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INVESTIGATION OF MAGNETIC ABRASIVE FINISHING PROCESS PARAMETERS OF SS316 MATERIAL USING TAGUCHI DESIGN ANOVA ANALYSIS

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ABSTRACT

Magnetic abrasive finishing (MAF) is an advanced surface finishing technique and has precise control over parameters those can significantly impact the final product quality. The optimization of the MAF process parameters in manufacturing is crucial for achieving desired outcomes, such as improved material removal rate. In this study, the taguchi method (L27) is applied to identify the optimal process settings, for finishing of SS316 material and ANOVA analysis is applied to find out the critical parameters those affective the material removal rate. Further, regression analysis was carried out to predict the MRR.

Keywords: Magnetic Abrasive Finishing Process, Taguchi's L27 orthogonal array, ANOVA analysis, material removal rate, regression analysis.

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1. Introduction

Magnetic Abrasive Finishing (MAF) is an advanced surface finishing technique that utilizes a controllable magnetic field to manipulate abrasive particles for precise material removal. Recent research has focused on optimizing key process parameters to enhance surface finish and material removal rate (MRR), particularly for hard-to-machine materials such as stainless steel (SS316), aerospace alloys, and biomedical components. Magnetic Abrasive Finishing (MAF) is a noncontact finishing process that utilizes a magnetically energized abrasive slurry to achieve controlled finishing in complex internal geometries. The process is particularly effective for internal finishing, where traditional methods struggle. This process is especially suitable for materials with superior mechanical properties and those requiring high-quality surface finishes[1]. Jain et al. [2] observed that working gap and circumferential speed affected the percentage increase in surface finish and material removal rate. Wang and Hu [3] analyzed the material removal rate of three distinct materials— Ly12 aluminum alloy, 316L stainless steel, and H62 brass self-possessed tubes and it was significantly influenced by three factors: speed, magnetic abrasive substance, and grain size. Jain and Kumar [4] provided a comprehensive review of MAF mechanisms, emphasizing the influence of magnetic field intensity, abrasive particle composition, and working gap on surface roughness (Ra). Their findings suggest that hybrid abrasives, such as silicon carbide (SiC) combined with aluminum oxide (Al_2O_3), significantly enhance surface quality. Similarly, Patel and Jain [5] explored hybrid abrasives incorporating diamond particles, leading to a 20% improvement in Ra over conventional abrasives. Kumar & Yadav [6] further examined the impact of abrasive size and composition, concluding that mixed abrasives (SiC + Al_2O_3) provide superior finishing performance. The effect of magnetic field intensity has been widely studied, with Wang and Li [7] determining that an optimal field strength of 0.8T balances high MRR with minimal surface defects. Sharma and Singh [8] experimentally analyzed MAF on SS316 and found that increasing rotational speed reduces Ra but also raises workpiece temperature, potentially altering microstructural properties. Kumar and Yadav [9] expanded on this by optimizing MAF for complex geometries in aerospace applications, demonstrating a 40% improvement in Ra using a hybrid abrasive mix (Al_2O_3 + SiC + diamond). Hybrid approaches have shown significant promise in improving MAF efficiency. Lee and Kim [10] integrated ultrasonic-assisted MAF, achieving a 40% enhancement in surface finish due to the reduction of abrasive clogging and more uniform material removal. Similarly, Li and Zhang [11] combined electrochemical finishing with MAF, achieving a 35% reduction in Ra compared to standard MAF techniques. Yadav and Tripathi [12] compared MAF with traditional finishing methods like grinding and electrochemical polishing, concluding that MAF achieves a superior surface finish (Ra = 0.08–0.15 µm) while maintaining higher MRR. Advanced abrasive technologies have further refined MAF performance. Khan and Gupta [13] investigated composite abrasives (SiC + diamond + Al_2O_3), reporting a 30% improvement in MRR and a 50% reduction in Ra compared to conventional abrasives. Sharma and Patel [14] introduced nano-structured abrasives (50–200 nm), achieving ultra-precision finishing with Ra as low as 0.05 µm on SS316 surfaces. Chen and Zhao [15] declares these developments are particularly relevant for high-precision applications, such as biomedical implants and aerospace components. The integration of artificial intelligence (AI) and machine learning in MAF is an emerging trend aimed at real-time process optimization. Zhao and Chen [16] developed a deep learning-based predictive model using artificial neural networks (ANNs) to forecast Ra and MRR with an error margin of only 1.8%. Mishra and Verma [17] further enhanced MAF efficiency by incorporating AI-driven real-time process monitoring using IoT sensors, dynamically adjusting process parameters to improve efficiency by 25%. Few researchers had applied Taguchi methods to select the optimum process parameters. Taguchi method is a statistical approach widely used for designing experiments and optimizing process parameters, Davis and John [18]. It employs orthogonal arrays to reduce the number of experiments required while still capturing the effects of multiple parameters on the desired outcomes. Shukla and Pandey [19] investigated the effect of various process parameters on the magnetic property (magnetization) of sintered MAPs. Design of experiments (DoE) was planned as per the L8 orthogonal array of the Taguchi method, and magnetizations along with M-H curves for all eight different MAPs were measured. Subsequently, various techniques are used to analyze the experimental data and optimize the process parameters. It was observed that sintering temperature affects magnetization the most. Gao et al. [20] reported on the polishing of paramagnetic materials in the magnetic abrasive finishing (MAF) process by using atomized-type magnetic abrasive powder (MAP). An orthogonal array containing five factors with three levels was applied in the experiment. Based on analysis results, the model of surface roughness was obtained, and the rotational speed of the MAPs played the most dominant role in the surface quality of both finished experimental materials. Singh et al. [21] measured the rise in temperature of aluminum 6060 micro finished surface. A Taguchi L9 Orthogonal Array (L9 OA) was employed to design the experiments with voltage, abrasive weight, working gap, and rotational speed opted as process parameters. Buckingham -theorem was used to formulate a semiempirical dimensional model to forecast the rise in temperature. Magnetic Abrasive Finishing (MAF) optimization has been extensively studied using the Taguchi method, particularly with the L27 orthogonal array, to enhance surface quality and material removal rate (MRR). Enemuoh et al. [22] applied taguchi and L27 orthogonal array design. It is a specific design that allows for the evaluation of up to 13 factors at three levels each, making it suitable for complex processes with multiple variables. Prasad and Reddy [23] uses L27 Orthogonal Array and Taguchi-Based Optimization for Magnetic Abrasive Finishing Process. Researchers such as Gupta and Sharma [24] and Patil and Deshmukh [25] identified abrasive concentration (40–60%) and rotational speed (1000–1500 RPM) as the most influential factors affecting surface roughness. Studies integrating ANOVA, Grey Relational Analysis (GRA), and Response Surface Methodology (RSM), such as Mehta and Roy [26] and Gupta & Sharma [27], demonstrated improved optimization precision, with hybrid approaches yielding better control over process variability. Further advancements, including multi-objective optimization techniques like GRA, TOPSIS, and Genetic Algorithms (GA) (Khan and Verma, [28]; Saha and Bose, [29]; Iqbal & Ahmed, [30], have enabled a balanced improvement in surface roughness and MRR. Additionally, research by Patel and Sharma [31]; Desai and Sharma [32] extended MAF optimization to complex geometries, enhancing process stability. From the literature review, it’s found that Taguchi method remains a reliable tool widely used for designing of experiments and optimization of process parameters.

The literature survey discloses that most of the studies are finishing different alloys using the MAF process with various process parameters and few of the studies are related to the selection of process parameters. In the present study In this study, the taguchi method (L27) is applied to identify the optimal process settings for improving the MRR in MAF for stainless steel SS316 material and ANOVA analysis is applied to find out the critical parameters those affective the material removal rate.

2. Design of Experiments

The experimental setup consists of machine engine lathe with rotary MAF setup and cylindrical work-piece of SS316 is considered for the machining using the Iron powder (Fe - mesh size: 300) and SiC (mesh size: 400, 600, 800) as abrasive materials with magnetic field source of permanent neodymium magnets (1.0, 2.0, 3.0 Tesla). The L27 orthogonal array is selected to study five parameters at three levels each, as shown in Table 1.

Table 1. Process Parameters with different three levels [33]

Parameters	**Level 1**	**Level 2**	**Level 3**
Rotational Speed (RPM)	320	480	640
Magnetic Flux Density (Tesla)	0.1	0.2	0.3
Abrasive Mesh Size (µm)	400	600	800
Working Gap (mm)	1.5	2.0	2.5
Percentage Weight of Abrasives (grams)	20	25	30

A total of 27 experimental runs were conducted to find the MRR and input and output of each runs are listed in Table 2.

Table 2. Design of Experiments based on Taguchi L27 Orthogonal Array [33]

Sr. No.	Chuck RPM (rpm)	Magnetic Flux Density (T)	Abrasive Mesh Size (µm)	Working Gap (mm)	% Weight of Abrasives (grams)	MRR (mg/min)
1	320	0.1	400	1.5	20	1.20
2	320	0.1	400	1.5	25	2.50
3	320	0.1	400	1.5	30	1.10
4	320	0.2	600	2.0	20	1.70
5	320	0.2	600	2.0	25	2.30
6	320	0.2	600	2.0	30	1.80
7	320	0.3	800	2.5	20	2.60
8	320	0.3	800	2.5	25	3.60
9	320	0.3	800	2.5	30	2.20
10	480	0.1	600	2.5	20	1.60
11	480	0.1	600	2.5	25	3.50

12	480	0.1	600	2.5	30	2.40
13	480	0.2	800	1.5	20	2.10
14	480	0.2	800	1.5	25	3.20
`15	480	0.2	800	1.5	30	3.10
16	480	0.3	400	2.0	20	2.80
17	480	0.3	400	2.0	25	3.90
18	480	0.3	400	2.0	30	3.30
19	640	0.1	800	2.0	20	5.50
20	640	0.1	800	2.0	25	7.10
21	640	0.1	800	2.0	30	6.60
22	640	0.2	400	2.5	20	3.40
23	640	0.2	400	2.5	25	5.20
24	640	0.2	400	2.5	30	4.70
25	640	0.3	600	1.5	20	5.40
26	640	0.3	600	1.5	25	6.00
27	640	0.3	600	1.5	30	5.70

3. Regression Analysis and its results

Multiple regression statistical technique has been used to analyze the relationship between a output variable MRR and input variables such as chuck rpm, magnetic flux density, abrasive mesh size, working gap and percentage weight of abrasives. Figure 1. Shows the main effect plot for MRR and it found that chuck rpm has a maximum influence on MRR. An increase in abrasive mesh size increases the MRR while chuck rpm decreases the MRR. Magnetic flux density, working gap and percentage weight of abrasives have little effect on MRR. The main effect plot for MRR indicates that the MRR can be maximized if 640 chuck rpm, 0.3 Tesla magnetic flux density, 800 abrasive mesh size, 2.0 mm working gap and 25 gram of percentage weight of abrasives have been selected as machining parameters.

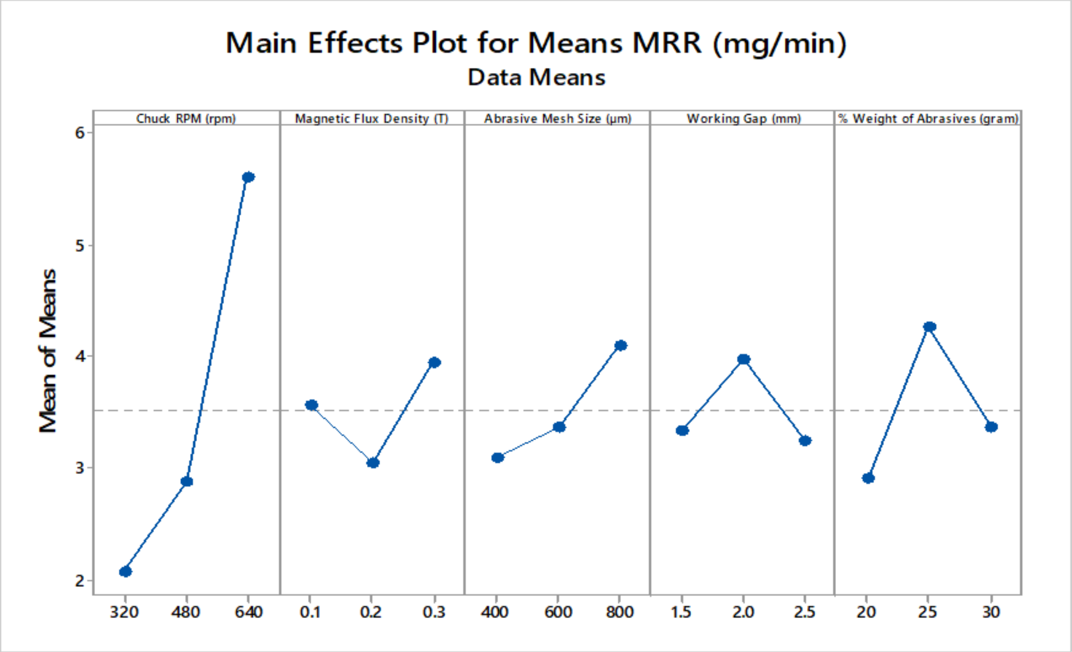
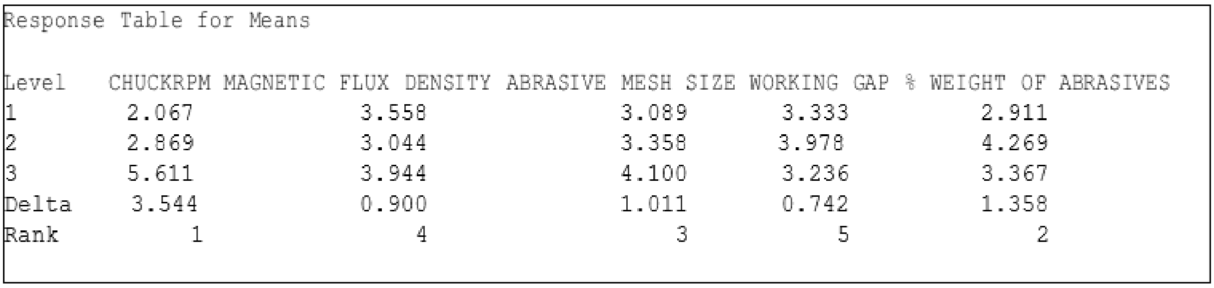


Figure 1. Main Effect Plot for MRR

Table 3 shows the response table for means of MRR for SS316 material. In order to have a maximize MRR, third level of chuck rpm, the third level of magnetic flux density, the third level of abrasive mesh size, the second level of working gap and the second level of percentage weight of abrasives should be preferred. If the objective is only to maximize MRR without considering the other response, then setting of these parameters can be suitable.

Table 3 Response table for means for MRR for SS316 material



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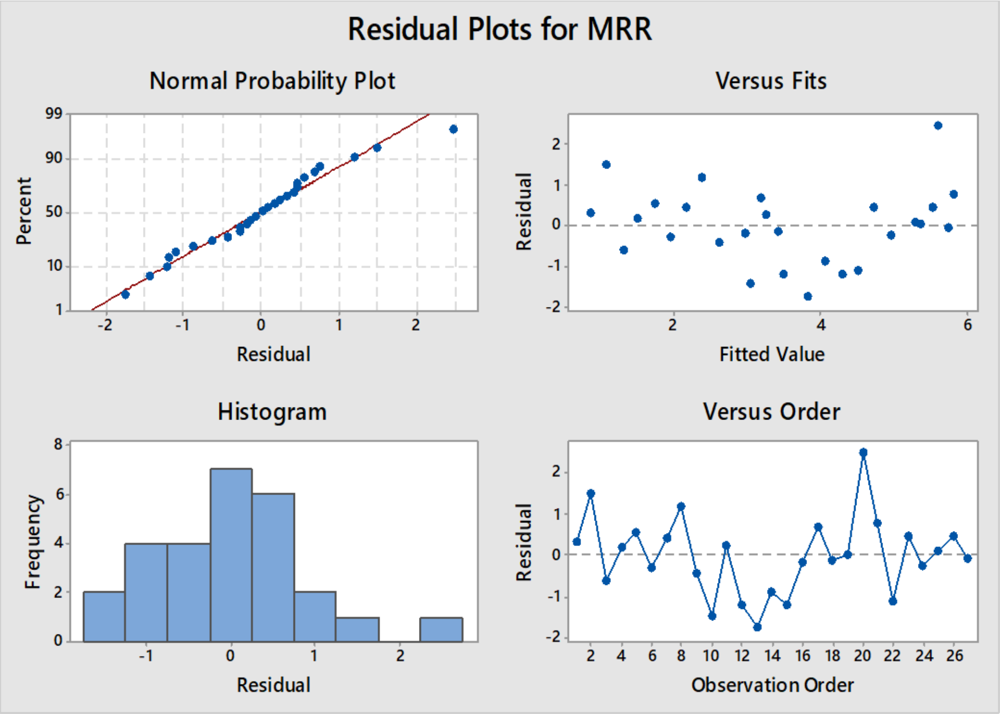
Response Table for Means

Level   CHUCKRPM MAGNETIC FLUX DENSITY ABRASIVE MESH SIZE WORKING GAP % WEIGHT OF ABRASIVES
1          2.067                 3.558              3.089       3.333                  2.911
2          2.869                 3.044              3.358       3.978                  4.269
3          5.611                 3.944              4.100       3.236                  3.367
Delta      3.544                 0.900              1.011       0.742                  1.358
Rank           1                     4                  3           5                      2
```

Figure 2. shows the model summary of MRR of SS316 material shows that the R-square (predicted) value is close to the R-square and R-square (adj) values, the model does not appear to overfit and has an adequate predictive ability.



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Model  Summary

       S      R-sq    R-sq(adj)    R-sq(pred)
1.04539   73.23%       66.86%        56.07%
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Figure 2. Model Summary and Regression equation of MRR

Regression analysis suggested the following equation for prediction of MRR.

```
MRR = -4.65 + 0.01108 CHUCK RPM + 1.93 MAGNETIC FLUX DENSITY + 0.00253 ABRASIVE MESH SIZE
- 0.098 WORKING GAP + 0.0456 % WEIGHT OF ABRASIVES
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4. Analysis of Variance (ANOVA)

A total of 27 experimental runs were conducted, and was measured**.** The optimized parameters for maximize MRR were determined from the highest S/N ratio (Figure 1). Chuck rpm and abrasive mesh size had the most significant effect, followed by magnetic flux density, working gap and % weight of abrasives.

The ANOVA table detailed breakdown are as follow:

- Chuck RPM (rpm): With the highest F-value (51.73) and a p-value of 0.000, RPM has the strongest influence on MRR. Changes in RPM are likely to have the most substantial impact on the Material Removal Rate.

- Abrasive Mesh Size (µm): Also has a significant effect (F-value = 4.21, p-value = 0.053), suggesting abrasive mesh size (µm) plays a considerable role in MRR.

Magnetic Flux Density (T), Working Gap (mm) and % Weight of Abrasives (gram): Though statistically significant and have low influence than Chuck RPM (rpm) and abrasive mesh size. This suggests they likely have a measurable but comparatively smaller influence on MRR.

Table 4. ANOVA Table for MRR

Factor	F-Value	P-Value	Remarks
Chuck rpm (RPM)	51.73	0.000	SIGNIFICANT
Magnetic Flux Density (Tesla)	0.62	0.441	
Abrasive Mesh Size (µm)	4.21	0.053	SIGNIFICANT
Working Gap (mm)	0.04	0.845	
Percentage Weight of Abrasives (grams)	0.85	0.366	

5. Conclusion and Future Work

In the present work, L27 taguchi approach and ANOVA analysis are used to study the effect of MAF process parameters on MRR. Study reveals that the chuck rpm and abrasive mesh size are the most influential parameters for MRR using ANOVA analysis and it confirms statistical significance with a 95% confidence level. This finding shows the usefulness of the MAF of SS316 material.

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