Investigation of the Effective Parameters on Surface Roughness in Magnetic Abrasive Finishing Process Using Design of Experiments

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Abstract

In this article, the effect of parameters like working gap, work piece rotational speed and material removal mechanism(injection of the SiC Abrasive slurry and Al_2O_3, use of diamond paste as abrasive tool) in Magnetic Abrasive Finishing process using designing of experiments on the external surface of Cylindrical work pieces of Stainless steel AISI 440C to get minimum surface roughness has been investigated. For implementation of tests, a mechanism was designed and after carrying out the tests, the obtained data was analyzed using Minitab software. Using response surface method the predicted model, the value of surface roughness was represented. Input parameters to produce optimum have also been reached using the predicted model and desirable surface roughness. Also, results show that the surface roughness has been improved by 50% with the working gap of 2 mm and work piece rotational speed of 355 rpm and using diamond paste.

Keywords

Magnetic Abrasive Finishing, Surface roughness, Design of experiments, Analysis of Variance

1. Introduction

Advances in material science are made very rapidly and yet, demand for better quality and less production cost is increasing. Continuous request for decreasing time of work is from design step to production step and also, finishing process usually included ~15% of the total cost of machining in production circle [1]. In traditional finishing processes (grinding, and so on), abrasive particles are connected via glues or other ways. The connected abrasive particles are stretched on the work piece surface and apply cutting force on it. This will form chips separately and on the surface texture of the work piece, some slots will form due to these processes. But in advanced finishing processes, abrasive particles will include between work piece surface and magnetic poles and then will apply pressure on the work piece surface that will form very tiny chips so that a smooth and uniform surface is produced. On the other hand, high quality of finishing work pieces leads to better operation and significant increase of their longevity [2]. In light of these, the need for replacing traditional finishing process with advanced finishing process is felt. The basic goal of abrasive finishing processes is using numerous erratic cutting edges (with indistinctive direction and geometry) to obtain effective material removal like chip. These chips are smaller than those chips that are produced in machining process using cutting tool with regular and specific edges. Very tiny chips that are produced in abrasive machining lead to better finishing surface, closer tolerance, creating complex surface details, machining harder materials and hard-to-cut materials [3].

One of the new techniques in abrasive finishing that uses magnetic force (using permanent magnet or temporary ones) to material removal in micro-nanometer scale is magnetic abrasive finishing (MAF). This technique does not have the restrictions of traditional techniques (do not finishing work pieces that have shape restriction as complex surface and work piece with low thickness like capillary tubes, etc.); so, in the last decades, it has been attended in many industries like aerospace, medicine, military, etc. With respect to specifications and capability of the MAF process, for finishing the fine parts and free geometry parts and parts that have shape restriction, this technique in some emergency cases may be a good choice for finishing surface [4].

The first article in magnetic abrasive finishing field was published in 1938 in Russia. Krull was the first one who published an article in this field [5]. Japanese scientists from the beginning of the 80s followed this work and began laboratory research to industrialize this technique. In fact it was after this moment that the magnetic abrasive finishing process was widely welcomed all over the world. Nowadays, many researches are developed on magnetic abrasive finishing. In 2007, Lin et al. finished parts made of stainless steel with free geometry using the MAF process. They used permanent magnet for their experiments and the emergency equipment for experiments was installed on the CNC machine. These researchers used Taguchi design of experiments. After analyzing Taguchi method, parameters such as the working gap and feed rate and mass of abrasive were found to have significant effect on surface finishing. For these parameters, an optimum value of 2.5 mm and a feed rate of 10 mm. $\min^{-1}$ and abrasive mass of 2 gr was found [6]. In 2004, Singh and et al. investigated the most important effective parameters on surface quality such as applied voltage on electric magnet, working gap, mesh size abrasive powders and rotational speed on stainless steel plates using Taguchi design of experiments. They found that applied pressure on electric magnet and working gap as the most effective parameters on surface quality [7]. In 2009, Kim and Kwak began researches in magnetic abrasive polishing field on thin plates of magnesium alloy. These Korean researchers optimized input parameters such as current, working gap, rotational speed and mass of powder using optimization parameters by Taguchi method, analyzing signal to noise ratio and design of experiments on orthogonal arrays [8]. Safavi et al. finished a plate of aluminum using the MAF process. They investigated the most effective parameters in variation of surface roughness on the basis of design of experiments, analysis of variance and regression [9]. Fadaei Tehrani et al. began researches on finishing aluminum pipes using the MAF process. These researchers investigated the interaction of effective parameters on process using design of experiments method and postulated a regression model between parameters and investigated the effect of each of them on surface roughness [10]. Vahdati and Sadeghinia finished aluminum flat plates using the finishing abrasive process. They investigated effective parameters such as the percentage of combined abrasive particles, lubricant value, and relative hardness between the work piece and abrasive particles using design of experiments. They also postulated a regression model that created a relationship between parameters and surface roughness and hence extracted optimum condition to reach the best surface roughness [11].

One the issues that is related to this process that in our country and even on international level has not been investigated is the effect of MAF process on stainless steel (AISI 440C). In this research, effect of the MAF process input parameters such as working gap, work piece rotational speed and material removal mechanism (injection of abrasive slurry of Sic and Al_2O_3 and also without injection of abrasive slurry using diamond paste as abrasive tool) on external surface of cylindrical stainless steel parts has been investigated. Also, the effect of their interactions on surface roughness has been investigated using design of experiments. Finally, the predicted model of surface roughness was postulated in the form of mathematical formulas for optimization of the process.

2. MAF process theory and its material removal mechanism

In the MAF process, a part of magnetic abrasive particles that includes ferromagnetic particles (such as iron powder) and another part including the SiC abrasive particles, Al_2O_3, CBN, diamond, are used as material removal tool. The value of the finishing pressure supplies with magnetic field. Fig. 1 shows the schematic of operation principles of the MAF process in which the abrasive particles in magnetic fields lines direction between S and N poles are magnetically connected and form flexible magnetic abrasive brush. With respect to the cutting edge of the abrasive particles flexible magnetic abrasive brush behaves as a multiple cutting edge. When a cylindrical work piece with rotational speed enters this magnetic field, flexible magnetic abrasive brush moves on the work piece surface. With respect to low forces, surface defects, such as micro-cracks, are so little or do not exist and material removal happens quite properly. The MAF process machines roughness in 10nm and the result is a mirror-like surface.

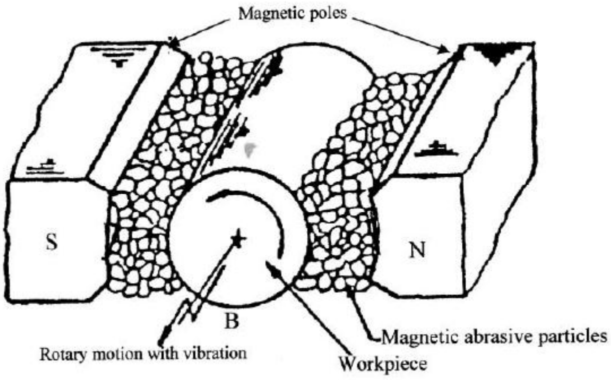

Fig. 1. Schematic of the MAF process for external surface of cylinders [12]

3. Materials and used mechanism

In this research, a mechanism was designed and made. The design was made on a method that work piece has rotational speed and the magnets have linear speed. Linear moves of magnets are adjustable with respect to the design and this leads to adjustable and controllable distance between work piece and magnets poles. Also, rotational speed of work piece is supplied by a lathe and for accurate positioning of the work piece in magnetic field a fixture was designed and made. To hold the magnets with specified dimensional and also appropriate positioning of magnets to work piece, two fixtures were designed and made. This fixture was designed with respect to permanent magnet and work piece dimensions. To avoid magnetic fields lines deviation in the finishing zone, non-magnetic materials should be used for equipment. For this purpose, Teflon plates and aluminum pollen were used. The designed fixture was installed on table of lathe by clamp and T-slot screws. Fig. 2 shows lathe and other equipment.

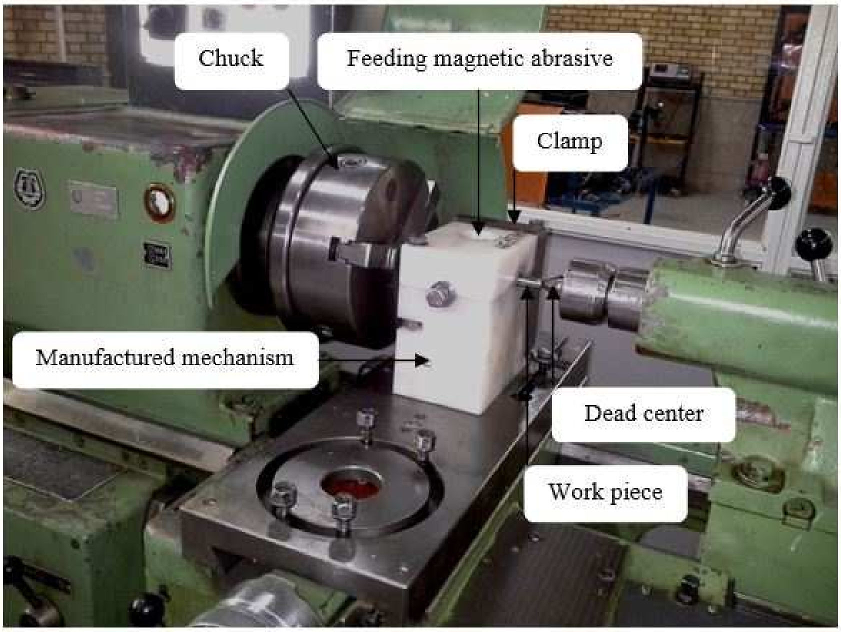

Fig. 2 Lathe with other equipment for implementation of experiments in the MAF process

In this study, by investigating various materials stainless steel AISI 440C was selected. This steel is used in manufacturing of bearings, nozzles, abrasive parts of airplane pipes (spool slave valves), insert moulds, medical equipment (surgical instruments), etc. Chemical analysis of this steel by testing via Quantometer Device is given in table 1.

Table1.Chemicalcomposition ofstainless steelAISI 440C,reported bytheQuantometre Device

Chemical element	wt%
Fe	79.5
C	0.98
Si	0.76
Mn	0.40
Cr	17.3
Mo	0.44
Ni	0.20

4. Design of the experiments

Factorial design of the experiments is important due to its comprehensiveness. If tests are implement based on full factorial design not only we can investigate the effect of main factors, but we can also feasibly investigate the whole interaction between factorial interactions. In this research, factorial design of the experiments method with 3 parameters and 3 levels for each factor was used. Table 2 shows the process input parameters.

Table2**.** Input parametersandlevels

Input parameters	Firstlevel	Secondlevel	Thirdlevel
Working gap(mm)	1	2	3
Work piece rotational speed(RPM)	250	355	500
Material removal mechanism	Injecting the abrasive slurry of Sic	Injecting the abrasive slurry of Al_2O_3	No injecting the abrasive slurry(Diamond paste)

By importing the input parameters specifications to Minitab software and design of experiments based on factorial, 27 tests have been performed.

5. Results and discussion

After passing factorial design of experiments, the tests were implemented based on the design of experiments. Then surface roughness of samples was measured in multiple points via roughness measuring device Perthometer M2 (Mahr Co., Germany) and their average was introduced as surface roughness. Then by using Minitab software the recorded data from design of experiments were analyzed with analysis of variance and a regression model that relates input parameters to output parameter that is surface roughness was found. And by using this regression and response surface method optimum value of working gap and rotational speed of work piece was extracted.

5.1. Analysis of variance and table investigating (ANOVA)

Table 3 shows the analysis of variance, the fitted model up to ~93.06% is coincident on output of experiment and the quality of model is proved. Also, the value of R-adjusted is 97.86% and standard deviation is 0.01%. So, it is almost appropriate and shows that there are not too many unimportant factors in the model and the good quality of the model is confirmed.

5.2 Testing independent of errors and fixed variance value

Fig. 3 shows that points are randomized and do not obey any special form and this is satisfaction of errors independent condition. To ensure the independence of data, it is enough that the distribution of points be totally random and that they do not obey any special form.

Table3. Analysis of variance for the output process (surface roughness)

Parameter	DF	Seq SS	Adjusted SS	Adjusted MS	F-Ratio	P-Value
Working Gap	2	0.0021140	0.0021140	0.0010570	5.91	0.026
Workpiece Rotational Speed	2	0.0027742	0.0027742	0.0013871	7.76	0.013
Material removal mechanism	2	0.0553162	0.0553162	0.0276581	154.75	0.000
Working Gap× Workpiece Rotational Speed	4	0.0014804	0.0014804	0.0003701	2.07	0.177
Working Gap× Material removal mechanism	4	0.0027744	0.0027744	0.0006963	3.88	0.049
Workpiece Rotational Speed × Material removal mechanism	4	0.0010436	0.0010436	0.0002609	1.46	0.300
Error	8	0.0014298	0.0014298	0.0001778	-	-
Total	26	0.0669327	-	-	-	-
S = 0.0133687	R-Sq = 97.86 %		R-Sq (adj) = 93.06 %			

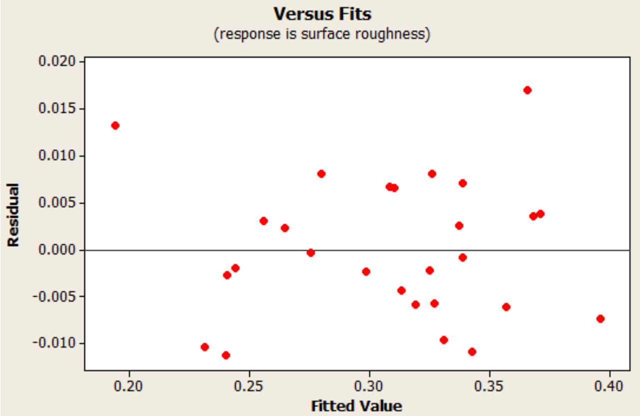

Fig. 3. Plot of residual versus fitted values for surface roughness

5.3 Investigation of analyzed quality

Plot of normal probability distribution assists to investigating of experiment errors of assumption normal distribution that is needed for analysis of the variance start. This plot is in fig. 4. With respect to low value of Anderson Darling (AD) characteristic number AD = 0.247 and also value of P-Value = 0.729 for plot of normal distribution that is higher than level of confidence 0.05, it can be concluded that the assumption normal distribution of errors is satisfied and the obtained plot is like a straight line.

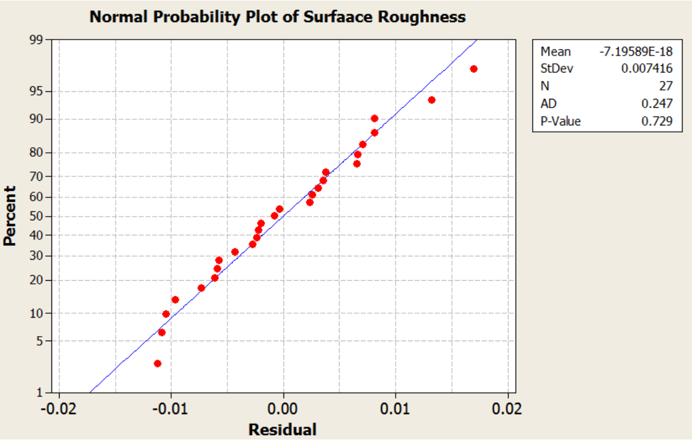

Fig. 4. Plot of normal distribution probability for surface roughness

5.4 Investigation of main interaction

For further investigating the effect of each parameter on the output parameter process (surface roughness), main parameters effect plot can be depicted as fig. 5. According to these plots, it can be seen that the most effective parameter on percentage of surface roughness is diamond paste. Also, the best surface roughness is in working gap of 2. Increase of working gap leads to decrease of surface roughness and increase of the work piece rotational speed up to 355 rpm decreases surface roughness but with increase of this value surface roughness will increase.

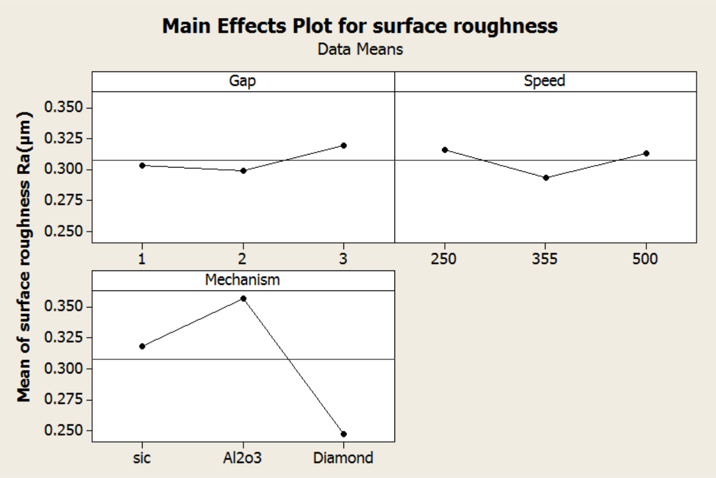

Fig. 5. Plot of the input parameters effect on the output of process (surface roughness)

As can be seen in fig. 6, from the interaction between input parameters the effect of material removal mechanism is more than working gap and work piece rotational speed and effect of work piece rotational speed is known as the second factor and a little interaction between material removal mechanism and working gap and other interactions are not very effective. From interaction plots it can be seen that the effect of working gap decreases when mechanism is used without diamond paste to material removal and it is not very important that its value was used for material removal. Plots of interaction between parameters show that the surface roughness in the working gap of 2 mm, work piece rotational speed of 355 rpm and use of abrasive tool (diamond paste) in the value of 50% will be improved.

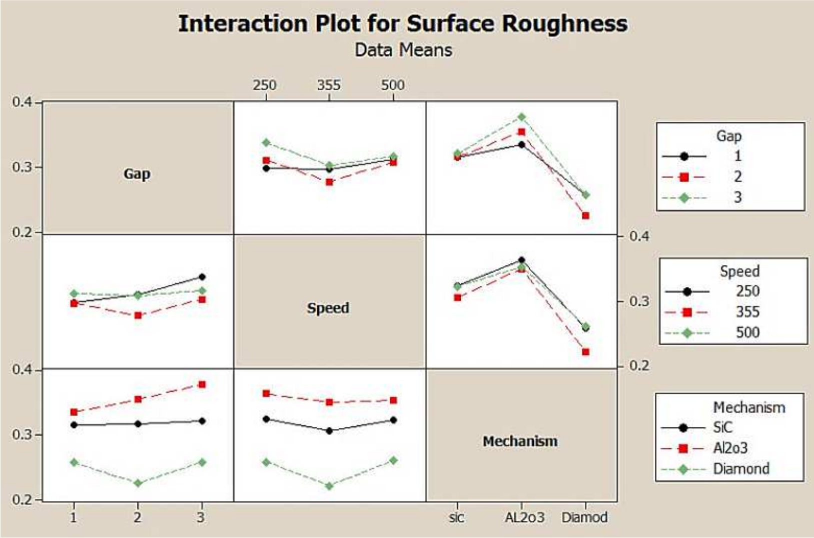

Fig. 6. Plots of interactions of input effect on the output of process (surface roughness)

5.5 Analysis of regression on the output process (surface roughness)

In this research, in order to represent a predictive model of surface roughness value, a relation as mathematical model between outputs of tests and working gap, work piece rotational speed, use of diamond paste as material removal tool by regression using Minitab software has been obtained.

With respect to the coefficients and constants that have obtained from software, for each parameter a mathematical model dominant on test results for surface roughness can be provided as follows:

$$Ra = 0.621802 - 0.102450 * mm - 0.00171563 * RPM + 0.032000 * mm^2 + 0.00000248188 * RPM^2 - 0.00000675568 * mm * RPM. \quad (1)$$

6. Conclusion

1. Improvement of surface roughness in the MAF process can be achieved by accurate choice of the input parameters such as working gap, work piece rotational speed, and material removal mechanism using analysis of variance, investigation of input parameters and effect of interactions on surface roughness.
2. In modeling the MAF process, in design of experiments and investigation of input parameters, process can be very well modeled in three levels.
3. Considering that there are too many effective parameters on the MAF process, investigation of effective parameters due to design of experiments is a very effective method with appropriate responses.
4. By increase of the work piece rotational speed, surface roughness is improved and with increase of the working gap up to 2 mm, surface roughness is improved and with further values the surface roughness will decrease.
5. Results of tests showed that surface roughness has been improved up to 50%. with the working gap pf 2 mm and the work piece rotational speed of 355 rpm and use of diamond paste

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