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Experimental Investigations on Magnetic Field Assisted Abrasive Finishing of SS 316L

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Abstract

Magnetic Field Assisted Abrasive Finishing (MFAAF) is one of the advanced fine finishing process uses a magnetic field for finishing the surfaces of the workpieces with controlled forces. However, it is difficult to predict the final surface finish of this process, due to non-uniform nature of the magnetic flexible abrasive brush and the nonlinear interactions between the process parameters. In the present study, experimental investigations were carried out to understand the effect of key process parameters in MFAAF of AISI 316L using Taguchi's L_{27} orthogonal array and investigate the influence of each selected process parameters on the process. The data obtained from the experiments were statistically analyzed using signal to noise ratio and the results were presented. It is found that MFAAF process results in better surface finish (Ra) while adopting the optimal process parameters recommended in the study. The outcomes of the specific studies will be highly beneficial to the end users.

Keywords: Magnetic field assisted abrasive finishing; Design of Experiments; Surface roughness; Material removal rate; Statistical analysis

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1. Introduction

Finishing is the last stage operation in any manufacturing that consumes more time, most labour intensive and least controllable process. Usually, traditional finishing processes namely grinding, lapping and honing depend upon the machine tool system, and are usually prone to quasi state errors as well as dynamic errors. Magnetic Field Assisted Abrasive Finishing (MFAAF) process is one of the upcoming, advanced finishing processes developed to overcome the setbacks associated with the traditional ones. MFAAF process uses a magnetic field for finishing the surfaces of the workpieces with controlled forces. It has been employed to finish optical, mechanical, and electronic components with sub-micrometer form accuracy and surface roughness with hardly any surface defects [1,2].

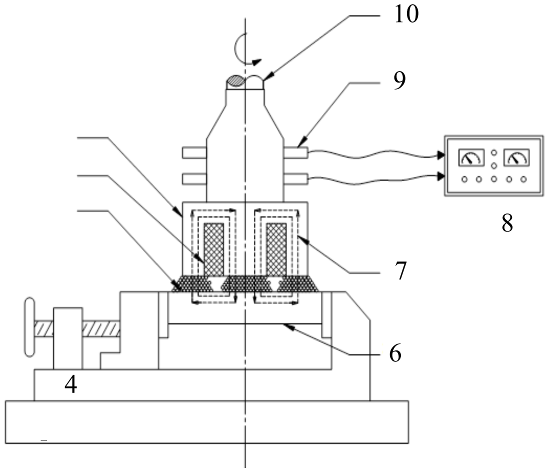
Shinmura and co-workers in Japan carried out extensive studies to understand the principle of MFAAF process on magnetic and nonmagnetic materials for flat and cylindrical surfaces [3-5]. The researchers observed that Magnetic Abrasive Flexible Brush (MAFB) supplies sufficient abrasion pressure to finish the work surface corresponding to the strength of the magnetic field. Further, many researchers have contributed towards improvement in MFAAF process to obtain improved surface finish and better material removal. Jayakumar et al. [6] conducted MFAAF experiments based on Taguchi design of experiments to find out the optimum process conditions. Jain et al. [7] investigated the effect of working gap and circumferential speed on material removal, change in surface finish and the percentage improvement in surface finish. It is opined that the material removal decreases with increasing working gap or decreasing the circumferential speed of the workpiece. The research studies indicated that the speed, process, electromagnet input voltage, working gap, the RPM of electromagnet and mesh number of SiC magnetic field, spindle revolution, feed rate, working gap, abrasive, and lubricant and grain size have critical effects on the material removal rate (MRR) on various materials [8-12]. The research outcomes attested that the use of high voltage, low machining gap, high rotational speed and fine abrasive particles are desirable for improving the surface finish. Kanish et al. [13] carried out the MFAAF experimental investigations to analyses the effect of different process parameters such as voltage supplied to the electromagnet, machining gap, rotational speed of electromagnet and abrasive mesh size with the response variable like improvement in surface roughness and Material Removal on AISI 316L work material. Similar works were attempted on AISI 440C stainless steel cylinders [14], Copper work piece [15] and AZ91 magnesium alloy [16].

During the MFAAF process the temperature of the workpiece surface raises due to the rubbing action of Magnetic Abrasive Particles (MAPs) and heat generated in the electromagnet coil. Mishra et al. [17] reported that the temperature rise was in the range of 34º to 51º C. If the electromagnet is continuously used in the same location without any linear relative motion (feed) for more than 30 minutes resulted in burning marks on the work surface. The burning marks due to temperature rise can be reduced at the work–brush interface by providing feed motion to the workpiece during MFAAF process. It is found that limited investigations [18, 19] have been reported to address the effect of feed rate to avoid heat accumulation in the workpiece during MFAAF Process. Therefore, in this study the effect of feed rate also studied along with other process parameters over the response variable like improvement in surface roughness (%ΔRa) and Material Removal (MR).

2. Experimental Procedure

2.1. Experimental Setup:

One of the most important aspects of MFAAF process is that it does not require a sophisticated machine tool. The existing machine tools (lathe or milling) can be used for the MFAFF process by adding a magnetizing unit (electromagnet or permanent magnet) to the machine. In this study, a MFAAF setup was designed for finishing of plane surfaces and it was integrated with a milling machine. The experimental setup consists of a precision vertical milling machine, electromagnet (round and flat faced electromagnet Ø60 mm and height 50mm) spindle assembly and magnetization unit. The Schematic view of MFAAF experimental setup spindle assembly is depicted in Fig. 1.



Item No	Item Name
1	Electro Magnet
2	Coil
3	MFAB
4	Machine Vice
5	Machining Table
6	Workpiece
7	Magnetic Flux(Φ)
8	Power Supply
9	Slip Rings
10	Machine spindle

Fig 1. Schematic view of MFAAF Experimental Setup spindle assembly [20]

2.2. Work Material

The work material selected for the present investigation is austenitic stainless steel 316L grade. It is a non-magnetic material, which has superior mechanical strength, better wear resistance, excellent corrosion resistance and minimum carbon content. Due to this superior properties, AISI 316L is widely used in automotive, biomedical implants, nuclear reactors applications, etc. The composition of AISI 316L is given in Table 1.

Table 1 Chemical composition of Stainless Steel grade 316L

Alloying Elements	Cr	Ni	Mo	Mn	Si	P	S	C	Fe
Observed weight ratio (%)	16.12	10.04	2.03	1.85	0.51	0.034	0.003	0.021	Remaining

2.3. Selection of Process parameters and experimental design

Even though various process parameters are affecting the outcomes of MFAAF process, identification of key process parameters influencing surface finish and material removal were established from a detailed literature survey. In the present study, the effect of process parameters is investigated to improve the surface roughness (%ΔRa) and Material Removal (MR), a detailed experimental investigation has been carried out on AISI 316L work material using appropriate L_{27} Taguchi experimental design. In addition to the process parameters [12], feed rate of work material is also considered in this work. The selected process parameters for different levels are given in Table 2.

Table 2 Selected process parameters and their levels

Notation	Process parameters	Unit	Levels		
			1	2	3
A	Voltage	V	18	20	22
B	Machining gap	mm	1.5	1.75	2.0
C	Rotational speed of electromagnet	rpm	270	405	540
D	Abrasive size	Mesh no.	400	800	1200
E	Feed Rate	mm/min	35	70	105

Further, the process parameters such as grain size (300 mesh) of abrasive, the total amount of magnetic abrasive particle (10 g) and mixing ratio (80% Fe, 20% SiC abrasive) and finishing time (15 min) were kept constant.

2.4. Measurement of response variables

In the present work, the machining performance of MFAAF is characterized as a percentage improvement in surface finish (%ΔR_a) and Material Removal (MR), as these variables describe the surface characteristics of the finished surface in MFAAF process. Surface roughness measurements were established using 'Mahr Marsurf instrument GD120". The surface roughness values were measured at the same points (using the template) where the initial finish values were measured after the MFAAF process. ΔRa is defined as the difference between the surface finish value before and after MFAAF. The percentage improvement in surface finish (%ΔRa) is calculated using the Eqn. 1 and Eqn. 2.

$$\Delta R_a = \text{Initial } R_a \text{ Value} - \text{Final } R_a \text{ Value} \qquad \text{(Eqn. 1)}$$

$$\%\Delta R_a = \frac{\Delta R_a}{\text{Initial } R_a \text{ Value}} \times 100 \qquad \text{(Eqn. 2)}$$

The material removal (MR) is calculated by measuring the initial and final weight of the finished workpieces using a precision weighing balance and it is given by the following equation:

MR (in mg) = Initial weight of workpiece – Final weight of workpiece (Eqn. 3)

The experimental combinations and their output responses are shown in Table 3. It is observed that the maximum value for the percentage improvement in surface finish (%ΔRa) and material removal (MR) is found to be 75.04% and 101 mg respectively.

Table 3 Experimental Matrix (L_{27}), and its output responses (%ΔRa and MR)

Expt No.	A (V)	B (mm)	C (RPM)	D (Mesh	E (mm/	(%ΔRa (%)	MR (mg)
1	18	1.50	270	400	35	47.36	46
2	18	1.50	270	400	70	40.25	40
3	18	1.50	270	400	105	34.15	32
4	20	1.75	270	800	35	46.49	45
5	20	1.75	270	800	70	40.28	41
6	20	1.75	270	800	105	32.14	29
7	22	2.00	270	1200	35	63.43	68
8	22	2.00	270	1200	70	56.32	56
9	22	2.00	270	1200	105	52.95	52
10	22	1.50	405	800	35	75.04	101
11	22	1.50	405	800	70	71.24	90
12	22	1.50	405	800	105	67.73	77
13	18	1.75	405	1200	35	49.29	48
14	18	1.75	405	1200	70	46.84	44
15	18	1.75	405	1200	105	43.28	43
16	20	2.00	405	400	35	34.53	33
17	20	2.00	405	400	70	30.94	25
18	20	2.00	405	400	105	26.8	21
19	20	1.50	540	1200	35	70.81	85
20	20	1.50	540	1200	70	68.08	79
21	20	1.50	540	1200	105	66.24	75
22	22	1.75	540	400	35	70.35	84
23	22	1.75	540	400	70	65.28	72
24	22	1.75	540	400	105	58.32	60
25	18	2.00	540	800	35	35.24	35
26	18	2.00	540	800	70	31.54	27
27	18	2.00	540	800	105	28.56	23

3. Results and Discussion

The data obtained from the experiments were statistically analyzed using MINITAB® statistical software and the results were presented in this section. To identify the influencing process parameters on percentage improvement in surface finish and MR, S/N ratio and ANOVA analysis were carried out.

3.1. S/N Ratio

As the higher percentage improvement in surface finish (%ΔRa) and higher Material Removal (MR) are desirable, "Larger is better" quality characteristic was chosen for the present investigation. In order to analyze the effect of individual process parameters on %ΔRa, and MR, the delta value is calculated using mean values of S/N ratios. The delta value is the difference between the highest and lowest average value of S/N ratio for each factor. Tables 4 and Table 5 show the ranking of different parameters based on the values of delta obtained for %Δ Ra and MR respectively. The factor having the highest value of delta was assigned as first rank and so on. The mean of S/N ratios for the process parameters on %ΔRa and MR were depicted in Fig. 2 and Fig. 3 respectively.

Table 4 Response table for Signal to Noise ratios for %Δ Ra

Level	A	B	C	D	E
1	31.81	35.28	33.04	32.66	34.43
2	32.76	33.79	33.37	32.98	33.6
3	36.14	31.63	34.3	35.07	32.67
Delta	4.33	3.65	2.41	2.41	1.76
Rank	1	2	5	3	4

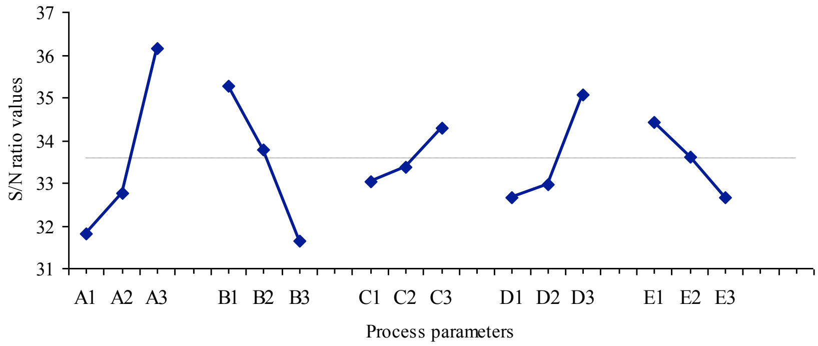


Fig. 2 Main effect plot for %Δ Ra

Table 5 Response Table for Signal to Noise ratios for MR

Level	A	B	C	D	E
1	31.26	36.26	32.88	32.37	35.00
2	32.60	33.88	33.43	33.13	33.66
3	37.11	30.83	34.66	35.46	32.31
Delta	5.86	5.43	1.79	3.09	2.69
Rank	1	2	5	3	4

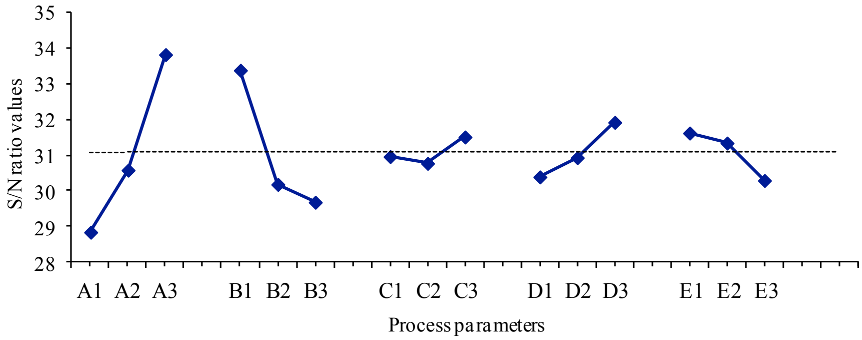


Fig. 3 Main effect plot for MR

From the S/N ratio results, it is inferred that the %ΔRa and MR are significantly influenced and maximum at the following experimental combinations, maximum voltage (A3), minimum machining gap (B1), higher abrasive size (D3), lower feed rate (E1) followed by higher rotational speed of electromagnet (C3). The confirmation experiments have been performed at optimum levels combination (A3B1C3D3E1) obtained from S/N ratio and the results are shown in Table 6.

Table 6 Confirmation test result for optimal process parameters combination

Optimal combinations					Confirmation Results	
A (V)	B (mm)	C (rpm)	D (mesh no.)	E (mm/min)	%ΔRa (%)	MR (mg)
22	1.5	540	1200	35	81.28	107.31

3.2. Analysis of Variance

The significant process parameters influencing the %ΔRa and MR are determined using Analysis of Variance (ANOVA). The ANOVA results for %ΔRa and MR are shown in the Table 7 and Table 8 respectively and the percentage contributions of factors on %ΔRa and MR are depicted in Fig. 4 and Fig 5.

Table 7 ANOVA results for %ΔRa

Source	DOF	SS	MS	F-ratio	P-value
A	2	2993.71	1496.86	459.31	0.000**
B	2	1812.02	906.01	278.01	0.000**
C	2	369.94	184.97	56.76	0.000**
D	2	750.61	375.30	115.16	0.000**
E	2	376.96	188.48	57.83	0.000**
Error	16	52.14	3.26		
Total	26	6355.38			

** Highly Significant ($P < 0.05$); $F_{0.01, 2, 16}$ = 3.6337

Table 8: ANOVA results for %ΔRa

Source	DOF	SS	MS	F-ratio	P-value
A	2	6082.9	3041.4	266.73	0.000**
B	2	4532.7	2266.3	198.75	0.000**
C	2	957.6	478.8	41.99	0.000**
D	2	1056.2	528.1	46.31	0.000**
E	2	984.2	492.1	43.16	0.000**
Error	16	182.4	11.4		
Total	26	13796.0			

** Highly Significant ($P < 0.05$); $F_{0.05, 2, 16}$ = 3.6337

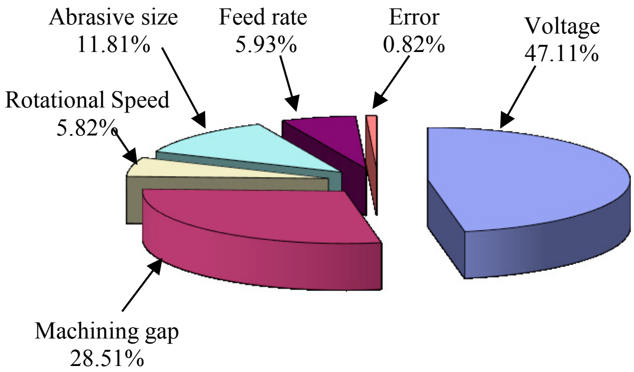


Fig. 4 Percentage contributions of process parameters on %ΔRa

The magnitude of F-values for Voltage (A), machining gap (B), rotational speed(C), abrasive mesh number (D) and feed rate (E) are 459.31, 278.01, 56.76, 115.16 and 57.83 respectively. These values are greater than the F-critical (F0.05, 2, 16 = 3.6337) for a significance level of α = 0.05. It indicates that the process parameters are statically significant for 95% confidence level.

The calculated F-values for Voltage (A), machining gap (B), rotational speed(C), abrasive mesh number (D) and feed rate (E) are 266.73, 198.75, 41.99, 46.31 and 43.16 are greater than the F-critical (tabulated value F0.05, 2, 16 = 3.6337) for a significance level of α = 0.05. It indicates that the process parameters are statically significant for 95% confidence level.

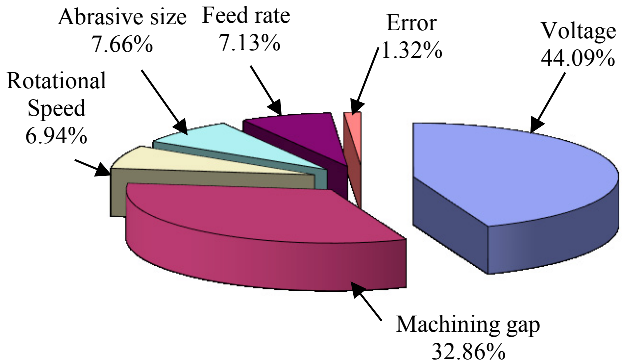


Fig. 5 Percentage contributions of process parameters on MR

From the ANOVA results, it is found that the %ΔRa and MR are significantly influenced by voltage (A) applied to the electromagnet, machining gap (B), Abrasive size (D), Feed rate (E) followed by rotational speed of the electro magnet (C). It is also to be observed that the ANOVA results obtained for %ΔR_a and MR confirms the results obtained by S/N ratio analysis.

4. Conclusions

Selection of optimal values of process parameters in MFAAF process is important for maximizing percentage improvement in surface finish (%ΔRa) and material removal (MR). The present research work is aimed at developing MFAAF process for finishing of AISI 316L material and identifying the optimal process parameters for improving the surface finish improvement, material removal during MFAAF process. Based on the experimental investigations on MFAAF process and the results, the following conclusions were drawn from the present investigations:

- Based on the S/N ratio analysis and ANOVA analysis, it is found that %ΔRa and MR are significantly influenced by the high level voltage of 22V, low level machining gap of 1.5mm, higher mesh size of 1200 mesh, low level feed rate of 35mm/ min followed by higher rotational speed of 540 rpm.
- From the experimental study it is found that Feed rate also one of the significant influencing process parameter while comparing rotational speed of the electro magnet.
- From the experimental results, it is inferred that increase in voltage, rotational speed and abrasive size have positive effect on %ΔRa and MR, whereas increase in machining gap and feed rate have negative effect on %ΔRa and MR.
- MFAAF process produces mirror like surface finish on AISI 316L with the surface finish (Ra) value of 76.6 nm at the following cutting conditions: Voltage supplied to electromagnet = 22V; Machining gap = 1.5 mm; Rotational speed of the electro magnet = 540 rpm; Abrasive grain number =1200 mesh number and Feed rate =35 mm/min.

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