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Research Article

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Development of Experimental Setup and Parametric Study of Magnetic Abrasive Finishing Process of Plane Workpieces

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Abstract

In many engineering applications, components require high surface finish. Achieving micro/nano-level surface finish with conventional finishing process becomes challenging due to the use of new alloy and superalloy workpiece materials and complex pro-files of workpiece. Magnetic abrasive finishing (MAF) is a promising approach to provide better surface finish for not only for softer but also for harder materials. In this paper, development details of MAF setup for plane workpiece are presented. The developed setup was attached to a trainer CNC milling machine. With the developed setup, the effect of selected input process parameters, namely, rotational speed of electromagnet, abrasive mesh number, and working gap, was studied on percentage improvement in the surface finish (PISF) for mild steel workpiece. In the parametric study, L9 orthogonal array was used for designing the experiments to study the effect on PISF. With Taguchi and ANOVA (analysis of variance), it was identified that the abrasive particle size has more influence on PISF (42.32%), followed by working gap and rotational speed. A linear regression model was developed for the selected input and process parameters of MAF. The percentage error of the predicted PISF and experimental PISF on the optimum input parameter was 8.04%.

Keywords

Magnetic abrasive finishing, Surface roughness, Taguchi Method, Analysis of variance, Silicon carbide

Introduction

Advanced materials are being developed for the applications in aviation, automobile, and medical industries. Many of the applications require good surface finish of the components. Therefore, there is a need of an environment-friendly process to achieve micro/nano-level surface finish with high accuracy, low cost, and in less time [1-3]. It is difficult to finish complex shapes (free-form surfaces) with conventional finishing process such as grinding and lapping. In addition, to perform the finishing, they require special fixtures depending on the shape and size of the components [4, 5]. The MAF is a promising surface finishing process, which is capable to generate better surface finish up to micro/nano level with minimum effect to the quality of the surface. The MAF process can be carried out on both magnetic and non-magnetic workpieces. Some of the input process parameters of MAF are magnetic field strength, working gap, rotational speed, and abrasive mesh number, while the output process parameter are surface finish and material removal rate. The MAF is capable to remove very fine asperities to get a nano range of surface finish and improve surface texture. The MAF can also remove burrs and scratches, which are left in the grinding, milling, and drilling processes [6, 7]. The fine surface finish obtained with MAF process will have better corrosion resistance, fatigue strength, and tribological and aesthetic properties. Materials that are hard and brittle, like glass [8], ceramics, and silicon wafers [1] can also be processed using the MAF.

In MAF, the workpiece is positioned between two magnetic poles so that the lines of the magnetic field pass through the workpiece. Ferromagnetic particles mixed with abrasive particles are placed in between the workpiece and the magnet. Ferromagnetic particles along with abrasive particles arrange themselves along the lines of magnetic field to form as a flexible brush. Schematic diagram of the MAF process for plane workpiece is shown in figure 1a. When the workpiece material is magnetic, the flexible brush will be formed between the magnet and the workpiece. However, when the work-piece material is non-magnetic, MAF requires two magnets, one above and the other below the workpiece to form the flexible abrasive brush. The mixture of ferromagnetic and abrasive particles is usually in the range of 70:30 to 80:20. In MAF process two types of force are generated, normal force (Fn) and tangential force (Ft). The indentation on the workpiece is caused by the normal force, whereas the tangential force is responsible for removing asperities in the form of microchips. The material removal mechanism of MAF is shown in figure 1b. With the magnetic abrasive particles in the micrometre range, MAF process can remove chips of micro/nano size for excellent surface finish [9, 10].

In this paper, development details of MAF setup for plane workpiece are presented. The developed setup was attached to a trainer CNC milling machine. With the developed setup, the effects of selected input process parameters, such as, rotational speed of electromagnet, abrasive mesh number, and working gap, were studied on PISF for mild steel workpieces.

Experimentation

Development of experimental setup

The developed MAF experimental setup consists of the following components: (i) Electromagnet, (ii) Slip ring, (iii) Clamp, clip, and carbon brush assembly, (iv) power supply, and (v) magnetic chuck. The developed MAF setup is shown in figure 2. The specifications of the components used in the fabrication of the setup are given in table 1. The developed MAF setup was fitted on a trainer CNC milling machine (Denford TRIAC milling machine retrofitted with MACH3 controller).

Electromagnet was selected to generate a maximum of 500 Gauss magnetic field. A single-phase slip ring having two copper rings was selected with an internal diameter of 25 mm and an outer diameter of 64 mm. A clip with carbon brushes was connected to a supply power. The complete setup of electromagnet assembly was fastened to the spindle of CNC milling machine spindle with a fabricated holding device. For holding magnetic workpieces, magnetic chuck was used, which also acts as a south pole during the finishing process. The magnetic chuck was mounted on the machine table. Mach3 controller of CNC milling machine controls the rotational speed of electromagnet, working gap, and movement of magnetic chuck with suitable G-M codes. The MAF setup was designed while considering the ranges of process parameters, such as magnetic field strength, power supply, and rotational speed of electromagnet, available in the literature. With the developed MAF setup, experiments were conducted on mild steel workpieces to demonstrate the capability of the setup. The experimental details are presented in the below section.

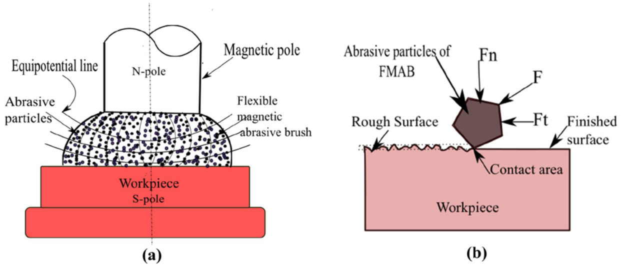

Figure 1: Schematic diagram of **(a)** MAF process for plane surface and **(b)** material removal mechanism.

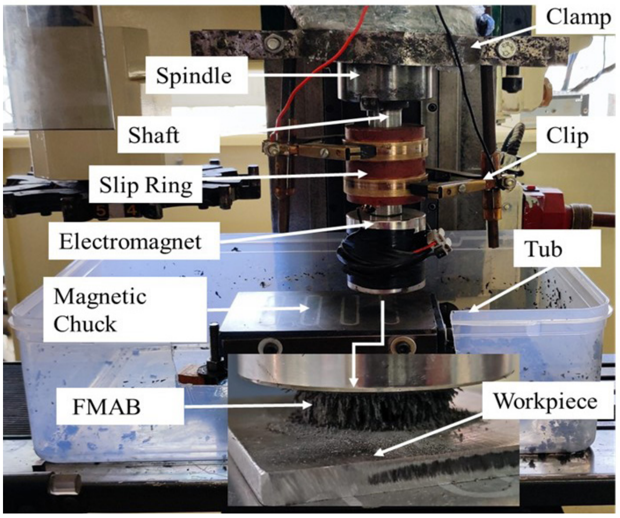

Figure 2: Photograph of the developed MAF setup.

Experimental procedure of MAF

The developed MAF setup was successfully tested to run the spindle with electromagnet at different "rpm" (rotations per minute) while maintaining different working gaps (gap between electromagnet and workpiece). To analyze the general characteristics of the MAF process with the developed setup, mild steel workpiece material was selected for experimentation. The dimensions of the selected workpiece are 70 x 70 x 5 mm. Initially, all the workpieces were machined on a conventional vertical milling machine to remove surface asperities and defects and their surface roughness were measured with surface roughness tester with least count of 0.001 µm. Readings from three random locations on each workpiece were taken to calculate average surface roughness values.

Table 1: Specifications of selected components of the developed MAF setup.

S. No.	Name of the component	Specification
1	Electromagnet	24 V, 1.4 A, suction force 100 kg
2	Power supply	24 V/3 A DC power supply SMPS
3	Magnetic chuck	4 pole with 30 mm pitch of 150 mm x 100 mm x 70 mm

For MAF process, MACH3 controller of CNC milling machine controls the rotation of the electromagnet, maintains the gap between the electromagnet core and workpiece sample and the movement of the table in X and Y directions. A mixture of loosely bonded magnetic abrasive particles was prepared by mixing ferromagnetic particles with silicon carbide particles of specific mesh number and lubricant oil (servo oil) in the ratio of 65:25:10 by weight as shown in figure 3. Prepared magnetic abrasive particles were placed in the working gap. Three input parameters with three levels were considered for analyzing the PISF while keeping all the other parameters at constant levels. For all the experiments Magnetic flux density was maintained at 500 Gauss and each experiment was performed for 15 minutes.

L9 orthogonal array was used for designing the experiments to study the effect of selected three factors at three levels (Rotational speed - 400, 600, 800; Abrasive mesh no. - 400, 600, 1200 and Working gap - 2, 3, 4) on PISF. Nine experiments were designed with Minitab 17 software, as shown in table 2. After performing the MAF on all prepared workpieces, the surface roughness was again measured to check the improvement in the surface finish. PISF was calculated according to equation (1) as given in table 2.

Taguchi analysis was performed to determine the optimum level for each input process parameter. The S/N ratio value was used to calculate the PISF based on the larger-is-better categories represented by equation (2). Further, the percentage contribution of each parameter was calculated with the help of ANOVA. A linear regression model was developed for the selected input and output process parameters of MAF.

S/N ratio formula for larger-is-better =

$$-10*\log\left(\sum\left(\frac{1}{Y^2}\right)\Big/n\right) \tag{2}$$

Where, Y = response for the given factor level combination and n = number of responses in the factor level combination.

Figure 3: Preparation of magnetic abrasive particles.

Table 2: Experimental conditions and responses.

Exp. No.	Rotational speed (rpm)	Abrasive mesh no	Working gap (mm)	SR Before MAF (μm)	SR After MAF (μm)	PISF
1	400	400	2	1.943	0.692	64.38
2	400	600	3	2.537	0.992	60.89
3	400	1200	4	1.128	0.626	44.50
4	600	400	3	0.539	0.320	40.46
5	600	600	4	1.338	0.397	70.30
6	600	1200	2	2.307	0.518	77.54
7	800	400	4	0.913	0.577	36.77
8	800	600	2	1.972	0.346	82.45
9	800	1200	3	1.896	0.448	76.37

Results and Discussion

The number of different combinations of operating parameters of experimental conditions and its corresponding output response (PISF) is given in table 2. S/N ratio values for various input parameters and respective levels are given in table 3. The maximum values of S/N ratios value are highlighted and represent the optimum levels of the process parameters. It also gives information regarding the most influencing parameter. The PISF is noted to be maximum for the rotational speed of electromagnet at level 3, mesh number of abrasive particles at level 2, and working gap at level 1. Therefore, predicted optimum process parameters for the highest improvement in PISF using the Taguchi method were found as speed = 800, mesh number = 600, and working gap = 2 mm.

Table 3: S/N ratio values for PISF.

Level	Rotational speed (rpm)	Abrasive Mesh no	Working gap (mm)
1	34.94	33.21	**37.43**
2	35.62	**36.98**	35.16
3	**35.76**	36.14	33.74
Delta	0.82	3.78	3.69
Rank	3	1	2

The S/N ratios value of PISF for mild steel in relation to rotational speed, abrasive mesh number, and working gap at different levels are shown in figure 4. As per the interpretation, as the rotational speed increases from 400 to 800 rpm the PISF also increases, but the effect is very less on PISF due to smaller range of rotational speed. Whereas PISF increases with an increase in mesh number of abrasive particles up to 600, thereafter, it starts decreasing may be due to lower material removal rate. Further, PISF is more at lower working gap this could be as a result of the increased magnetic flux density, which results in higher material removal rate. PISF decreases with increase in the working gap may be due to lower magnetic flux density.

The percentage involvement of each input parameter on the PISF was calculated with ANOVA and are given in table 4. The results are found in agreement with the Taguchi anal-

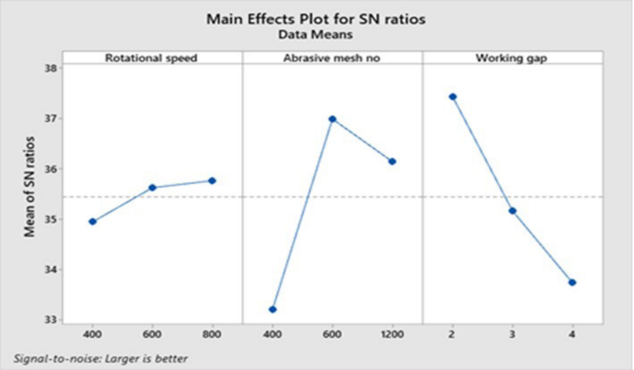

Figure 4: Main effect plots for S/N ratio values of PISF.

ysis. The sequence of influencing parameters was found to be mesh number, working gap, and rotational speed. From the table 4, the abrasive mesh number is observed to be the most influencing parameter (42.32%) for improving the surface finish on the workpiece. The electromagnet rotating speed has minimal effect on PISF may be due to lesser variation in speed in the experiments.

Table 4: ANOVA for S/N ratio values for PISF.

Source	DOF	Seq SS	% Contribution
Rotational speed(X_1)	2	1.153	2.07
Abrasive mesh no (X_2)	2	23.561	**42.32**
Working gap (X_3)	2	20.790	37.37
Residual error	2	10.168	18.26
Total	8	55.673	-

A linear regression model was developed for the selected input and output process parameters by performing regression fit in Minitab software. The predicted model of PISF is represented with equation (3). The fit of the model is adequate as the cumulative normal probability of PISF shows linear behavior, as shown in figure 5.

$$PISF = 73.1 + 0.0215 * X_1 + 0.0163 * X_2 - 12.13 * X_3 \quad (3)$$

Where, X_1 is rotational speed, X_2 is abrasive number, and X_3 is working gap.

The percentage error in PISF between the experimental and predicted values at the optimum level of input parameters is shown in table 5. There was an error of 8.04% between the predicted value with regression model and the experimental value.

Conclusion

The developed MAF setup was able to successfully finish mild steel plane workpieces. With L9 orthogonal array and Taguchi analysis, the optimum input parameters for PISF were found at Speed of 800 rpm, mesh number of abrasive particles at 600, and working gap at 2 mm. Similar results were observed with ANOVA also. According to ANOVA, PISF was considerably influenced by the mesh size (42.32%) and working gap (37.37%). However, the rotational speed is found to be insignificant maybe because of the smaller range of speeds. A linear regression model was developed to establish the relation between the input and output parameters of the process. At the optimum levels of input parameters, an experiment was performed to find PISF, and it was found to be 82.45%. The result was predicted with linear regression model with an error of 8.04% at the optimum levels of input parameters. With the developed setup, workpiece above 25 mm thickness cannot be processed due to the range of movement of the spindle in the z-axis of the machine. In future, this setup can also be used to finish non-magnetic and difficult-to-machine materials. Further, experiments can be done with different feed rates to the workpiece in X and Y directions. The effects of other parameters, such as magnetic field strength and ratio of ferromagnetic and abrasive particles, can also be explored.

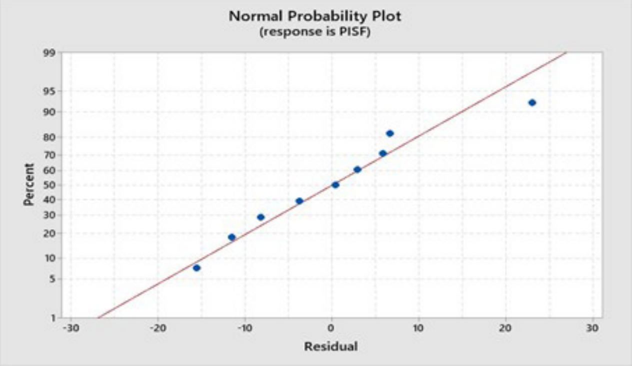

Figure 5: Cumulative normal probability plot of PISF.

Table 5: Experimentation at optimum levels of input parameters.

Optimal Levels			PISF		Error %
RPM (mm)	Abrasive mesh no	Working gap (2 mm)	Predicted	Experimental	
800	600	2	75.82	82.45	8.04

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Conflict of Interest

There is no conflict of interest.

Credit Author Statement

Rahul Kumar and Venkateswara Rao Komma: Conceptualization, Design, Experimentation, Writing - original draft preparation, Writing - review and editing. All the authors read and approved the manuscript.

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