments.

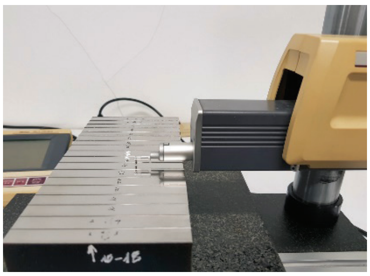
A Victor Vertical Machining Center 4 milling machine was employed in the experiment due to its capabilities and reliability in performing the required tasks. ø10 M520 ultra carbide end mills with four flutes guaranteed high-quality results.

Pure MQL and nanofluid MQL oil were employed as a lubricant in machining. The parameters of the nozzle angle, air pressure, and distance of the nozzle were fixed at 90 mL/h, 60 degrees, 3 kg/cm2, and 20 mm, respectively, to optimize the performance of the nanofluid MQL oil. The nanoparticle concentration in the nanofluid MQL was fixed at 0.5 vol% to ensure optimal lubrication.

Four primary input process parameters were carefully selected to attain our research objectives. Cutting velocity (vc) had three levels: 40 m/min, 50 m/min, and 60 m/min. The cut (ap) depth also had three levels: 0.3 mm, 0.6 mm, and 0.9 mm. Feed per tooth (fz) had three levels: 0.02 mm/tooth, 0.03 mm/tooth, and 0.04 mm/tooth. Finally, the cutting condition had two options: pure MQL or nanofluid MQL. Our materials and methods were meticulously

Magnetic stirrer for nanofluid


Carry-out experiment


Surface roughness measurement

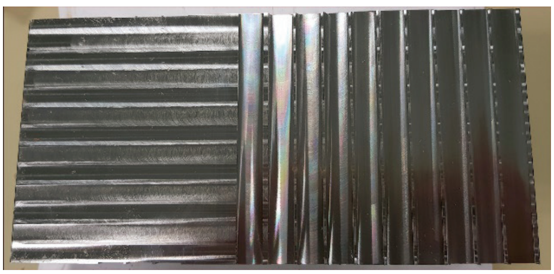

Finished workpiece

Fig. 1. Experimental details set-up for SKD 61 material with nanofluid MQL.

chosen and designed to achieve our research objectives while ensuring high-quality results. Fig. 1 gives a representation of the experimental setup's details.

The combination of GRA and the Taguchi technique has been demonstrated as an effective approach for optimizing machining parameters for hard milling of SKD-61 steel in pure MQL and nanofluid MQL environments in this study. The ANOVA analysis indicated the essential factors impacting the response parameters, while the GRA analysis determined the best combination of machining parameters for the three responses. This study delves into multi-objective optimization methods, allowing for high-quality goods with efficient manufacturing procedures.

III. RESULTS AND DISCUSSION

Table 1 provides the study results, including each experiment's grey relational grade (GRG). The table reveals that, of the 16 trials, the one with the cutting condition, cutting velocity, depth of cut, and feed per tooth set to nanofluid MQL, 80 m/min, 0.2 mm, and 0.01 mm/tooth, respectively, had the lowest surface roughness, cutting force, and highest material removal rates. The findings show that the Grey-Taguchi approach helps improve the machining parameters for hard milling SKD-61 steel.

Table 1. Experimental results and GRG for GRA

No.	C (%)	v_c (m/min)	a_p (mm)	f_z (mm/tooth)	R_a (µm)	F_c (N)	MRR (mm^3/min)	GRG	Rank
1	0	40	0.2	0.03	0.32	222.81	305.7	0.3538	18
2	0	40	0.4	0.01	0.18	140.1	203.8	0.4873	10
3	0	40	0.6	0.02	0.22	269.76	611.5	0.4029	17
4	0	60	0.2	0.01	0.14	94.7	152.9	0.5976	3
5	0	60	0.4	0.02	0.20	207.99	611.5	0.4429	16
6	0	60	0.6	0.03	0.24	279.88	1375.8	0.4628	12
7	0	80	0.2	0.02	0.20	130.96	407.6	0.4927	8
8	0	80	0.4	0.03	0.23	238.76	1222.9	0.4627	13
9	0	80	0.6	0.01	0.18	237.08	611.5	0.4478	15
10	0.5	40	0.2	0.02	0.19	130.95	203.8	0.4908	9
11	0.5	40	0.4	0.03	0.19	210.55	611.5	0.4488	14
12	0.5	40	0.6	0.01	0.11	181.75	305.7	0.5922	4
13	0.5	60	0.2	0.03	0.19	140.5	458.6	0.4946	7
14	0.5	60	0.4	0.01	0.13	139.62	305.7	0.5815	5
15	0.5	60	0.6	0.02	0.18	220.02	917.2	0.4815	11
16	0.5	80	0.2	0.01	0.14	60.7	203.8	0.6854	1
17	0.5	80	0.4	0.02	0.17	143.42	815.3	0.539	6
18	0.5	80	0.6	0.03	0.18	223.69	1834.4	0.6528	2

The Taguchi technique was used to estimate the GRA's GRG after further investigating the findings. The signal-to-noise (S/N) ratio is shown in Fig. 2, revealing the same tendency as the GRA results. The optimum parameters determined using the GRA and Taguchi methods agreed, proving the robustness and efficiency of the combined methodology in discovering the best machining parameters.

In line with the findings, the Grey-Taguchi technique is an essential methodology for the multi-objective optimization of machining parameters in the manufacturing industry. The GRA technique converts a complicated multi-objective optimization issue into a single-objective problem, whereas the Taguchi approach aids in determining the best amounts of input parameters for the chosen objective. The combined technique improves machining performance by lowering surface roughness, increasing cutting force, and boosting the material removal rate.

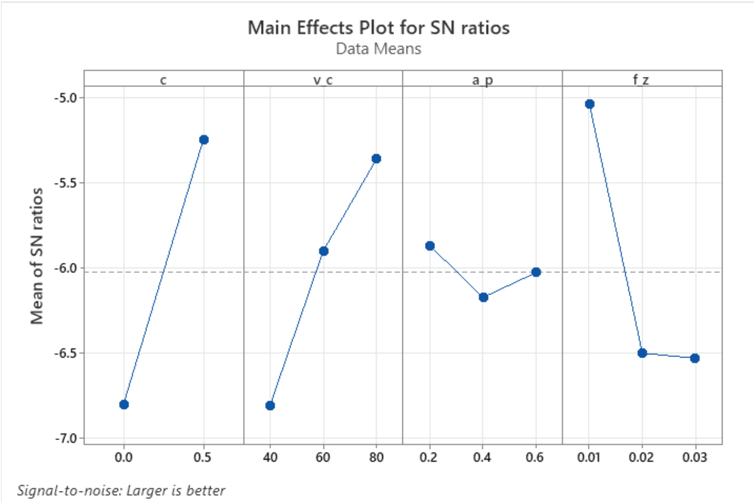


Fig. 2. Plot S/N for GRG simulation.

To summarize, the Grey-Taguchi technique is an efficient method for optimizing machining parameters in hard milling of SKD-61 steel in pure and nanofluid MQL cutting conditions. The findings show that the ideal machining parameters are obtained when the cutting condition, cutting velocity, depth of cut, and feed per tooth are adjusted to nanofluid MQL, 80 m/min, 0.2 mm, and 0.01 mm/tooth, respectively. The combination of GRA with the Taguchi approach aids in the simplification of the multi-objective optimization problem and the identification of the optimal levels of the input parameters. The manufacturing industry uses this method to generate high-quality goods with efficient manufacturing procedures.

Table 2. ANOVA for GRG of grey relational analysis

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
c	1	0.037001	29.36%	0.037001	0.037001	27.17	0.006
vc	2	0.021338	16.93%	0.021338	0.010669	7.84	0.041
ap	2	0.001943	1.54%	0.005437	0.002718	2.00	0.250
fz	2	0.031166	24.73%	0.031166	0.015583	11.44	0.022
c*vc	2	0.014741	11.70%	0.014741	0.007371	5.41	0.073
vc*fz	4	0.014368	11.40%	0.014368	0.003592	2.64	0.185
Error	4	0.005447	4.32%	0.005447	0.001362		
Total	17	0.126004	100.00%				

In addition to the Grey-Taguchi approach, the ANOVA analysis was incorporated into this work to evaluate further the significant factors impacting the response parameters (Table 2). Cutting condition, feed per tooth, and cutting speed were shown to be essential determinants, with P-values less than 0.05 suggesting statistical significance. The ANOVA study offered more details regarding the effect of input parameters on response parameters, which contributed to the optimization process.

IV. CONCLUSION

The following conclusions may be derived from the study's findings and discussions:

1. The Grey-Taguchi method successfully improved the machining parameters for hard milling SKD-61 steel in pure MQL and nanofluid MQL environments.

2. The outcomes demonstrated that the nanofluid MQL, cutting speed of 80 m/min, depth of cut of 0.2 mm, and feed per tooth of 0.01 mm/tooth combined to produce the lowest surface roughness, cutting force, and maximum material removal rate.

3. The ANOVA analysis revealed that the most important factors influencing the response parameters were cutting condition, feed per tooth, and cutting speed.

4. The Grey relational grade (GRG) and Grey relational analysis (GRA) were effective techniques for evaluating multi-objective machining parameter optimization.

5. The Taguchi approach offered an excellent indicator of the signal-to-noise ratio and aided in determining the parameter responsivity.

6. In a multi-objective scenario, the combination of Grey relational analysis and the Taguchi technique proved an effective way for optimizing machining factors.

Overall, this study provides valuable insights into using the Grey-Taguchi technique to optimize machining parameters for hard milling of SKD-61 steel in pure MQL and nanofluid MQL environments. These discoveries have the potential to be valuable in industrial applications as well as future studies in the field of machining optimization.

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