

Micro Machining of AISI 440C Stainless Steel using Magnetic Field and Magnetic Abrasive Particles

Yahya Choopani^{1*}, Mohammad Reza Razfar²

¹MSc, Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran

*Email of Corresponding Author: yahya.choopani@smc.iaun.ac.ir

²Assoc.Prof, Department of Mechanical Engineering, Amirkabir University of Technology, Tehran, Iran

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Abstract

Magnetic abrasive finishing (MAF) is a micromachining process that uses magnetic field and magnetic abrasive particles to conduct the mechanism of material removal in micro-nanometer scales. In this paper, by an experimental method and statistical analysis, the effects of parameters like working gap, work-piece rotational speed and material removal mechanism (injection of abrasive slurry of Al_2O_3) in the MAF process, on the external surfaces of cylindrical pieces of stainless steel (AISI 440C) were investigated on surface roughness. To do the experiments, a mechanism was designed and constructed. The results of this research show that the working gap and work-piece rotational speed have a significant effect on the improvement of the surface roughness. It has been indicated that in vitro surface roughness improved 20% as a result of the gap working of 2 mm, workpiece rotational speed of 355 rpm, using the injection of abrasive slurry of Al_2O_3 .

Keywords

Micro machining, Magnetic abrasive particles, Stainless steel (AISI 440C), Al_2O_3 abrasive slurry, Surface roughness.

1. Introduction

Nowadays, nuclear energy, medical equipment, aircraft components, and other advanced industries need production of parts with highly smooth and defect-free surfaces. In order to meet these demands, magnetic abrasive finishing (MAF), which is one of the advanced machining processes, has been proposed and developed [1]. It is mainly applied for finishing the pieces with form limitations such as complex surfaces, the curves that cannot be finished with traditional finishing methods like grinding, etc. [2].

The MAF process has attracted a rigorous attention of researchers due to its low cutting force, low temperature of machining (a maximum of 200° C), creation of no surface defects on the workpiece surface, and improvement of longevity of the parts, [3].

Shinmura and Aizawa finished sanitary pipes of stainless steel (SUS304) using the MAF process. They utilized permanent magnet to create the magnetic field, and they used Al_2O_3 abrasive particles and iron particles with an average diameter of 80 μ m mixed with 15% machining fluid to carry out the experiments. The results of their experiments indicated that surface roughness improved from 0.4 to 0.1 μ m after finishing for 10 minutes [4]. In a similar study, Shinmura et al. explored the principles of the MAF process. They investigated the effect of magnetic abrasive particles on improvement of the rate of surface roughness and the cost of material removal. The results of their

study showed that the rate of surface roughness was effectively reduced from 0.45 to 0.04 μm . Moreover, they referred to rounding the edges and removing the burrs caused by grinding as other applications of the MAF process [5].

Fox et al. finished rollers of stainless steel using the MAF process in order to obtain an excellent quality surface free from surface defects like microcracks. To conduct their experiments, they utilized two types of bonded magnetic abrasive particles (sintering) and unbonded magnetic abrasive particles (without mixing with oil). They concluded that the bonded magnetic abrasive particles provided better finishing compared to the unbonded ones. They also reported that a smoother surface could be obtained with the increase of the magnetic flux density [6]. In another study, Jain et al. examined the effects of parameters like working gap and circumferential speed in the MAF process on the external surface of stainless steel cylindrical pipes. In so doing, they utilized iron particles (with mesh of 300 and size of 51.4 μm) and Al_2O_3 abrasive particles (with mesh of 600 and size of 25.7 μm) mixed with some amount of a lubricant called Servospin-12. The results of their study indicated that working gap and circumferential speed had a remarkable effect on parameters like the rate of material removal and percentage changes in surface roughness, so that as working gap rises and circumferential speed drops, the rate of material removal decreases. They also figured out that percentage changes in surface roughness increase with a rise in circumferential speed [7].

In their study, Mulik and Pandey combines the MAF process with ultrasonic process and proposed a new process termed Ultrasonic Assisted Magnetic Abrasive Finishing (UAMAF). Utilizing the UAMAF process, they could successfully finish anti-friction bearing of high-carbon steel (AISI 52100) with hardness of 61 (HRC61). To carry out their experiments, they used unbonded magnetic abrasive. They reported the attainment of surface roughness of 22 nm in 80 seconds [8]. In a recent research, Yamaguchi et al. used the MAF process sharpened the cutting tools edge for machining of titanium alloys. To do the experiments, they used the ferromagnetic particles (iron particles with 44-105 μm diameter and steel grit with 700 μm mean diameter) and the abrasive particles (diamond paste with 0-1 μm mean diameter). Their results showed that by using this process, the tool life has increased to 150% [9].

In the present study, the effect of parameters like working gap, workpiece rotational speed, and material removal mechanism (injection of abrasive slurry of Al_2O_3) in the MAF process on the external surface of cylindrical pieces of stainless steel (AISI 440C) has been investigated by using an experimental method and statistical analysis (designing of experiments and Analysis of Variance) in order to reach the minimum surface roughness.

2. The theory of MAF process and the material removal mechanism

Fig.1 represents the schematic of the MAF process for finishing the external surface of cylinders. In this figure, distribution of the magnetic field and the magnetic force applied to a ferromagnetic particle are indicated. As observed in Fig.1, in position A that is outside the working gap, the forces applied to a ferromagnetic particle are shown[4]:

$$F_x = V X_m \mu_o H \left(\frac{\partial H}{\partial x} \right) \quad (1)$$

$$F_y = V X_m \mu_o H \left(\frac{\partial H}{\partial y} \right) \quad (2)$$

Where x is the direction of the line of magnetic force, y is the direction of the magnetic equipotential line, x_m is susceptibility of the ferromagnetic particles, μ_o is permeability of vacuum, V is volume of the ferromagnetic particles, H is the magnetic field strength at point A, and $\partial H/\partial x$ and $\partial H/\partial y$ are gradients of magnetic field strength in the x and y direction, respectively. In equations (1) and (2), F_y is the magnetic force, The magnetic force stimulates the abrasive particles and F_x is the cutting force, and is the main reason of penetration into the work piece which does the material removal operations.

As can be seen in equations (1) and (2), the magnetic forces F_x and F_y are proportional to both the susceptibility and the volume of ferromagnetic particles, the magnetic field strength and its gradient. The magnetic forces represented in equations (1) and (2) not only centralize the ferromagnetic particles in the working gap where magnetic field strength is upper, but also arrest the ferromagnetic particles from the strew due to work piece rotation. The magnetic abrasive particles are magnetically connected to each other at the end of the magnetic forces lines between the magnet poles of S and N, and they form the flexible magnetic abrasive brush (FMAB). This brush causes pressure P on the workpiece surface. This pressure will act on the SiC abrasive beneath the ferromagnetic particles, to produce abrasion. The SiC abrasive cannot perform the material removal operations unless it obtains abrasion pressure from the ferromagnetic particles. Equation (3) shows the pressure P [4]:

$$P = \frac{\left[\mu_o H^2 \left(1 - \frac{1}{\mu_m} \right) \right]}{2} \quad (3)$$

Where μ_m is the relative magnetic permeability of the ferromagnetic particles. In Fig. 1, the excitation forces that act on the ferromagnetic particles near the work piece surface are in position B. As can be seen in Fig.1, regarding the rotation of the work piece, a cutting strength, R_t , will act on the ferromagnetic particles in the tangential direction of the rotational motion. More over, due to the magnetic field strength gradients in the working gap, the ferromagnetic particles exert a normal force, R_n , to the work piece surface, while simultaneously a magnetic force, F_m , will act on the ferromagnetic particles in the anti-direction of R_t . F_m will prevent the ferromagnetic particles from flowing or dispersing out of the working gap, which ensures that the finishing process will be successful.

The SiC abrasive does the primary cutting into the unbonded magnetic abrasive, and the ferromagnetic particles are responsible for the secondary cutting. However, SiC does not contain the ferromagnetic property; therefore, the pressure required for the SiC abrasive to abrade must be derived from the contiguous ferromagnetic particles. Accordingly, the ferromagnetic particles motion behavior has an important effect on the finishing operation. When F_m is greater than R_t , the ferromagnetic particles will execute a regular cutting state on the work piece surface and will also transfer abrasion pressure to the SiC abrasive below it. However, if the workpiece has a high degree of hardness, the ferromagnetic particles cutting effect is reduced and they will slide on the work

piece surface. Also, when F_m is smaller than R_t , the ferromagnetic particles will roll on the work piece surface. However, when F_m is very small, the ferromagnetic particles will splash out of the working gap and finishing operations are disturbed.

When ferromagnetic particles begins to roll, the pressure to the SiC abrasive below it will disappear. As a result, the finished quality will not be appropriate. Hence, for the shape and size of the ferromagnetic particles on the abrasive behavior treatment to be effective, the ferromagnetic particles must be prevented from not only splashing out of the working gap, but also rolling there in and a strong flexible magnetic abrasive brush is formed and an appropriate finishing is implemented [10].

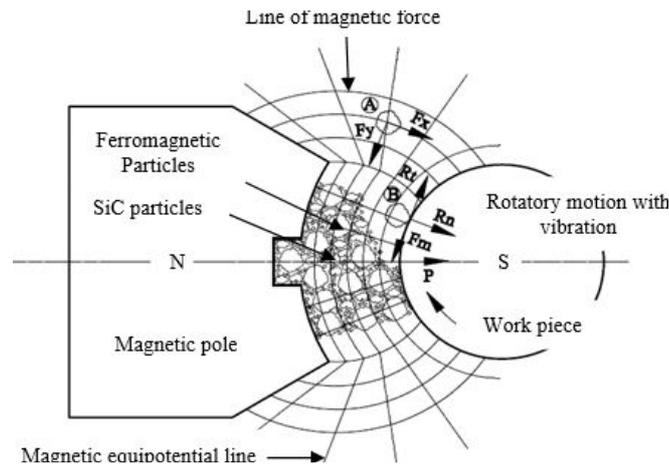


Fig. 1. The schematic of the MAF process for finishing the external surface of cylinders [10]

3. Utilized materials and equipment

In the present study, cylindrical pieces of AISI 440C (HRC 50) stainless steel with a diameter of 20 mm and length of 150 mm were used. For the experiments, a mechanism was designed and constructed (Fig.2). The designing has been carried out according to a method in which the work piece has the rotational motion and the magnets move linearly. The linear motion of the magnets is adjustable regarding the designing and it causes the distance between the work piece and magnets poles to be adjustable and controllable. In addition, the rotational motion of the work piece was provided by means of a lathe machine. The abrasive slurry, including the Al_2O_3 abrasive particles and water, was injected during the finishing process in order to improve the finishing surface quality. In addition, the abrasive slurry leads to the finishing surface cooling and decreases the friction forces. Moreover, it is a supplement of the Al_2O_3 abrasive operation. The abrasive slurry was injected by means of a suction pump. Regarding the implemented designing, this pump simultaneously does the mixture work and also injects the abrasive slurry in to the finishing zone (Fig.2). The chemical composition of the stainless steel (AISI 440C) which is indicated in Table 1 was measured with Foundry-Master quantometer device (Germany). For experiments, the abrasive powders of Al_2O_3 (particle size 18 μm) were used (fig.3a). Also, the iron particles with the average particle size of 150 μm were used as the ferromagnetic particles (fig. 3b). To determine the powders particle size, the Image Analyzer Olysia software was used. Using the Perthometer M2 roughness measuring device (Mahr, Germany), the initial surface roughness of the samples at a number different spots was measured and their mean, i.e. the amount of 0.418 μm , was recorded. Fig. 4 indicates the method of measuring the surface roughness.

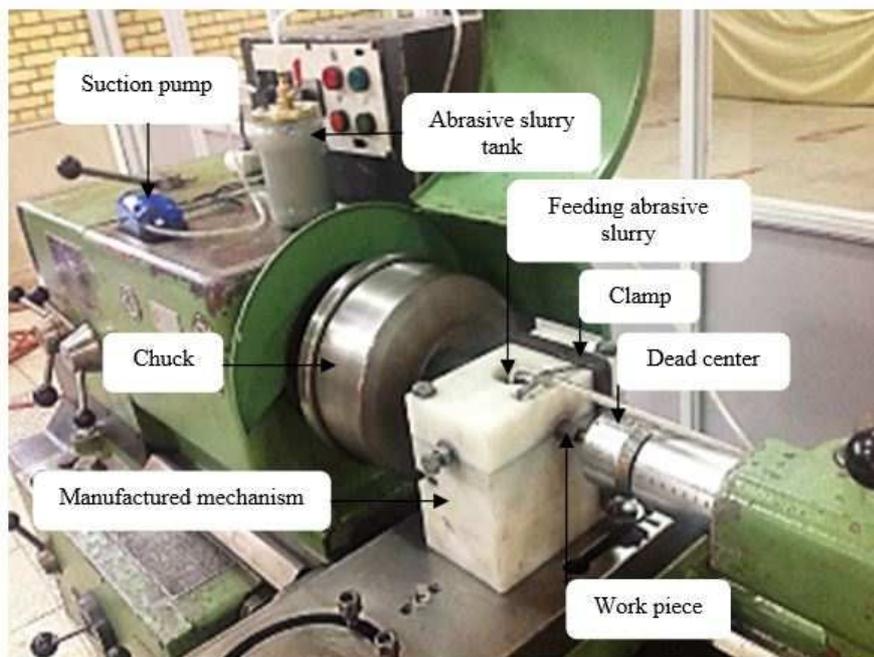
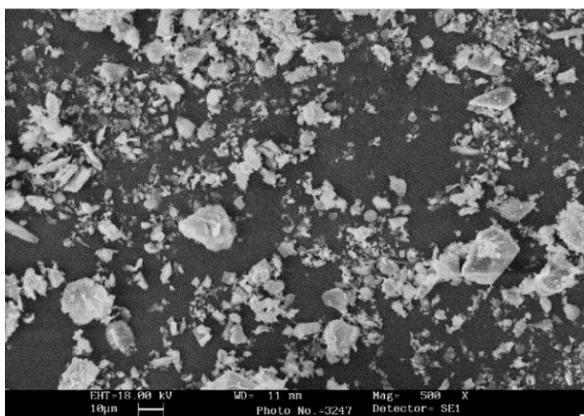


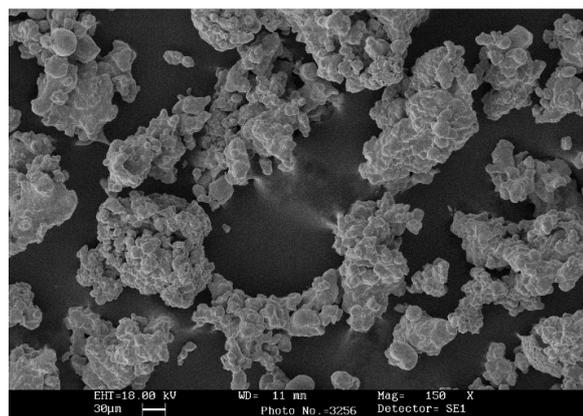
Fig.2.The manufactured mechanism and other equipment used for conducting the experiments of injecting abrasive slurry

Table 1.Chemicalcomposition of AISI 440Cstainless steel

Chemical element	wt%
Fe	79.5
C	0.983
Si	0.769
Mn	0.405
Cr	17.3
Mo	0.445
Ni	0.206



(a)



(b)

Fig. 3. SEM images of a (The Al_2O_3 particle smagnified as 500 with the average particle size of 18 μm , b) Iron particles magnified as 150 with the average particle size of 150 μm



Fig.4. the method of measuring the surface roughness

4. Design of experiments

In the present study, some initial experiments were carried out in order to select the appropriate scope on the cylinders of stainless steel (AISI 440C) using MAF process. Input parameters of the process and their surfaces for the performed experiments injection of abrasive slurry of Al_2O_3 are presented in Table 2. The length of finishing in all experiments was constantly 25 mm. The experiments were carried out by a full factorial method, which resulted in 9 experiments. Table 3 provides the conditions of the experiments.

Table2. Input parameters and levels

Input parameters	Firstlevel	Secondlevel	Thirdlevel
Working gap(mm)	1	2	3
Work piece rotational speed(RPM)	250	355	500

Table 3.Experimental conditions

Name of parameter	Value of parameter
Magnetic field	ND-Fe-B permanent magnet: $\varnothing 25\text{mm} \times 25\text{mm}$ Magnetic flux density: 1.4 T
Al_2O_3 magnetic abrasive	1-particle: Iron powder amount: 4g 2- abrasive: Al_2O_3 amount: 1g Lubricant: SAE40 oil, 0.6 g
Al_2O_3 abrasive slurry	abrasive slurry: Al_2O_3 Mixed ratio of slurry: water: $Al_2O_3=20:1$ (by wt.) Flow rate of slurry: 3.5 cc/min
Finishing time	30 min

5. Data analysis

The present study was aimed at investigating the effect of parameters like working gap, workpiece rotational speed, and material removal mechanism (injection of abrasive slurry of Al_2O_3) in the MAF process on the external surface of cylindrical pieces of stainless steel (AISI 440C) in order to achieve the minimum surface roughness. The collected data from the experiments were analyzed

using Minitab 16.0 software in order to determine the rate and the manner of the effect of each of these parameters on surface roughness.

5.1 Analysis of variance and related tables(ANOVA)

As can be seen in Table 4, the P-values of the working gap, workpiece rotational speed are larger than the significance level of 0.05, which means that the two input parameters of the process do not influence the surface roughness. In addition, the fitness model with the results about 33.03% is almost consistent with the experimental data, and the R modified rate is 66.51 % and the standard deviation is 0.01 %.

Table 4. Analysis of variance of the process output (surface roughness)

parameter	DF	Seq SS	Adj SS	Adj MS	F	P
Working Gap	2	0.0027802	0.0027802	0.0013901	3.60	0.128
Workpiece Rotational Speed	2	0.0002889	0.0002889	0.0001444	0.37	0.710
Error	4	0.0015451	0.0015451	0.0003863		
Total	8	0.0046142				

S = 0.0196540R-Sq = 66.51%R-Sq(adj) = 33.03%

5.2 Examination of the parameters

The main effects of the input parameters on surface roughness are indicated in Fig.5. The best surface roughness was obtained in the working gap of 2 mm. With more amount of the working gap than 2 mm, surface roughness increased. It is also observed that as the work-piece rotational speed rises to 355 rpm, surface roughness drops. From this speed onward, finishing operation is not appropriately conducted.

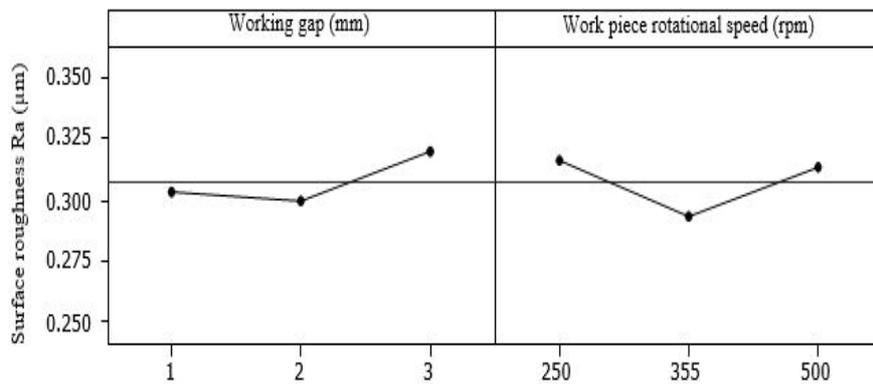


Fig. 5. The main effects of input parameters on surface roughness

Fig.6 presents the interaction effects of the input parameters on surface roughness. These effects can be interpreted in this way: the interaction between working gap and material removal mechanism (injection of abrasive slurry of Al₂O₃) is observable to some extent; however, other interactions are not very effective. As can be observed in Fig.6, when the injection of abrasive slurry of Al₂O₃ is utilized in material removal, the effect of the working gap on surface roughness drops, regardless of the amount of working gap applied in material removal.

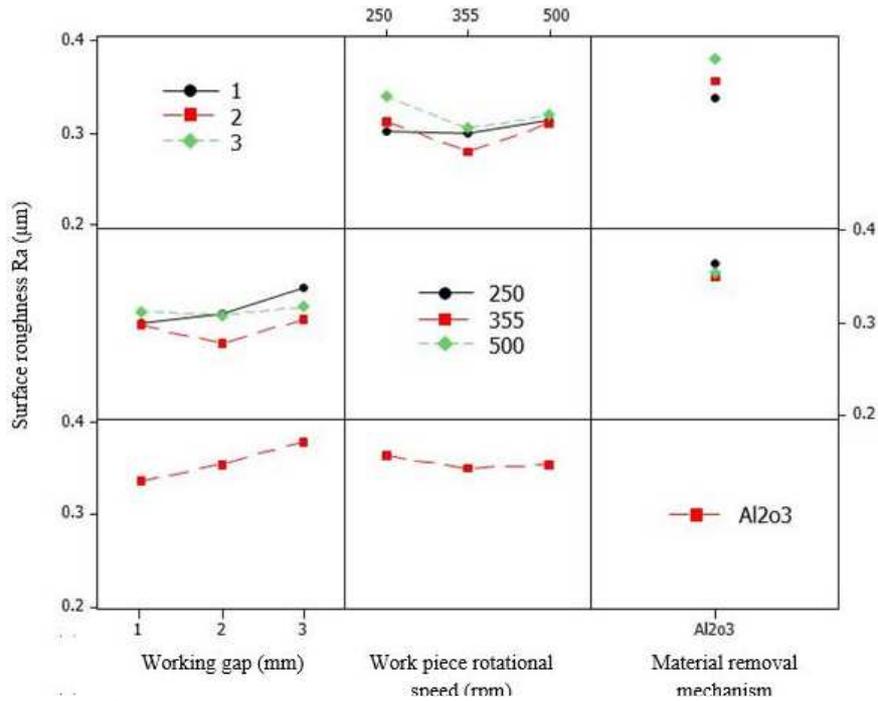


Fig. 6. Interaction effects of the input parameters on surface roughness

6. Results and discussion

6.1 The effect of the working gap on the process output (surface roughness)

As can be seen in figs. 5 and 6, the best degree of the smooth surface in the working gap has been obtained as 2 mm. From this amount forward, increasing the working gap decreases the smooth surface. This can be explained by the notion that increasing the distance between the magnets and work piece surface (working gap) causes the decrease of the magnetic flux density. When the magnetic flux density is decreased, the magnetic field lines are formed in shapes of curves with greater radii, resulting in decreasing the magnetic force which stimulates the abrasive particles. Once the magnetic force is decreased, because of the work piece rotation, the ferromagnetic particle are spattered outside which results in the flexible magnetic abrasive brush formation in not a good manner and the abrasive particles pressure on the work piece surface is decreased. Consequently, finishing operations are not desirably performed and the smooth surface is not in an appropriate level.

6.2 The Effect of work piece rotational speed on the process output (surface roughness)

The diagrams of figures 5 and 6 show that with increasing the work piece rotational speed up to 355 rpm, the surface roughness decreases, but with more increase in this amount, the surface roughness will increase. The reason for such a behavior of this parameter is that when the work piece rotational speed increases, more abrasive particles are in touch with the work piece and surface roughness decreases, but with increasing the work piece rotational speed more than this amount the magnetic force will be less than the cutting resistance. This causes the throwing of ferromagnetic particles from the working gap and decreases the imposed pressure on the abrasive particles. As a

result, a weak flexible magnetic abrasive brush is formed and an inappropriate finishing operation is performed.

6.3 The Effect of Al_2O_3 abrasive slurry on the process output (surface roughness)

As the diagrams of the effects of input parameters in Fig. 6 indicate, the Al_2O_3 abrasive slurry injection has improved the surface roughness as 20%. Such a behavior of this parameter can be explained by the following two reasons. First, the abrasive particles shape in the MAF process is of high importance, because it determines the geometrical shape of the material removal tools. These abrasive particles shape does not follow a specific principle, they are more spherical and polyhedron, as shown in Fig. 3a. In this way, the magnetic abrasive particles form the flexible magnetic abrasive brush on the work piece surface under the magnetic force situation; and because this abrasive is not uniform, finishing is disturbed and an inappropriate smooth surface is resulted. Second, another factor which has amazing significant effect on the smooth surface is the proportion of the ferromagnetic particles size to the abrasive particles. The ferromagnetic particles (fig. 3b) average size and Al_2O_3 is 150 μm and 18 μm , respectively. The proportion of the ferromagnetic particles size to the abrasive particles of Al_2O_3 has been considered inappropriately. This decreases the abrasive pressure on the work piece surface. The reason could be that the larger the ferromagnetic particles size than the Al_2O_3 abrasive particles, not only it causes the more material removal, but the surface roughness will also be improved. On the other hand, when the ferromagnetic particles size is beyond the permitted limits, the abrasive pressure on the Al_2O_3 particles increases, which leads to more material removal and more inappropriate surface roughness.

7. Conclusions

1. According to the results of the experiments, analysis of variance, and the P-value of the parameters, it can be concluded that the input parameters have a not remarkable effect on surface roughness.
2. By decreasing the working gap the surface roughness increases. According to the conditions of the experiments, the best smooth surface was obtained at 2 mm in the working gap. From this amount forward, the smooth surface decreases.
3. By increasing the work piece rotational speed up to 355 rpm, the surface roughness is improved. From this speed forward, an appropriate finishing is not performed and the obtained smooth surface is not as appropriate as that at the lower rotational speeds.
4. In the MAF process, the magnetic force applied to the abrasive particles and hardness of the magnetic abrasive brush is more dependent on the type, shape, and size of the abrasive particle. According to the size and shape of the Al_2O_3 abrasive and the conditions of the experiments, injecting the slurry of this abrasive during finishing does not remarkably reduce surface roughness.
5. The obtained surface roughness under the conditions of the working gap of 2 mm, the work piece rotational speed of 355 rpm, and using the Al_2O_3 abrasive slurry injection has improved as 20%.

8. References

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