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Investigations on the finishing forces in Magnetic Field Assisted Abrasive Finishing of SS316L

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Abstract

Magnetic Field Assisted Abrasive Finishing (MFAAF) process is one of the advanced fine finishing process which uses a flexible multipoint cutting tool to finish the workpiece. The knowledge of finishing forces acting during the MFAAF process is essential to understand the nature of surface finish produced. This paper presents the effect of process parameters like voltage supplied to the electromagnet, machining gap, rotational speed of electromagnet, abrasive size and feed rate on finishing forces during MFAAF process. The work material selected was SS316L material. The experiments were carried out as per Taguchi L_{27} orthogonal array. Kistler cutting force dynamometer (Model 9257B) and charge amplifier (Model 5070A) were utilised to measure the normal and tangential forces. From the experimental results, it was found that higher voltage (22 V) and lower machining gap (1.5 mm) resulted in maximum magnitude of the normal and tangential forces to 33.92 N and 14.16 N respectively. Also it was observed that the voltage supplied to the electromagnet and the machining gap have significant effect in determining the normal and tangential cutting forces.

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Keywords: Magnetic field assisted abrasive finishing, Dynamometer, Normal force, Tangential cutting force, Design of Experiments, Electromagnet

1. Introduction

In general, finishing operations are considered as the most critical and expensive phase of overall production processes. Recent advances in technological fields demand the use of advanced materials like stainless steels, non ferrous metals and ceramics. However, it is difficult to finish the advanced engineering materials economically by the conventional finishing techniques such as grinding, lapping and honing. Magnetic Field Assisted Abrasive Finishing (MFAAF) process is one of the popular finishing processes which

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has the capability to produce micro/nano level surface finish with minimal surface defects. In MFAAF process, a homogeneous mixture of abrasive and iron particles is prepared and placed in the machining gap between the workpiece and the electro magnet. This properly configured mixture of iron and abrasive particles forms a Magnetic Abrasive Flexible Brush (MAFB) between the workpiece and the electromagnet. During MFAAF process, magnetic stress is created on the workpiece surface and MAFB interface due to the magnetic lines of force passing through the workpiece [1]. The magnetic force acting on an abrasive particle in the machining gap is considered as the finishing force and it has two components: One in the direction normal to the workpiece top surface (Fn) and tangential cutting force (Fc) at 90^0 to this normal force and in the plane of workpiece surface as shown in Fig. 1.

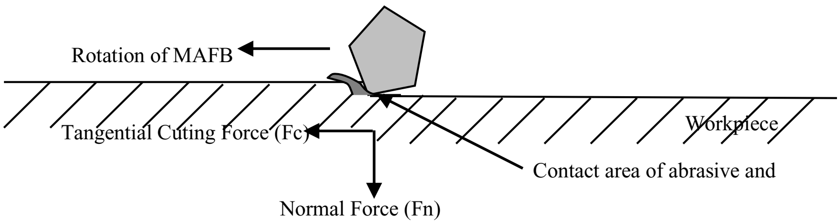


Fig. 1 Schematic view of abrasive indentation and force components acting during MFAAF [2]

The finishing forces have direct influence on the generation of finished surface and accuracy of the workpiece. As the induced magnetic force plays a main role for the formation of magnetic abrasive flexible brush and providing abrasion pressure against the work surface, the knowledge of finishing forces acting during MFAAF is important to understand the mechanism of material removal [2,3].

To understand the effect of process parameters on the finishing forces in MFAAF process, theoretical studies have been made to reveal the forces involved in MFAAF process. Kim and Choi [4,5] developed mathematical models to study the finishing pressure applied by the MAFB during magnetic polishing of free form surfaces. They found that the finishing pressure is less than 50 kN/m^2 and finishing force varies between 16 to 75 N depending upon the machining gap. Mori et al. [6] analysed the mechanism of MFAAF process by developing the theoretical equation for normal and tangential force generated during the process. They observed that the variation in normal force for different magnetic abrasive weight percentage and it is found to vary between 0 to 20 N. The calculated values of normal forces agree well with measured values for a nonmagnetic stainless steel material. Jayswal et al. [7] proposed a finite element model to study the magnetic force distribution on the work piece. Though these theoretical investigations provided a basic understanding of forces involved in MFAAF process, they were inadequate as the developed theoretical equations for the forces are established based on the general assumptions such as homogeneous mixture and uniform strength of MAFB, density of the brush. However, in practice, MAFB strength is non uniform and the distribution of active cutting edges interacting with the work piece surface is not homogeneous in the brush [8].

Several experimental studies have been carried out on MFAAF process for analysing the effect of process parameters on the finishing forces. Shinmura and co-workers in Japan have extensively studied the MFAAF process on magnetic and nonmagnetic materials for flat and cylindrical surfaces. Shinmura et al. [9] studied the effect of various process parameters like magnetic flux density, working gap, different types of abrasives, and cutting speed on finishing characteristics. It was found that the magnetic abrasive particles exert sufficient pressure on the work piece surface depending upon the value of magnetic flux density. Shinmura et al. [10] conducted experimental studies to understand the principle of magnetic abrasive process. They noticed that MAFB supplies sufficient abrasion pressure to finish the work surface corresponding to the strength of magnetic field. Recently, Jain et al. [2] analysed the finishing forces acting on magnetic and non magnetic materials. They reported that percentage of oil in MAFB is not a significant factor for normal force, but it is a significant factor to the tangential force. Singh et al. [11] designed and fabricated a strain gauge based force transducer (ring dynamometer) which measures the forces as low as 0.5 N. In continuation of his work, Singh et al. [12] performed further experiments to study the correlation between the surface finish and the finishing forces. From the experimental studies, it was observed that the normal and tangential finishing forces are important parameters which influence the surface finish generated by MFAAF process. Oh and Lee [13] measured force signals using a Kistler dynamometer for monitoring and predicting the surface finish of S136 die steel work piece. It is found that the finishing force signal is significantly affected by the major process parameters such as machining gap, abrasive size, and feed rate during MFAAF process as observed by Singh et al. [12]. Mulik and Pandey [14] studied the finishing forces using various process parameters like voltage to the electromagnet, working gap, abrasive weight percentage and rotational speed. Out of all selected process parameters they found that voltage to the electromagnet and working gap played a dominant role. Through experimentation they also observed that the normal force varied between 12-24 N and the finishing torque value was found within 4-11 Nm. Kala and Pandey [15] measured force and torque for their newly developed double disk magnetic abrasive finishing process. It is found that the average normal force varies between 45 to 73 N and average finishing torque is 0.214 to 0.478 Nm.

From the literature survey, it is understood that finishing force analysis in MFAAF process is important to understand the mechanism of material removal in MFAAF process. It is also noted that extensive experimental study on finishing force measurements in MFAAF process has been carried out by various researchers, however, the effect of feed rate on finishing forces is not included in the experimentation. This paper presents the experimental measurement results of finishing forces in MFAAF process of SS316L grade non magnetic material. The effect of different process parameters on the finishing forces were analyzed using statistical analysis and results were discussed in this paper.

2. Experimental Details

In the present work, an experimental investigation was carried out to study the effect of process parameters on finishing forces in MFAAF process for SS316L material. The MFAAF setup was developed in a milling machine suitable for finishing planar surfaces. Kistler cutting force dynamometer was utilized for measuring finishing forces during MFAAF process. The proposed experimental setup consists of a precision vertical milling machine, electromagnet spindle assembly, magnetization unit, instrumentations and PC based data acquisition system. The photographic view of MFAAF experimental setup is depicted in Fig. 2.

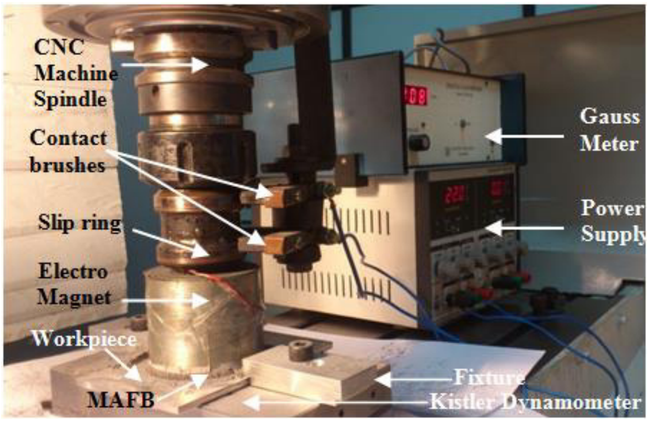


Fig. 2 Photographic view of MFAAF experimental setup [16]

2.1. Selection of process parameters

In the present work, a detailed experimental investigation has been carried out to study the effect of process parameters on finishing forces in MFAAF process for SS316L work material using Taguchi experimental design. Based on the preliminary experiments and the available literature on MFAAF process [11, 12, 14], the key process parameters and their levels that strongly influence the process outcomes were identified. Table 1 shows the levels of the selected variable process parameters and the other parameters like finishing time (15 min), iron particle grain size (300 mesh), total amount of magnetic abrasive particle (10 g) and mixing ratio (80% Fe, 20% SiC abrasive) were kept constant for the experiment.

Table 1 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

2.2. Force measurement in MFAAF process

The experimental arrangement of MFAAF process in a milling machine with the force measurement system is shown in Fig. 2. The finishing forces (Normal Force and Tangential force) were recorded using Kistler force dynamometer (Model 9257B) with charge amplifier (Model 5070A). Fig. 3 shows the sample acquired force data for normal and tangential force from KISTLER dynamometer. It was observed that the magnitude of normal force is higher than the tangential force.

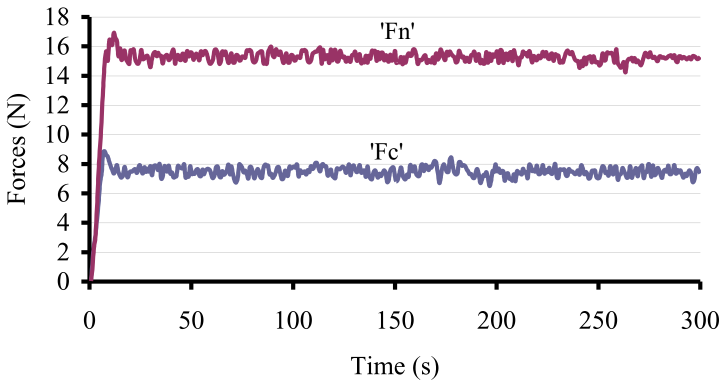


Fig. 3 Forces at voltage = 20 V, machining gap = 2.0 mm, mesh no.= 400, Rotational speed = 405 RPM, Feed rate = 105mm/min (Expt. no :18).

3. Results And Discussions

This section presents the experimental data analysis for the finishing forces acquired during the MFAAF process. Table 2 shows the Taguchi L_{27} orthogonal array selected to investigate the effect of selected process parameters and its output response like measured normal force and tangential force. In order to identify the influencing process parameters on finishing forces of MFAAF process, standard statistical analysis such as signal to noise ratio and analysis of variance (ANOVA) has been carried out on the finishing force data. Minitab statistical software is used for the statistical data analysis and the results are presented in this section.

Table 2 Experimental Matrix (L_{27}), and output responses (Fc and Fn)

3.1.

Expt No.	*A* (V)	*B* (mm)	*C* (RPM)	*D* (Mesh no.)	*E* (mm/ min)	*Normal Force (Fn)* (N)	*Finishing Force (Fc)* (N)
1	18	1.50	270	400	35	19.78	10.04
2	18	1.50	270	400	70	17.58	9.76
3	18	1.50	270	400	105	18.16	8.54
4	20	1.75	270	800	35	16.03	9.52
5	20	1.75	270	800	70	10.50	10.01
6	20	1.75	270	800	105	16.97	5.29
7	22	2.00	270	1200	35	30.77	10.56
8	22	2.00	270	1200	70	23.43	10.3
9	22	2.00	270	1200	105	21.02	10.06
10	22	1.50	405	800	35	33.2	14.16
11	22	1.50	405	800	70	33.50	8.42
12	22	1.50	405	800	105	20.26	8.91
13	18	1.75	405	1200	35	15.68	8.30
14	18	1.75	405	1200	70	11.23	6.34
15	18	1.75	405	1200	105	16.6	12.27
16	20	2.00	405	400	35	14.26	8.29
17	20	2.00	405	400	70	14.17	8.25
18	20	2.00	405	400	105	15.26	7.83
19	20	1.50	540	1200	35	23.8	11.13
20	20	1.50	540	1200	70	20.51	12.69
21	20	1.50	540	1200	105	24.42	10.98
22	22	1.75	540	400	35	21.02	10.62
23	22	1.75	540	400	70	25.88	10.49
24	22	1.75	540	400	105	27.20	11.65
25	18	2.00	540	800	35	13.07	7.20
26	18	2.00	540	800	70	13.04	6.94
27	18	2.00	540	800	105	12.99	6.83

3.1. S/N ratio Analysis:

Since higher finishing forces are desirable for the improved material removal in MFAAF process, S/N ratio is calculated from the experimental finishing force data which provides a measure of robustness to identify the control factors that reduce the variability in the process. It is calculated as the ratio of the desirable values (i.e., mean for the output characteristic), and noise represents the undesirable values (i.e., the square deviation for the output characteristic). The S/N ratio is calculated using the following formula:

$$\eta = -10\log\left(\frac{1}{n}\sum\frac{1}{y_i^2}\right) \quad (1)$$

Where n represents the number of measurements and y_i is the measured values.

In this study, the-larger-is-the-better type of the signal-to-noise ratio was selected as the quality characteristic. In order to analyze the effect of individual process parameters on normal force and tangential force, the delta value were 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 3 and Table 4 show the ranking of different parameters based on the values of delta obtained for normal force and tangential force respectively. The factor having the highest value of delta was assigned as first rank and so on.

Table 3 Response Table for Signal to Noise Ratios for Normal Force (Fn)

Level	A	B	C	D	E
1	23.58	27.18	25.41	25.47	25.94
2	24.49	24.65	25.13	24.79	24.9
3	28.23	24.48	25.76	26.05	25.46
Delta	4.65	2.7	0.63	1.26	1.05
Rank	1	2	5	3	4

Table 4 Response Table for Signal to Noise Ratios for Tangential Finishing Force (Fc)

Level	A	B	C	D	E
1	18.37	20.31	19.26	19.48	19.83
2	19.16	19.17	19.04	18.36	19.14
3	20.4	18.45	19.64	20.09	18.96
Delta	2.03	1.86	0.61	1.73	0.87
Rank	1	2	5	3	4

Based on the S/N ratio analysis on experimental finishing force data, it is observed that the voltage supplied to the electro magnet influences the finishing forces significantly followed by machining gap, abrasive size, feed rate and rotational speed of electro magnet. The mean of S/N ratios for the process parameters on normal force and tangential force were depicted in Figs. 4 and 5 respectively.

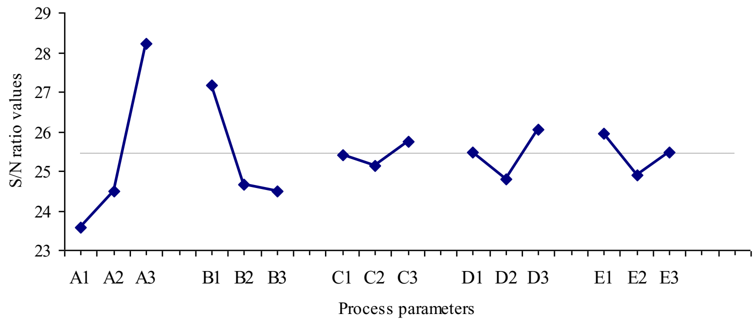


Fig. 4 Main effect plot for normal finishing force (Fn)

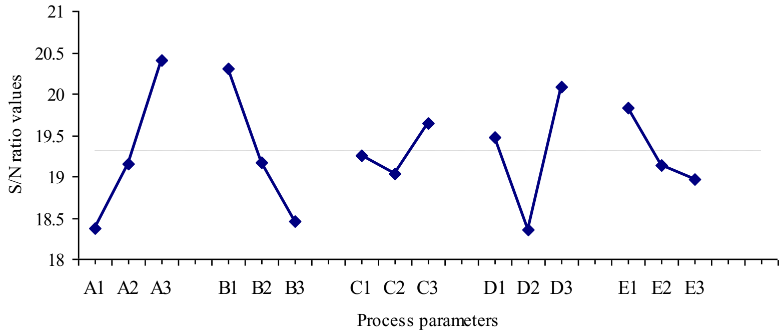


Fig. 5 Main effect plot for Tangential force (Fc)

From the S/N ratio results, it is inferred that the normal force and tangential force are significantly influenced 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).

3.2. Analysis of variance for normal and tangential finishing forces

In order to understand the significant process parameters influencing the normal force and tangential force in MFAAF process, Analysis of Variance (ANOVA) was carried out on the experimental data shown in Table 2. The ANOVA results for normal force and tangential force are shown in the Tables 5 and 6 respectively.

Table 5 ANOVA results for normal force (Fn)

Source	DOF	SS	MS	F-ratio	P-value
A	2	607.89	303.95	22.10	0.000**
B	2	198.22	99.11	7.21	0.006**
C	2	4.42	2.21	0.16	0.853
D	2	20.06	10.03	0.73	0.498
E	2	19.81	9.91	0.72	0.502
Error	16	220.08	13.76		
Total	26	1070.49			

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

The calculated F-values for voltage (A) and machining gap (B) are 22.10 and 7.21 respectively and it is greater than the F-critical (tabulated value $F_{0.05, 2, 16}$ = 3.6337) for a significance level of α = 0.05. It indicates that the process parameters are statically significant for 95% confidence level.

From the ANOVA results, it is found that the voltage applied to the electromagnet (56.79% contribution) and machining gap (18.52% contribution) have significant contributions on the generation of normal force (Fn). The effect of other factors such as abrasive size, feed rate and rotational speed of the electro magnet are insignificant on Fn.

Table 6 ANOVA results for Tangential Finishing Force (Fc)

Source	DOF	SS	MS	F-ratio	P-value
A	2	30.194	15.097	4.98	0.006**
B	2	28.804	14.402	4.87	0.007**
C	2	4.042	2.021	0.31	0.737
D	2	15.176	7.588	2.01	0.166
E	2	9.706	4.853	0.57	0.579
Error	16	22.408	1.276		
Total	26	110.329			

** Highly Significant (P < 0.05); F0.05, 2, 16 = 3.6337

The calculated F-values for voltage (A) and machining gap (B) are 4.98 and 4.87 respectively. Further, the computed F-value is greater than the F-critical ($F_{0.01, 2, 16}$ = 3.6337) for a significance level of α = 0.05. It indicates that the process parameters are statically significant for 95% confidence level.

It is also found that the tangential cutting force (Fc) is significantly influenced by voltage applied to the electromagnet (27.37%), machining gap (26.10%) and abrasive size (11.94%). The other process parameters like rotational speed of the electro magnet and feed rate are having less than 10% contribution on tangential force. It is also to be observed that the ANOVA results obtained for normal force and tangential force confirms the results obtained by S/N ratio analysis.

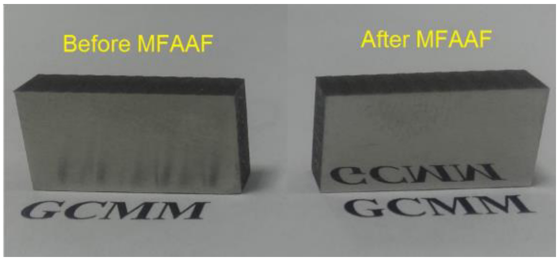
3.3. Validation of the experimental investigation

Confirmation experiments have been performed at optimum process parameter levels (A3B1C3D3E1) as obtained from S/N ratio. Table 7 shows the optimal process parameter combinations of MFAAF process and the corresponding results for normal and tangential cutting forces.

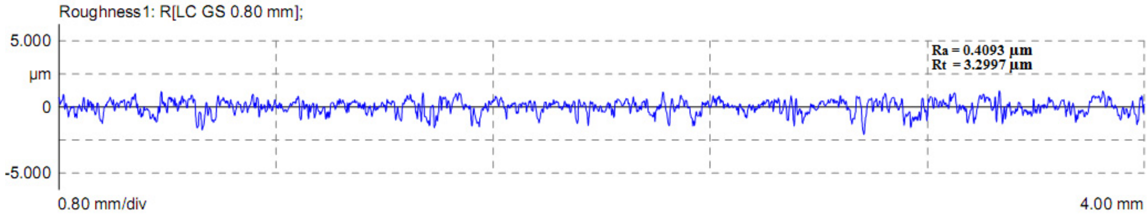
Table 7 Confirmation test result for optimal process parameters combination

Optimal combinations					*Confirmation Results*	
A (V)	B (mm)	C (rpm)	D (mesh no.)	E (mm/min)	Fn (N)	Fc (N)
22	1.5	540	1200	35	33.92	13.26

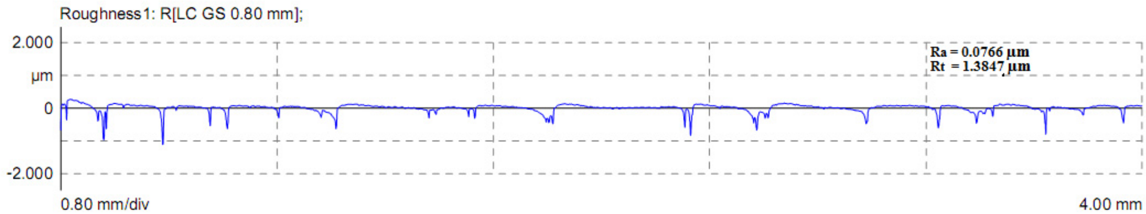
For the optimum process parameters, it was found that normal and tangential force was 33.92N and 13.26 N. The sample of measured surface finish (using Mahr surftest equipment) before and after MFAAF operation at optimum process parameters conditions are shown in Fig. 6 (b) and 6 (c) respectively.



(a) Workpiece sample before and after MFAAF process



b) Before MFAAF process



c) After MFAAF process

Fig. 6 Measured surface finish before and after MFAAF process at optimum levels
(A= 22V; B= 1.5 mm; C= 540 rpm; D= 1200 mesh no. E= 35 mm/min)

It can be seen that peaks in the work surface has been removed during MFAAF process which is due to the indentation and micro chipping provided by the normal force and tangential force respectively. This leads to the improved mirror like surface finish of 0.0766 µm on SS316Lwork surface as shown Fig. 6(a). These results prove the application of MFAAF process for obtaining the sub-micron level, mirror like surface finish on SS316L material.

4. Conclusion

This paper presented the statistical analysis of normal and tangential forces during MFAAF process on SS316L material for the process parameters like voltage supplied to the electromagnet, machining gap, rotational speed of electromagnet, abrasive size and feed rate. Taguchi design of experiments based L27 orthogonal array is selected to investigate the effect of selected process parameters. Based the results from the experimental investigations on MFAAF process, the following conclusions were drawn the present investigations:

- Based on the S/N ratio analysis and ANOVA analysis, it is found that finishing forces (Fn and Fc) are significantly influenced by the high level voltage of 22V, low level machining gap of 1.5mm, higher mesh size of 1200 mesh followed by higher rotational speed of 540 rpm.

- From the ANOVA analysis, It is observed that the calculated F-values are greater than the F-critical values for a significance level of $\alpha = 0.05$. It indicates that the selected process parameters are statically significant for 95% confidence level.
- The effect of voltage supplied to the electromagnet and the machining gap are the most significant factors in determining the normal and tangential cutting force generated during MFAAF process. Higher voltage (22 V) and lower machining gap (1.5 mm) increase both the normal and tangential forces. It is observed that, the maximum normal force and tangential force is found to be 33.92 N and 14.16 N respectively.
- MFAAF process produces mirror like surface finish on SS316L with the surface finish (Ra) value of 0.0766 μm at the optimal finishing conditions obtained.

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