Evaluation of Parameters Affecting Magnetic Abrasive Finishing (MAF) of Superalloy Inconel 718

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Abstract: Superalloys generally are among the materials with poor machinability. The removal of metal contaminations, stains, and oxides can positively affect their performance. Magnetic Abrasive Finishing (MAF) is a method which uses a magnetic field to control the material removal. As another advantage, this method can be used to polish materials such assuperalloys which have high strength and special conditions. In this paper, we investigated the magnetic abrasive finishing of nickel-base superalloy Inconel 718. Since the process is highly influenced by several effective parameters, in this study we evaluated the effects of some of these parameters such as percentage of abrasive particles, gap, rotational speed, feed rate, and the relationship between size of abrasive particles and the reduction of average surface roughness. Using Minitab software package the experiments were designed based on a statistical method. Response surface method was used as the design of the experiment. The regression equation governing the process was extracted through the assessment of effective parameters and analysis of variance. In addition, the optimum conditions of MAF were also extracted. Analysis of the outputs of MAF process experiments on IN718 revealed that gap, weight percent of abrasive particles, feed rate, rotational speed, and size of abrasive particles were the factors that affected the level of changes in surface roughness. The distance between the magnet and the work piece surface, i.e. the gap, is the most important parameter which affects the changes in surface roughness. The surface roughness can decrease up to 62% through setting up the process at its optimum state i.e. in a rotational speed of 1453 rpm, feed rate of 10 mm/min, percentage of abrasive particles equal to 17.87%, size of particles equal to #1200, and gap size of 1 mm. There is a discrepancy of 13% between this prediction and the predicted value by the regression model. With mounting a magnet with a different pole beneath the work piece, magnetic flux density increases up to 35%.

Keywords: Design of experiments, Inconel 718, Magnetic abrasive finishing, Response surface method, Smulation

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1 INTRODUCTION

Superalloys, which are known as heat-resistant or high-temperature alloys, are materials that can be machined at temperatures above 1000˚ F (540˚ C). Compared with other groups of alloys, superalloys have the best combination of several features, including high temperature corrosion resistance, oxidation resistance, and creep resistance. Because of these characteristics, superalloys are widely used in aircraft engine components and in industrial gas turbine components used for power generation. Because of their excellent corrosion resistance, they are also specifically utilized for petrochemical, oil, and biomedical applications. One of the main characteristics of superalloys is the relationship between their strengths and their high resistance to the temperature. In pure metals and most of alloys with an increase in temperature, strength decreases. However, this is not the case for strengthened superalloys [1].

When using superalloys for creating an object, generally, machining is required; the objects made from superalloys commonly require a sequence of machining processes. As there are some drawbacks with every type of material, historically superalloys have poor machinability. There are some features which make a material a perfect choice for high temperature applications however those features negatively affect the machinability. In comparison with other steels, machining superalloys is highly expensive. Additionally, decreased speed of a cutting tool can limit productivity. The higher cost of machining superalloys is due to their cutting speed which is about 5% to 10% of the cutting speed for other steels. Many of the machinability boosting methods do not work well for superalloys. Alloys modification and heat treatment are not feasible due to their negative influence on mechanical properties [2].

Mechanically finishing process is critical for aerospace components because the quality of the machined surface may influence the useful life of the components. Great care is taken to ensure the lack of metallurgical damage to the component surface after the final finishing. Moreover, surface finishing of superalloys is crucial since metallic contaminants, oxides, tarnish, and laminates resulting from hot working conditions or heat treating operations can adversely affect superalloys performance. Some contaminants such as lower-melting metals can cause severe surface attack and reduce a component to scrap.

After being in contact with cutting tools, forming dies, machining tool, and/or heat treatment fixtures, the surfaces of these temperature resistive alloys are contaminated with other metals. These pollutants are not always harmful, but in some conditions they are destructive. For instance, IN750 is usually not affected by Zn particles remained from drawing dies' surfaces but Al particles at high temperatures can interact with superalloys and reduce corrosion resistance and strength of the contaminated zone [3].

On the other hand, one of the other recently developed methods is finishing under the control of magnetic forces using the magnetic abrasive particles. In this method, magnetic field is imposed using a permanent magnet and abrasive particles join each other in chains. When these chains gather they make a magnetic abrasive brush. Abrasive particles have a smaller size than magnetic particles and they are attached to magnetic particles.The force imposed on magnetic particles leads abrasive particles with high hardness, like AL2O3,SiC, to penetrate in the surface of the work piece. The imposed forces and the penetration depth are expressed by measuring units of micro Newton and micro meters, respectively. After the initiation of a relative movement between abrasive brush and work piece, it becomes possible to remove the micro materials. Due to the flexibility of the magnetic abrasive, every type of surfaces with intricate shapes can be finished. Using the magnetic field guarantees the uniformity of the forces imposed on the work piece surface [5]. Some of the advantages of MAF over the other methods are: negligible shear stress due to small penetration depth, imposing compressive stresses, and reduction of the process heat. Furthermore, unlike most of chemical methods, this process does not cause environmental pollutions. In the past, MAF was mostly applied on the surface of ferromagnetic metals [6].

Some studies have been conducted to assess the application of MAF on non-ferromagnetic metals like Stainless steel 304 [7], [8]. Work pieces made of Aluminum, Brass, Magnesium and ceramic are also investigated in previous studies [9-12].

In order to improve the magnetic flux density in the working gap while finishing a paramagnetic material, Kim and Kwak [12] used a single pole electromagnet and installed a permanent magnet under a magnesium alloy work piece (AZ31). They reported an improvement in the magnetic flux density available in the working gap (maximum magnetic flux density of 0.2 mT). They observed that addition of permanent magnet yielded a better surface finish when compared with performing finishing without permanent magnet. They were able to reduce the surface roughness of the work piece from 0.358 m to 0.190 m in 15 min.

Using a similar approach [12] of incorporating a permanent magnet beneath the work piece, Kim et al. [11] finished aluminium–SiC based composite. By producing a maximum magnetic flux density of 0.2 mT they reduced the surface roughness of the composite material workpiece from 1.2 µm to 0.4 µm in 50 min. Mulik and Pandey exerted ultrasonic vibration to overcome the drawback of deep scratches in polishing the AISI 52100 steel surfaces [13]; Lin et al. employed MAF to polish free-form surface of the stainless SUS304 material [14].

This study aimed to assess the effects of MAF on the quality of IN718 surface. The objectives of this study were to specify the parameters influencing the process and determine the optimum conditions of MAF. The regression equation governing the process was extracted through the assessment of effective parameters and analysis of variance. In addition, the optimum conditions of MAF were also extracted. Analysis of the outputs of MAF process experiments on IN718 showed that gap, weight percent of abrasive particles, feed rate, rotational speed, and size of abrasive particles were the factors that affected the level of changes in surface roughness.

2 EXPERIMENTS

2.1. Simulation and measuring the magnetic flux density (Tesla)

The MAF is more efficient for ferromagnetic objects than for non- ferromagnetic materials. Producing a magnetic circuit between magnet pole and ferromagnetic metal leads to a higher density of abrasive particles and results in better outcomes. In such a condition, it becomes possible to keep abrasive powder concentrated on work piece surface even in high rotational speeds. In fact, ferromagnetic metal acts as an opposite pole of the magnet. However, this is not the case for non-ferromagnetic metals. When using such metals, a magnet pole which is the opposite of the pole of machining head can be mounted under the work piece to increase the efficiency of the process. IN718 is a non-ferromagnetic material with relative magnetic permeability coefficient of about 1. Table 1 presents the chemical composition of IN718 which was used in the present study. Table 2 presents the mechanical and physical properties of IN718 in 21°.

Table 1 IN718 chemical composition

%Al	%Mn	%Cr	%Mo
0.454	0.091	17.97	1.84
%Fe	%W	%V	Inconel
15.90	0.194	0.029	718
%Co	%Cu	%Ta	%Ti
0.122	0.034	0.269	1.13
%Hf	%Si	%Ni	%Nb
0.214	0.010	57.6	4.15

In order to investigate the effects of mounting an extra magnet with different pole under the work piece, simulation and measuring methods were used. Simulation was performed using MAXWELL finite element software which could present the changes in average magnetic flux density (mT) through mounting a magnet with different pole beneath the work piece. Using a gaussmeter, magnetic flux density was measured and compared with the results of the simulations. Fig. 1 shows the procedure of measuring magnetic flux density using PHWVE; the measurement was performed within a range of 0-2 Tesla.

Table 2 IN718 mechanical and physical properties in 21°

Yield strength (MPa)	Elastic modulus (GPa)	Hardness (HV150)
1110	206	370
Density (g/cm3)	Melting point (c)	Thermal conductivity (w/mk)
8.19	1300	11.2

Fig. 1 Measuring procedure of magnetic flux density (mT) using gauss meter

Fig. 2 clarifies the influence of opposite pole on magnetic flux density vector. Fig. 3 illustrates the distribution of magnetic flux density (mT) in the length of IN718 (16mm) and 2mm far from the surface of the magnet with (a) and without (b) opposite permanent pole according to the simulation and results of measurements. It should be mentioned that the effect of mounting a magnet with different pole beneath the work piece depends on its size (dimension) and its distance to the work piece. The conditions governing the simulation and measurements are presented in Table 3. All the tools used for the measurements were made of non-ferromagnetic materials to avoid unwanted influence on magnetic flux density. As shown, there was a good correlation between the results of simulations and measurements. However, maximum discrepancy was 28%.

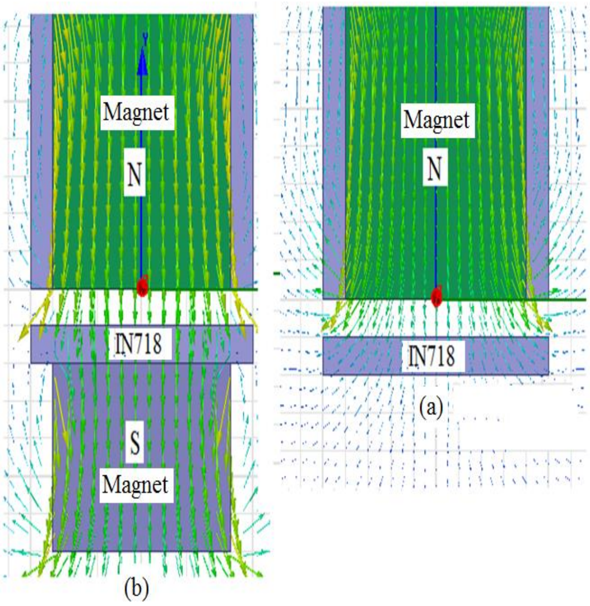


Fig. 2 Magnetic flux density vector on IN718(a-without permanent magnet with different pole ,b-with permanent magnet with different pole)

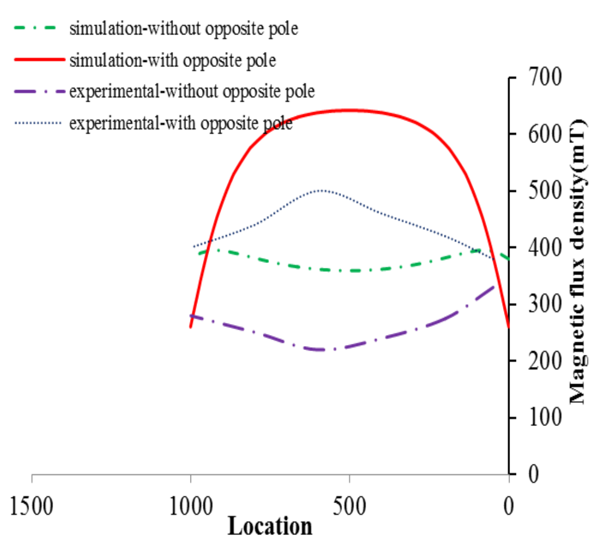


Fig. 3 Magnetic flux density distribution in IN718 using simulation and measuring results (miliTesla)

Table 3 The simulation and measuring condition

Item	Condition
Magnet	N35
Workpiece	IN718
Fixture	Al7075
gap	2 mm

2.2. Experimental setup

Due to the difficulties in using electrical magnets, in this study a permanent NdFeB was used. To carry out the experiments, aluminum fixtures were used to hold the cylindrical magnet with a diameter and height of 25 and 10 mm, respectively. The fixture used to hold IN718 work piece was made of Teflon; in addition, a slot is designed and set at the bottom of the fixture to mount the magnet with a different pole. The dimension of the sample was 600 mm× 200 mm× 3mm.The change in average surface roughness was considered as the output of the experiments. To increase the accuracy and reliability of the tests, before conducting the experiments on each sample, they were placed in an ultrasonic bath filled with acetone for 20 minutes. Then measurements were performed at the center of the work piece and also in an area with a length of 50 mm and a width of 30 mm. The measurements were performed at 8 points using surface roughness measuring set of Surtronic 3+ with a cut off length of 0.8. The measurement process was carried out in accordance with DIN EN ISO 0274:1998 standards [15].

The average surface roughness was achieved through calculating the average values of measurements. A 3-axis Computer numerical control (CNC) mill was used for the experiments. Fig. 4 depicts the procedure of the experiments and the equipment used in this study.

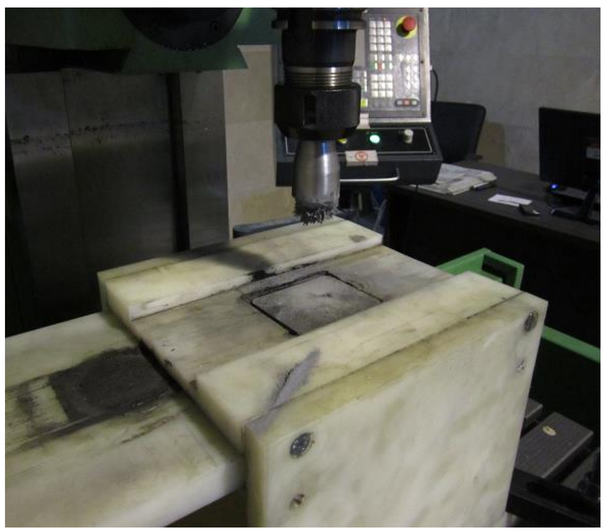


Fig. 4 Magnetic abrasive finishing process on IN718 surface

The MAF process relies on many different parameters (about 14 independent parameters). Simultaneous study of all these parameters needs too many experiments, where analysis and control of inevitable errors is very complicated. In this paper, based on statistical methods, effective parameters namely gap, rotational speed, feed rate, percentage, and size of the abrasive particles were investigated. Response Surface Method was used for designing experiments. This method decreases the number of required experiments; using analysis of variance (ANOVA), we investigated the effective parameters and optimum conditions [16]. Minitab V16 software package was used for designing and analysis of the experiments. Other process parameters, which were considered as constants, are listed in Table 4.

Table 4 The experiment's constants

Item	condition
Work piece	IN718
Weight of powder	4Gr
Fe size	400 mesh #
Abrasive	SiC
Weight ratio (Magnetic/ abrasive)	3/1
Lubricant	SAE30
Lubricant ratio in powder	٪5
Permanent magnet	35 N

To carry out the tests we used unbonded particles as they could be prepared more simpler and cheaper than other abrasive powder preparation methods like sintering and mechanical alloys. For the magnetized phase, we used Iron particles sized #400. They were mixed with SiC (with different meshes and different compound ratios) for 20 minutes using a mechanical stirring machine in different speeds. Taking into account the cross sectional area of the magnet and the space between magnet and work piece, the required volume of the powder was measured. In each experiment some new powder was used. Type and amount of lubricant can affect the surface quality. In our experiments, SAE30 lubricant with a combination percentage of 5% to the whole volume of the powder was applied. The percentage of changes in surface roughness was set as the desired response of the experiments and was calculated using Equation1.

$$\Delta \mathrm{Ra}(\%) = \frac{\text{initial roughness of the surface} - \text{finished roughness of the surface}}{\text{initial roughness of the surface}} \quad (1)$$

As shown in Table 5, the studied parameters and their values are presented in five levels. Considering α = 2 and using response surface method, the experimental design was performed for 5 parameters; hence, 33 experiments with two blocks were specified.

Table 5 The process parameters and levels to study percentage change in surface roughness

Factors	α–	-1	0	1	α
Gap(mm)-G	0.5	1	1.5	2	2.5
Percent (Wt%)-P weight of abrasives	10	17.5	25	32.5	40
Mesh number(abrasive) -M	400	600	800	1000	1200
(mm/min)- F Feed rate	10	20	30	40	50
Rotation (rpm)-V of magnet	100	600	1100	1600	2100

To avoid likely errors in experiments, tests were performed randomly and we did not follow the order presented in the table.

Table 6 The regression model coefficients and lack of fit in primary and modified model

Modified model		Initial model		
Coefficient Regression	P-value	Coefficient Regression	P-value	Terms
40.8679	0.000	40.8708	0.000	Constant
-	-	-0.0143	0.981	Block
-6.6692	0.000	-6.6692	0.000	Gap
-2.1078	0.003	-2.1075	0.008	%wt
4.5908	0.000	4.5908	0.000	Mesh #
-4.036	0.000	-4.0367	0.000	Feed rate
-2.9225	0.000	-2.9225	0.001	RPM
-1.7039	0.005	-1.7041	0.013	Gap×Gap
-2.1214	0.001	-2.1216	0.004	%wt×%wt
-	-	-0.2729	0.467	Mesh#×Mesh#
-	-	0.2696	0.651	Feed rate ×Feed rate
-3.9877	0.000	-3.9879	0.000	RPM×RPM
-	-	-0.9512	0.257	%wt×Gap
-2.2575	0.007	-2.2775	0.016	Mesh Number×Gap
-	-	0.6013	0.466	Feed rate×Gap
-2.8925	0.001	-2.8925	0.004	RPM×Gap
-	-	-1.0300	0.222	Mesh#×%wt
-	-	0.9287	0.268	Feed rate× %wt
-2.7625	0.001	-2.7625	0.005	RPM×%wt
-	-	0.5350	0.516	Feed rate×Mesh#
-	-	-0.4233	0.605	Feed rate×Mesh#
-	-	-0.5675	0.491	RPM×Feed rate
-	0.491	-	0.36	Lack of fit

2.3. Data analysis and results

Taking into account the results obtained for the changes in surface roughness, the model was modified, and insignificant parameters were deleted. Table 6 presents the results of analysis of variance(ANOVA) and the coded coefficients governing regression equations. It should be noted that effective parameters are those with a p value lower than 0.05 at a confidence interval of 95%. Considering the results obtained from data variance analysis and the modified model, the explicit regression equation governing the model, as a function of process variables, was calculated using Eq. (2).

$$\Delta R_a(\%) = -77.54 + 44.87 \times G + 2.41 \times P + 0.068 \times M - 0.40 \times F + 0.070 \times V - 6.8 \times G^2 - 0.03 \times P^2 - 3.98 \times V^2 - 0.022 \times G \times M - 0.011 \times G \times V - 2.76 \times P \times V \qquad (2)$$

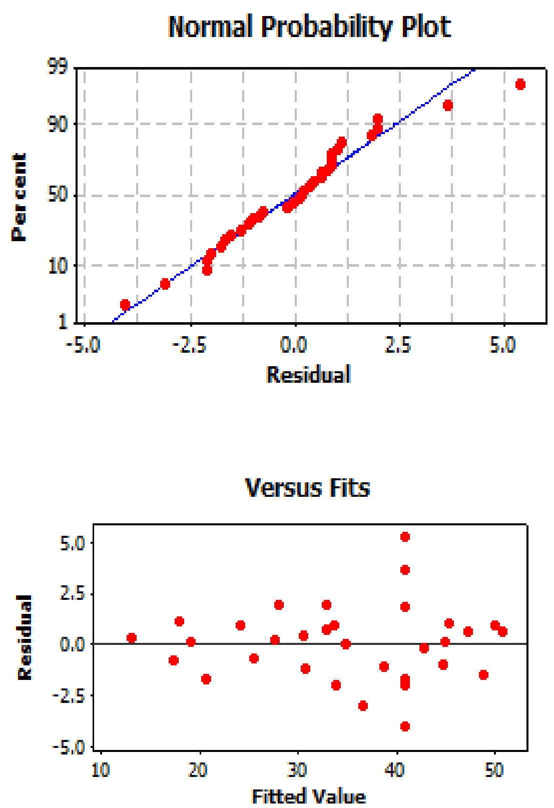


Fig. 5 Diagrams for residuals distribution

Where $R - Sq = 94.79\%$ and $R - Sq(adj) = 91.66\ \%$. It shows the acceptable accuracy of the proposed model designed using response surface method. Moreover, Fig. 5 shows the diagrams obtained from the analysis and scattering of the residuals which are well correlated. Hence, lack of fit of the model becomes ineffective.

2.4. Effects of significant parameters

To accurately analyze the effects of significant parameters, it is necessary to consider both the effects of main parameters and their interaction as well. As shown in Table 7, p values obtained for all the parameters are significant. Figure 6 illustrates the diagram of the effects of main parameters.

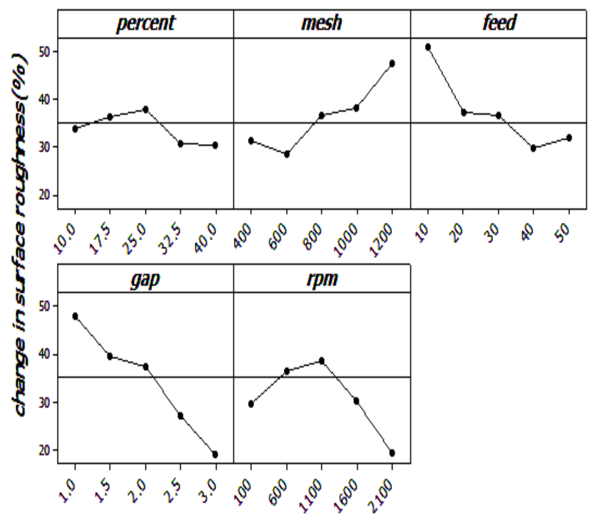


Fig. 6 Effect of main parameters

2.4.1. Effects of the main parameters

2.4.1.1. Effect of Gap

As shown in Fig. 6, with increasing the gap between the magnet and the work piece surface, the average surface roughness decreased. With increasing the distance between the work piece and the magnet surface, the amount of magnetic flux lines passing the surface, i.e. the magnetic flux density, decreased. Magnetic force is dependent on magnetic flux density and therefore with increasing the distance from the magnet surface, magnetic force decreases. The reduction in magnetic force affects surface roughness in two ways. First, since a weak joints- lubricant powder was used in rotational movement of the magnet, it was not able to hold the powder located in higher distances and they were thrown away. Therefore, the number of cutting edges decreased and therefore the changes in surface roughness decreased too. On the other hand, with a decrease in magnetic force, the depth of penetration into the work piece surface decreased and consequently abrasive particles were not able to remove ups and downs with a height or depth more than the penetration depth. This reduced the changes in surface roughness. Based on the results of regression coefficient table, it can be inferred that the effect of gap was more significant than the effects of the other variables. Moreover, since the second order of this parameter was effective, its behavior was not linear, and it was curved-shape. This curvature is shown in Fig. 7.

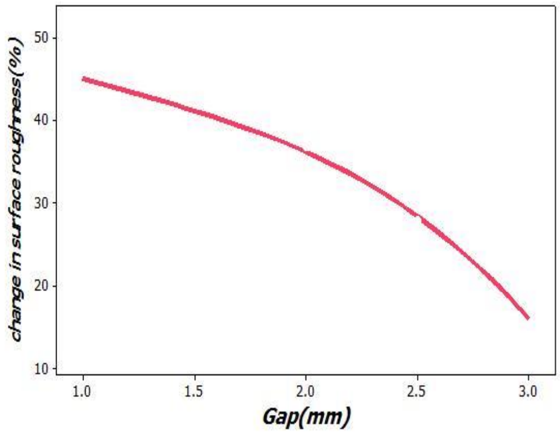


Fig. 7 Effect of finishing gap

2.4.1.2.Effect of weight percent of abrasives particles

As shown in Fig. 6, with increasing abrasive particles ratio in mechanical compound of finishing powder, the changes in surface roughness increased too but it stopped its increasing at higher abrasive particles ratios. In addition, with increasing the amount of abrasive particles in the finishing compound, the changes in surface roughness decreased. This phenomenon can be attributed to the fact that, at first with increasing abrasive particles ratio, the number of cutting edges increased which boosted change in surface roughness. However, the amplitude of the force acting on each particle decreased which in turn decreased the penetration depth. Nevertheless, very high magnetic force rose the penetration depth and caused a scratched surface which adversely affected the surface roughness. Overall, with increasing the number of abrasive particles in the compound with the same volume, the relative number of magnetic particles was reduced and since these particles transfered magnetic forces to abrasive particles, with a reduction in their number, the magnetic forces were not suitably transferred. This can lead to a reduction in penetration depth and process efficiency. Besides, when using higher rotational speeds, magnetic abrasive brush cannot hold abrasive particles and therefore the number of abrasive particles and cutting edges reduce. Considering the effectiveness of the second order of this parameter, its influence is depicted in Fig. 8.

2.4.1.3. Effect of particles size

With increasing the mesh size, the average diameter of abrasive particles decreased. Therefore, with a constant weight percent, the number of abrasive particles increased. This increase boosted the number of cutting edges and increased the efficiency of the process. On the other hand, with such an increase in the number of abrasive particles, the force imposed on abrasive particles decreased and this kept the penetration depth at a normal level which led to the preparation of a surface with a high quality.

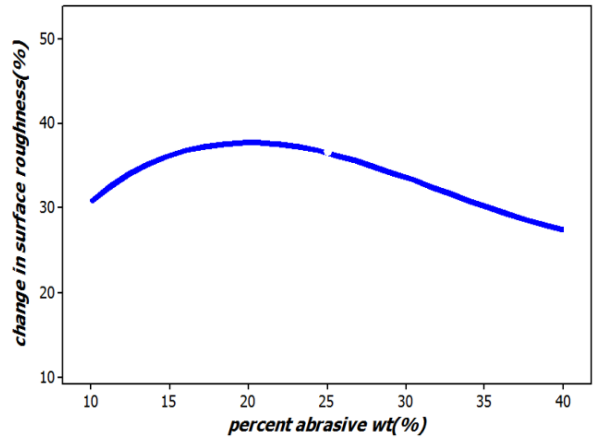


Fig. 8 Effect of percentage weight of abrasive particle

2.4.1.4. Effect of the feed rate

As shown in Fig. 6 with a decrease in feed rate, the changes in surface roughness increased. In lower feed rates, high quality surfaces could be achieved. In fact with a low feed rate, more abrasive particles can contribute in micro or nano material removal; therefore a higher level of roughness can be removed. Furthermore, in lower feed rates, when using machining ductile materials, continuous chips are produced which can decrease surface roughness.

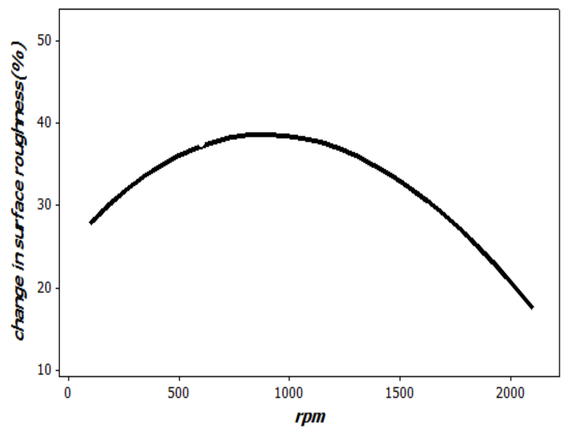


Fig. 9 Effect of rotational speed

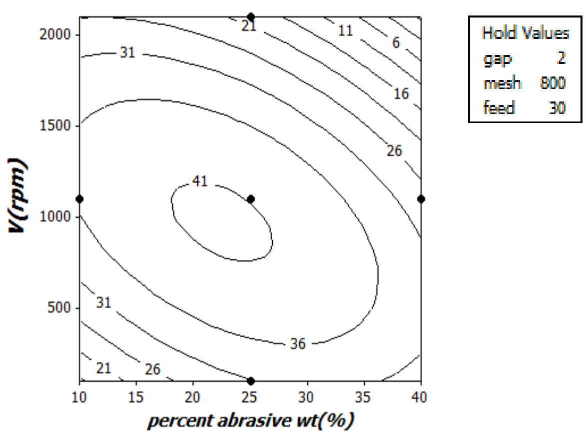
2.4.1.5. Effect of rotational speed

As shown in Fig. 6, with increasing rotational speed, the change in surface roughness increased too. In fact, with an increase in rotational speed more abrasive particles contributed in finishing process. Furthermore, in machining with higher cutting speed, plastic behavior of material changes and cutting forces reduce and consequently surface quality increases. However, this desirable behavior does not continue for higher rotational speeds. The increase in rotational speed leads to larger centrifugal forces which affect the particles and overcomes the magnetic forces; therefore, particles are moved to the sides and in many cases they become separated from the abrasive brush. Reduced number of abrasive particles leads to a decreased level of efficiency. This effect is shown in Fig. 9.

2.4.2. Effects of interaction between the parameters

Based on the results of analysis of variance, there was a significant interactions between the following pairs: gap and rotational speed, gap and size of abrasive particles, and the percentage of abrasive particles and rotational speed. When analyzing the interaction between the parameters, other parameters were considered at middle setting (central point). As shown in Fig. 10, the relation between the weigh percent of abrasive particles and rotational speed is similar to concentric ellipsoids.

Fig. 10 Interaction of rotational of magnet and percent



weight of abrasive particles

When having a fixed weight percent of abrasive powder, the same surface roughness can be achieved with two different low and high cutting speeds. Similarly, considering a fixed rotational speed, the same surface roughness can be achieved with two different levels of low and high percentages of abrasive particles. In a rotational speed of about 1100 rpm and having abrasive particles compound percentage of 20% to 25%, the best surface quality can be achieved. Higher levels of increase in the percentage of abrasive particles adversely affect the changes in surface roughness. However, with increasing the percentage the abrasive particles at a rotational speed of 1600 rpm, a descending trend can be observed for all the ranges. In a rotational speed ranged from 1600 rpm to 2100 rpm, acceptable output was not achieved. Fig. 11 shows the interaction between the particles size and finishing gap. With decreasing the gap and particles diameters, the largest change in surface roughness was achieved. Fig. 12 illustrates the interaction between the gap and rotational speed. As shown, with lower gaps, good results can be achieved when the rotational speed is ranged from 600 to 1600 rpm. When the gap value is 2.5 mm, the changes in the speed from 600 rpm to 1600 rpm reduce the change in surface roughness. When the gap value is 2 mm, with a rotational speed of 1100 rpm, 40% of change in surface roughness can be achieved.

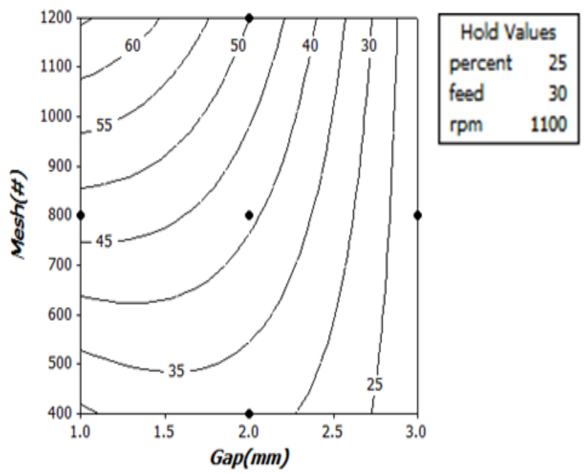


Fig. 11 The interaction of particles' size and finishing gap

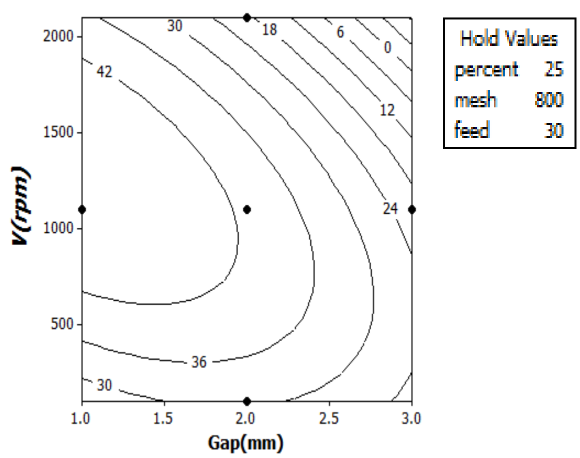


Fig. 12 Interaction of gap and rotational speed

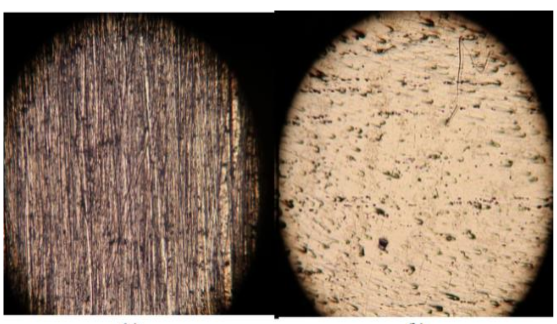
2.5. Optimum conditions for the process

Considering results obtained from the analysis of diagrams and mathematical model used for the experiments, software suggested an optimum solution and predicted the change in surface roughness. As shown, the results obtained from the analysis of the experiments were confirmed with a high precision and the changes in surface roughness were predicted with an accuracy of up to 75%. These results are presented in Table. 7. Fig. 13 shows the effects of the process on the work piece surface. The validity of this method for finishing the IN718 was also proved by scanning microscopic views of workpieces before and after MAF (Fig. 14, a&b).

Table 7 The optimum results

Optimization	Mesh number	Cutting speed	Feed rate	Gap	Percent weight of abrasive	Ra(%)Δ
Simulation	1200	1453	10	0.5	17.87	75.2 %
Experimental	1200	1453	10	0.5	18.0	62.1%

Fig. 13 Effect of MAF process on IN718 surface quality



(a) (b)

Fig. 14 Optical microscopic scanning views (×40) of the workpieces of experiment (a) before MAF (b) after MAF

4 CONCLUSION

Analysis of the outputs of MAF process experiments on IN718 revealed that gap, weight percent of abrasive particles, feed rate, rotational speed, and size of abrasive particles were the factors that affected the level of changes in surface roughness. The distance between the magnet and the work piece surface, i.e. the gap, is the most important parameter which affects the changes in surface roughness. Decreasing the gap can increase the changes in surface roughness and result in a better surface quality.

With decreasing abrasive particles diameter, the force imposed on each particle decreases and better IN718 surface quality is achieved. With increasing the percentage of abrasive particles up to 22%, the changes in surface roughness increases; in addition, higher levels of increase in the percentage of abrasive particles decreases the level of changes in surface roughness.

The effect of rotational speed is similar to the effect of the percentage of the abrasive particles. With increasing the rotational speed to 1100 rpm, the changes in surface roughness changes to 52% but this trend does not continue when increasing the rotational speed more than the mentioned level. With decreasing the feed rate, the changes in surface roughness increases. Moreover, the interaction between gap and rotational speed, and the interaction between gap and particles size are also effective. Moreover, the interaction between rotational speed and the percentage of abrasive particles have a significant effect on the changes in surface roughness.

The surface roughness can decrease up to 62% through setting up the process at its optimum state i.e. in a rotational speed of 1453 rpm, feed rate of 10 mm/min, percentage of abrasive particles equal to 17.87%, size of particles equal to #1200, and gap size of 1 mm. There is a discrepancy of 13% between this prediction and the predicted value by the regression model. With mounting a magnet with a different pole beneath the work piece, magnetic flux density increases up to 35%.

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