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Experimental Study On Finishing Forces In Double Disk Magnetic Abrasive Finishing Process While Finishing Paramagnetic Workpiece

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Abstract

Knowledge of finishing forces is important in any manufacturing process as the surface integrity of the finished surface is being affected. In the present work finishing force and torque were measured for a recently developed double disk magnetic abrasive finishing process. Investigations have been made to understand the effect of process factors namely upper and lower working gap rotational speed, abrasive weight percentage on the normal finishing force and finishing torque. Experiments were planned and performed based on Taguchi L_9 orthogonal array. Analysis of variance has been used to analyze the experimental data. The analysis of the experimental data showed that normal finishing forces is affected most significantly by lower and upper working gap and finishing torque is effected mostly by the lower working gap and rotational speed of the magnetic disk. The surfaces finished by DDMAF process are characterized by SEM and the surface morphology has been correlated to finishing force and torque values.

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Keywords: Magnetic abrasive finishing, paramagnetic material, normal finishing force, finishing torque.

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1. Introduction

Magnetic abrasive finishing (MAF) is a super finishing process which uses a resilient multi point cutting tool to finish the work pieces. Blend of iron and abrasive particle forms a flexible magnetic brush (FMAB) between the work piece and the magnetic tool. The force exerted by the FMAB on the workpiece is responsible for the finishing action. By varying various process factors the finishing force and torque acting on the workpiece can be varied.

Several research attempts have been made to understand the effect of process factors on the finishing force and torque in MAF process. Kim and Choi, (1995), Kim and Choi, (2007) presented a mathematical model to calculate the polishing pressure exerted by the FMAB. They validated the model with the experimental results and reported the polishing pressure between 0 to 50 KN/m^2. They also reported that the polishing force varied between 16 to 75 N depending on the working gap. Khairy, (2001) developed a mathematical model using the process kinematics. They reported the finishing pressure acting on the workpiece surface was in the range of 0.13-0.26 MPa. Mori et al. (2003) explained theoretically the formation of FMAB. They reported that the percentage weight of magnetic abrasive affected the physical characteristics of the FMAB. They also observed that the normal force acting, for different magnetic abrasive weight percentage, varied between 0 to 20 N. Singh et al. (2006) measured the finishing forces for different processing conditions. They reported that finishing forces increased with increase in the magnetic flux density while they decreased with increase in the working gap. Jayasawal et al. (2005) observed the finishing forces in case of MAF using a finite element analysis. They also estimated the change in surface roughness. Singh et al. (2004) through a statistical analysis reported that varying rotational speed had no significant effect on the finishing forces. They reported that normal force varied from 10 to 150 N while tangential force was in the range of 10 to 60 N depending upon the processing conditions. Yamaguchi and Shinmura, (2000) investigated the effect of increasing the abrasive weight percentage on the normal force. They reported the normal force to be in the range of 2 to 5 N. Mulik and Pandey, (2013) studied the effect of voltage to the electromagnet, working gap, abrasive weight percentage and rotational speed on finishing forces. They reported that voltage to the electromagnet and working gap played a dominant role. The normal force varied between 12-24 N and the finishing torque value was found within 4-11 N-m.

The above literature review reveals that magnetic flux density plays an important role in deciding finishing forces in MAF process. The magnetic flux density obtained in the working gap with a para/diamagnetic work piece is low which results in lower finishing forces that causes ineffective finishing. In a previous work Kala et al. (2013) authors developed double magnetic disk to improve the magnetic flux density in the working gap. The workpiece was consecutively subjected to ultrasonic vibrations while the copper alloy workpiece was being finished between the two disks. They have achieved 56 nm surface finish in ten minutes. The present work aims at investigating the finishing force and torque in double disk magnetic abrasive finishing (DDMAF) process. Special fixture has also been fabricated to measure force and torque using dynamometer [Shunk: DELTA sensor with SI-330-30 Calibration]. Experiments based on Taguchi L_9 orthogonal array have been performed to investigate the effect of process parameters namely upper working gap, lower working gap, abrasive weight percentage and rotational speed on finishing force and torque while finishing a copper alloy work sample. The study also correlates the effect of finishing force and torque on the surface finish which is characterized by SEM.

2. Details of experimental setup and measurement of finishing forces

The experimental setup used for the present study is shown in figure 1(a). The upper and lower disks shown in figure 1(a) are aluminium disks with four blind holes in each disk. A stack of ten small magnetic disks (Φ25 mm X 3 mm thick) was placed inside each blind hole. Each set of magnetic disk was placed such that they form a magnetic tool with four alternate poles as shown in figure 1(b). The four poles on each upper and lower disk have been selected to ensure a synchronous motion between the upper and lower aluminium disk. The space between the upper and lower disk was small to place a dynamometer with the workpiece therefore a special fixture was designed and fabricated to accommodate the dynamometer. The upper plate of the fixture is a 3 mm thick copper alloy plate$(120\ mm \times 100\ mm \times 3\ mm)$ which is attached to U-shaped perpex assembly. The bottom plate of fixture is bolted to the dynamometer [Shunk: DELTA sensor with SI-330-30 Calibration]. The dynamometer was connected directly to computer via a data acquisition system. figure 1(c) shows the schematic view of the experimental setup and the directions along which the normal force and the finishing torque act. figure 1(d) shows the variation in magnetic flux density along the radial direction of the aluminium disk at different upper working gap. In planar MAF normal force and finishing torque are mainly responsible for finishing action. The normal force and finishing torque along Z-direction were recorded because the axis of rotation coincided with the Z-direction.

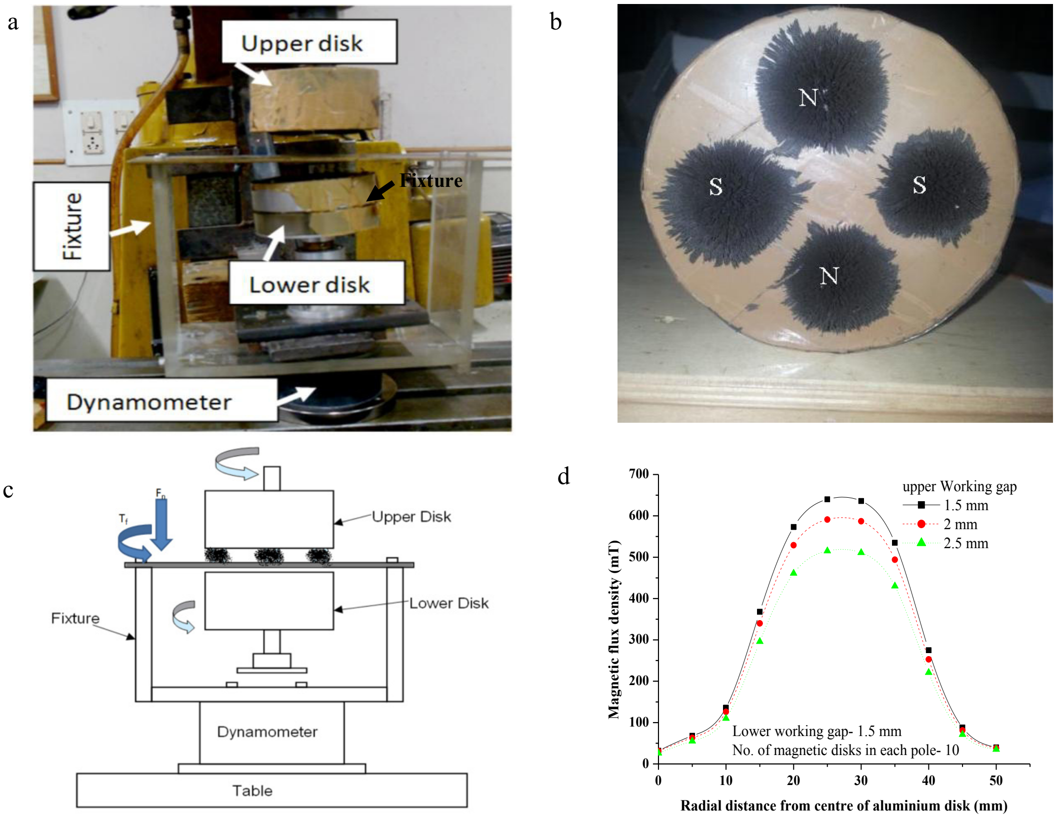

Fig. 1. (a) Experimental setup used in the study; (b) aluminium disk showing arrangement of magnetic poles; (c) schematic representation of the setup used for measuring finishing forces for double disk magnetic abrasive finishing (DDMAF); (d) magnetic flux density distribution over the work piece surface (lower working gap was fixed at 1.5 mm)

3. Experimental procedure

Based on the data available in the literature related to MAF, important process parameters that may significantly affect the finishing force/torque were identified. Preliminary experiments show that the varying abrasive mesh size had negligible effect on normal finishing force and finishing torque. Thus a fixed mesh size (#800) of alumina abrasive has been used. The abrasive powder was mechanically mixed with iron powder (#300) at different weight percentage of abrasives. As per preliminary experiments, the process factors and their range that may significantly affect the finishing forces and finishing torque are shown in Table 1.Table 2 shows the Taguchi L_9 orthogonal array that was selected to investigate the effect of considered process parameters. The measured average force and torque values have been presented in Table 2.

Table -Process factors and their levels considered to perform experimentation

Factors	Description	Level -1	0	1
X_1	Upper disk working gap (mm)	1.5	2	2.5
X_2	Lower dusk working gap (mm)	1.5	2	2.5
X_3	Percentage of abrasive	10	20	30
X_4	Rotational speed (rpm)	200	300	400

Table -Details of the experimental design and the corresponding average normal and finishing torque recorded for DDMAF

Exp. no.	Upper gap (mm)	Lower gap (mm)	% Wt. of abrasive	Rotational speed (rpm)	Average normal force (N)	Average finishing torque (N-m)
1	1.5	1.5	10	200	72.83	0.425
2	1.5	2.0	20	300	59.05	0.410
3	1.5	2.5	30	400	45.62	0.344
4	2.0	1.5	20	400	60.20	0.478
5	2.0	2.0	30	200	56.67	0.321
6	2.0	2.5	10	300	54.99	0.356
7	2.5	1.5	30	300	48.75	0.317
8	2.5	2.0	10	400	51.59	0.396
9	2.5	2.5	20	200	46.05	0.214

4. Analysis of experimental data

The ANOVA tables for the normal and the finishing torque are shown in Table 3 and Table 4 respectively. The Table 3 and 4 show that a strong correlation exist between e process factors and the normal force (R^2=95.4%) and finishing torque (R^2=93.10%).

Table -Analysis of variance for average normal force

Terms	Seq. SS	DF	F	P	R^2
Regression model ($\mathbf{F_n}$)	498.82	4	20.58	0.006	95.4%
Upper gap (X_1)		1			
lower gap (X_2)		1			
% wt of abrasive (X_3)		1			
RPM (X_4)		1			
Residual error		4			
Total		8			

Table - Analysis of variance for average finishing torque

Terms	Seq. SS	DF	F	P	R^2
Regression model $(\boldsymbol{T_f})$	277.576	4	13.49	0.014	93.10%
Upper gap $(\boldsymbol{X_1})$	67.127	1		0.023	
lower gap $(\boldsymbol{X_2})$	98.958	1		0.012	
% wt of abrasive $(\boldsymbol{X_3})$	40.633	1		0.048	
RPM $(\boldsymbol{X_4})$	70.857	1		0.021	
Residual error	20.572	4			
Total	298.153	8			

In order to have a better understanding of the effect of process factors on finishing force and torque the multivariable regression equations were obtained and are given below as equation 1 and 2.

$$\mathrm{F}_n = 127 - 10.4 \times X_1 - 11.7 \times X_2 - 0.946 \times X_3 - 0.0302 \times X_4 \quad ...1$$
$$\mathrm{T}_f = 0.734 - 0.0836 \times X_1 - 0.102 \times X_2 - 0.00651 \times X_3 + 0.00043 \times X_4 \quad ...2$$

where F_n is the average normal force, T_f is the average finishing torque , $X_1$is the upper working gap in mm, $X_2$is the lower working gap in mm, X_3 is abrasive weight percentage and $X_4$is rotational speed of disk in rpm.

5. Results and discussion

Figure 2 shows the percentage contribution of the considered process factors on normal and finishing torque. figure 2(a) shows that lower working gap dominantly affects the normal force followed by the upper working gap. The change in rotational speed was found to be affecting the normal force the least. Figure 2(b) shows that lower gap affects the finishing torque the most, followed by the rotational speed of the aluminium disk.

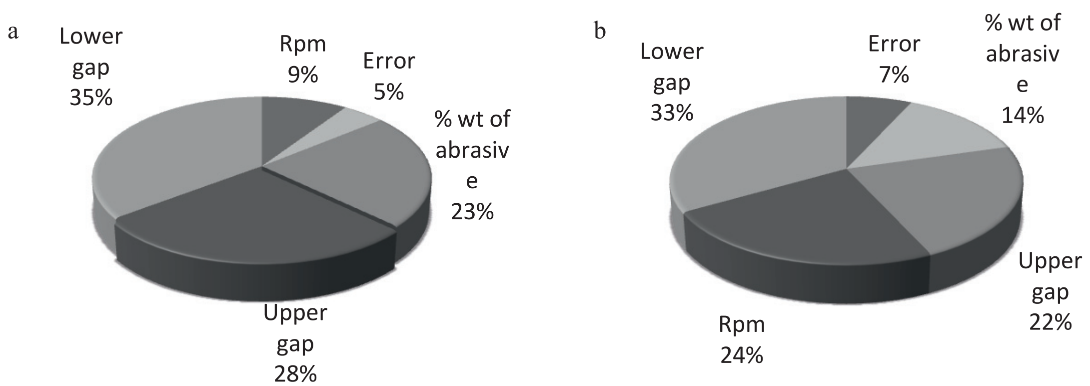

Fig. 2. Percentage contribution of process factors for (a) Average normal force; (b) Average finishing torque.

5.1. Effect of process factors on normal force

The effect of process factors on normal force has been shown in figure 3. Figures 3(a) and (b) show that as the lower or upper working gap is decreased the normal force increases. It is because when the upper or lower working gap is decreased the magnetic flux density in the working gap increases which results in the increase in normal force. However, the impact of decreasing the lower working gap is more than the upper working gap. This may be because when the lower working gap is decreased the air gap between the upper and lower magnetic pole decreases which causes a greater reduction in the magnetic reluctance path. Figure 3 (c) shows that as the abrasive weight percentage increases the normal force decreases. This may be because as the abrasive weight percentage increases the total number iron particle decreases; which may cause the FMAB chain to become less stiff. This reduction in the stiffness of the FMAB causes a decrease in the average normal force. figure 3(d) shows that as the rotational speed increases the average normal force decreases. This may be because as the rotational speed increases the available magnetic force may become insufficient to hold the FMAB chains because of which the FMAB chains starts breaking resulting in decrease in average normal force.

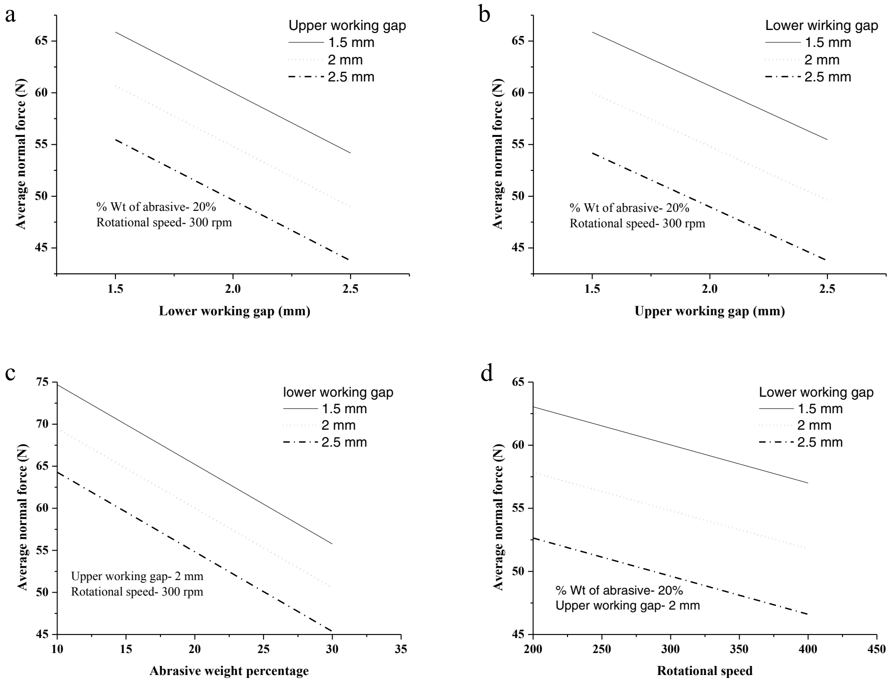

Fig. 3. Effect of varying (a) upper working gap; (b) lower working gap; (c) abrasive percentage weight; (d) rotational speed on average normal force

5.2. Effect of process factors on finishing torque

The effect of process factors on finishing torque has been shown in figure 4. Figure 4(a) and (b) show that the finishing torque decreases when either the lower or the upper working gap is increased. This may be because of the decrease in the available normal force (figure 3 (a) and (b)) which may result in the proportional drop in finishing torque. Similarly varying lower working gap affect the finishing torque more than the upper working gap. Figure 4 (c) shows that the finishing torque also decreases as the abrasive weight percentage is increased. This may be because as the abrasive weight percentage is increased the normal force decreases which might cause the finishing torque to decrease. figure 4(d) shows that as the rotational speed is increased, the finishing torque also increases. This may be because at high rotational speeds more number of abrasive particles shear the peaks of workpiece in unit time and hence the change in momentum per unit time is higher leading to high torque. Other added cause may be that due to high shear rate of peaks the workpiece hardening effect of work material may also contribute to the increase in torque. It can also be noted from figure 3(a) and (b) that rotational speed has a greater impact on finishing torque as compared to the normal force.

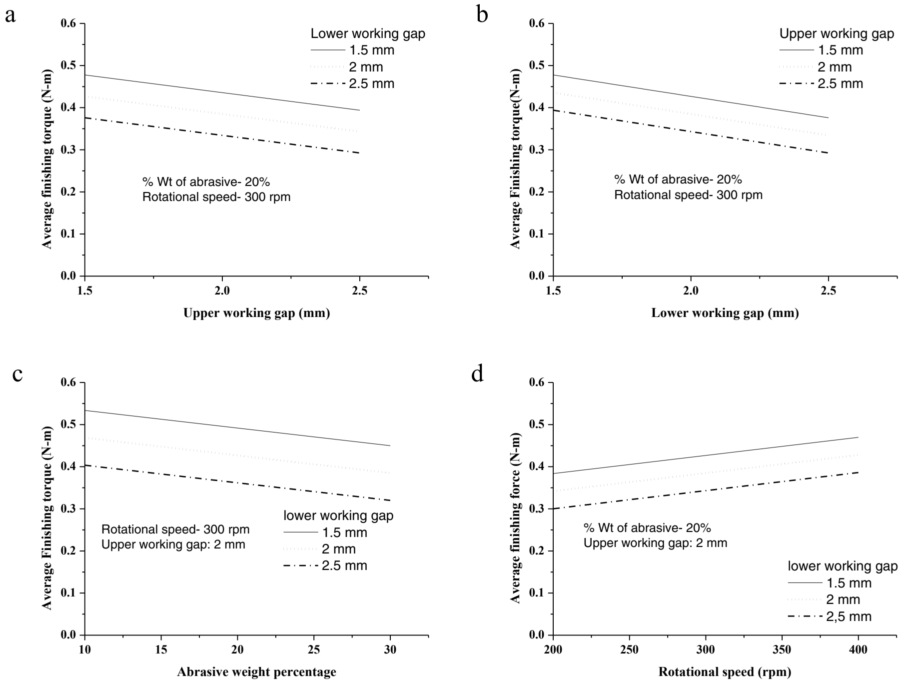

Fig. 4. Effect of varying (a) upper working gap; (b) lower working gap; (c) abrasive percentage weight; (d) rotational speed on average finishing torque

6. Effect of finishing force and torque on surface roughness

The SEM images obtained before and after finishing have been shown in figure 5. Figure 5(a) shows the SEM image of the grounded copper alloy sample while figure 5(b) and (c) show the work samples finished for 15 minutes at two different processing conditions. It can be observed from figure 5(b), which corresponds to experiment no.8, that average normal force is 51.59 N and an average finishing torque is 0.396 N-m, which could effectively reduce the surface roughness. However, figure 5(c) which corresponds to experiment no. 1 shows that higher value of normal force (72.83 N) and finishing torque (0.425 N-m) were able to remove the grinding lays but the normal force produced at the condition (experiment no.1) resulted in excessive indentation on the workpiece surface that produced scratch- marks.

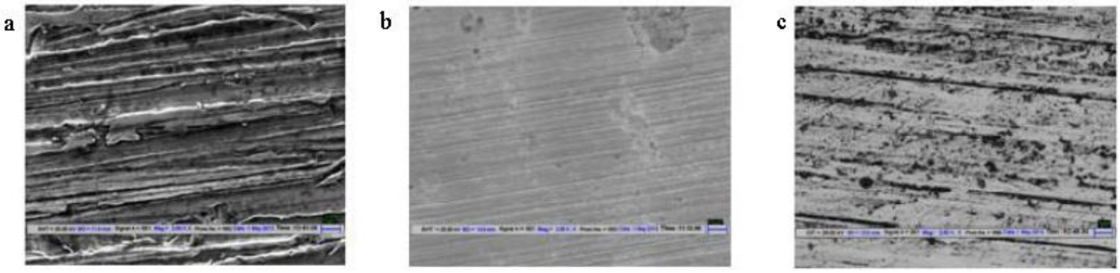

Fig. 5. SEM image of (a) grounded work sample; (b) work sample finished at rotational speed-300, lower working gap-2 mm, upper working gap-2.5 mm, abrasive weight percentage-15% for 15 minutes; (c) work sample finished at rotational speed-200, lower working gap-1.5 mm, upper working gap-1.5 mm, abrasive weight percentage-15% for 15 minutes

7. Conclusion

The finishing force and torque were measured successfully in DDMAF process. The statistical analysis of the experimental data for the normal force showed that lower working gap had the maximum percentage contribution followed by the upper working gap, abrasive weight percentage. Varying rotational speed showed the least effect on the normal finishing force.An increase in any of the four parameters resulted in a decrease in normal force. The statistical analysis of the experimental data for the finishing torque showed that the lower working gap had the maximum contribution on the finishing torque which was followed by the rotational speed, upper working gap and abrasive weight percentage.An increase in upper working gap, lower working gap and abrasive weight percentage resulted in decrease in finishing torque. However, an increase in rotational speed caused an increase in finishing torque.

The SEM image obtained for the grounded and the finished workpiece shows that the finishing forces developed in the DDMAF process were capable of effectively finishing a paramagnetic material like copper alloy. SEM image of another finished workpiece showed that at smaller working gaps the normal force during finishing was high enough to produce small scratches on the workpiece surface.

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