SUPERFINISHING OF ALLOY STEELS USING MAGNETIC ABRASIVE FINISHING PROCESS

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Abstract

Magnetic abrasive finishing (MAF) process is the one in which material is removed in such a way that surface finishing and deburring are performed simultaneously with the applied magnetic field in the finishing zone. The mechanism of superfinishing in any finishing process is widely focused by the knowledge of forces involved in the process. This paper reports the findings about the forces acting during MAF and provides correlation between the surface finish and the forces. The resistance type force transducer (Dynamometer) has been designed and fabricated, and used to measure normal magnetic force responsible for microindentation into the workpiece and tangential cutting force producing microchips. The force data have been recorded on-line by making virtual instruments (using Lab-View software).

Key Words: MAF, Dynamometer, Force analysis, FMAB, Design of experiments

Introduction

The technology for superfinishing needs ultra clean machining of advanced engineering materials such as silicon nitride, silicon carbide, and aluminum oxide which are used in high- technology industries and are difficult to finish by conventional grinding and polishing techniques with high accuracy, and minimal surface defects, such as microcracks. Therefore, magnetic abrasive finishing (MAF) process has been recently developed for efficient and precision finishing of internal and flat surfaces. This process can produce surface finish of the order of few nanometers. The method was originally introduced in Soviet Union, with further fundamental research in various countries including Japan [1-2]. An attempt has been made to measure forces acting on the workpiece and to evolve correlation between the surface finish and forces.

In MAF, two types of forces generated by flexible magnetic abrasive brush (FMAB) are responsible for finishing: (i) normal magnetic force responsible for packing the magnetic abrasive particles and providing microindentations into the workpiece, and (ii) tangential cutting force responsible for microchipping due to rotation of the FMAB.The FAMB pushes abrasive particles downward against the workpiece surface. The relative motion between the FMAB and the workpiece is provided by rotating the magnet. As a result, the abrasive particles remove the surface material circumferrentially resulting in the finished surface. The schematic diagram of the plane magnetic abrasive superfinishing apparatus is shown in Fig.1. In this process, the magnetic flux density of 0-0.44 T is used in the working gap of 1.00 –2.00 mm. Both magnetic as well tangential cutting forces are varied by changing the magnetic flux density and the working gap. The magnetic flux density is varied by changing input current to the electromagnet. On the supply of current to the magnet, the workpiece gets magnetized and magnetic lines of force emanate from the north pole of the magnet and terminate at the south pole via magnetic abrasive particles and workpiece, completing magnetic circuit (Fig.1). The space between the flat workpiece and flat-faced pole (also known as working gap/finishing gap) is filled with a mechanically made homogeneous mixture of silicon carbide abrasives (mesh no. 600) and ferromagnetic iron particles (mesh no. 300), known as unbounded magnetic abrasive particles (UMAPs) in 25:75 ratio by weight. In UMAPs, silicon carbide particles are not physically bonded to ferromagnetic iron powder. In the magnetic field, the abrasive particles can freely move around within the constraint of the adjacent ferromagnetic particles. The UMAPs are joined to each other along the magnetic lines of force and form FMAB (Fig. 2) between magnetic north pole and workpiece. This brush behaves like a multi point cutting tool. When the magnet north pole rotates, the FMAB also rotates concomitantly with the same rotational speed resulting in relative motion between the brush and the workpiece leading to finished workpiece surface. Here, cutting speed is continuously varying from the center to the periphery of FMAB.

The mechanism of superfinishing in any finishing process can be understood by the knowledge of forces involved in the process. Hence a precise force measuring device (Ring type Dynamometer) has been designed, fabricated, and calibrated as per the standard procedure [3], and used to measure forces as low as 0.5N. The force signals from the dynamometer have been acquired using a data acquisition card, and analysed by using Lab View software.

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Design of Experiments and Experimental Procedure

Experiments have been planned using statistical technique-central composite rotatable design to get useful inferences by performing minimum number of experiments. If the yield (response) 'Y_u' is a function of the levels of quantitative variables (X_{iu}), then this function can be approximated satisfactorily, within the experimental region, by a polynomial equation in the variables X_i [4]. The general form of the quadratic polynomial fitted to the experimental data is given below:

$$Y_u = b_0 + \sum_{i=1}^{k} b_i X_{iu} + \sum b_{ii} X_{ii}^{2} + \sum_{i \le j}^{k} b_{ij} X_{iu} X_{ju} \quad \ldots\ldots(1)$$

where k is no. of variables, b_i, b_{ii}, and b_{ij} are coefficients and b_0 is a constant to be evaluated. X_{iu} represents the level of the i^{th} variable in the u^{th} experiment. X_{ii}^2 is the square term and $X_{iu}X_{ju}$ represents the interaction term.

The ranges of operating parameters have been selected from earlier studies [5] and set-up constraints, and are given in Table-1. Five independent controllable parameters thus selected are (i) current to the coil of magnet, (ii) working gap, (iii) percentage of lubricant, (iv) rotational speed of magnet, and (v) finishing time.

The workpiece fixture is mounted on the ring dynamometer (force transducer), which is clamped on the table of the milling machine and leveled by using a dial gauge (least count: 1.0 μm). The required gap between the flat-faced pole and workpiece is maintained. At the end of each experiment, the fixture and workpiece are taken out from the MAF set-up and properly cleaned by ultrasonic vibrating cleaner. The change in surface roughness value (ΔRa) is determined by measuring Ra (center line average value) before and after MAF by Taly Surf-5000 (Federal make). The difference in these two values is called ΔRa .The measurements of Ra have been done in the selected area and perpendicular to the lays obtained in the MAF process.

Response Surface Analysis (RSA)

The following response surface equations no. 2, 3, and 4 consisting of only significant parameters for magnetic force (Fm), tangential cutting force (Fc), and change in surface roughness (ΔRa) respectively have been obtained by employing MINITAB- statistical software [6].

$$F_m = 48.0 + 12.0X_1 - 7.22X_2 + 6.38X_3 - 0.58X_4 + 0.19X_5 + 3.48X_1^2 + 0.08X_2^2 + 2.51X_3^2 - 1.17X_1X_2 + 4.03X_3X_4 \quad \ldots\ldots(2)$$

$$Fc = 35.1 + 6.27X_1 - 6.05X_2 + 1.39X_3 - 2.45X_4 + 0.114X_5 - 1.04X_4^2 \quad \ldots\ldots(3)$$

$$\Delta Ra = 0.22 + 0.26X_1 - 0.041X_2 + 0.015X_4 - 0.023X_1X_2 + 0.018X_2X_4 \quad \ldots\ldots(4)$$

Table.1 parameters

Parameter	*Unit*	*Range*
Current (X_1)	Amp	0.5-1.0
Working Gap (X_2)	mm	1.0- 2.0
Lubricant (X_3)	Wt %	1.0- 5.0
Rotational Speed of magnet(X_4)	RPM	63-250
Finishing time (X_5)	min	15-75

Table 2: Analysis of Variance (ANOVA) of Regression

Table.2a	Magnetic Force (for Eq2)				
Source	DOF	SS	F	P	%age
Regression	20	6660.48	9.57	0	94.6
Residual Error	11	382.83			5.4
Total	31	7043.31			100
Table. 2b	Tangential Cutting Force (for Eq3)				
Regression	20	2084.05	16.25	0	96.7
Residual Error	11	70.56			3.3
Total	31	2154.61			100
Table. 2c	Change in Ra (for Eq3)				
Regression	20	0.106	3.93	0.012	87.73
Residual Error	11	0.015			12.27
Total	31	0.121			100

The ANOVA (Tables-2a-c) indicates that the correlation between predicted and experimental data for Fm, Fc, and ΔRa are quite adequate (87.0%-96.7%) and the calculated variance ratio (F) is more than standard F (=2.65) at 95% confidence interval (α=0.05) [7]. This variance ratio (F value) is used to measure the significance of the regression under investigation. Responses have been calculated using Eqs. (2), (3) and (4) to study the effects of various process parameters on magnetic force, cutting force, and change in Ra respectively. At the center point of the experimental design, six experiments were carried out for the same value of variables to check the repeatability of the process results. There is very little difference within the 6 values of Fm as well as Fc (Table-3). Hence, it is concluded that the process repeatability is good. Further, The experimental points (•) in Figs.3 and 4 are very close to the computed results hence response surface analysis (RSA) results can be treated as representative experimental results.

Results and Discussion

A relationship shown in Fig.3 between magnetic force and electric current (dc) to the magnet for different working gaps has been established by using Eq.2. The trend of the curves is similar for different working gap values but the magnitude of the force is higher at lower gap. Lower gap increases the intensity of the magnetic field hence higher magnetic force. This will increase the packing density of the magnetic abrasive particles. As a result, rigidity of the FMAB increases which results in deeper microindentations into the workpiece as well as larger magnetic force. It is also observed that magnetic force increases with increase in current for a specified gap. This is so because increase in current also increases magnetic flux density in the gap resulting in increased packing density of FMAB and hence mass of abrasive particles in the FMAB gets increased. Therefore more no. of abrasive particles come in contact with the workpiece, which also contribute to the increased magnetic force.

A relationship between tangential cutting force with current for different working gaps has been established by Eq.3 and is shown in Fig. 4. The cutting force is basically a mechanical force responsible for the removal of material in the form of the microchips. This force increases with increase in current for a specified gap. This is so because increase in current increases magnetic force which increases rigidity of FMAB and depth of indentations by the particles. Therefore, resistance to the rotation of FMAB offered by the workpiece would be more and therefore cutting force increases.

Ultimately it is the force which plays most important role in any superfinishing process controlling the surface finish. Therefore in this paper the correlations between change in surface roughness (Δ Ra) and both magnetic force (Fm) (Fig. 5a) and cutting force (Fc)(Fig.5b) have been established by employing STATISTICA-Software to the experimental data. The following equations have been evolved:

$$\Delta Ra = (0.0200566)(Fm)^{0.583} \qquad (5)$$

With Correlation Factor = 0.51

$$\Delta Ra = (0.008742)(Fc)^{0.885} \qquad (6)$$

With Correlation Factor = 0.64

It is very clear from the Fig. 5a and Fig. 5b that there is a scatter in the experimental data and hence the deviation from the calculated values. Therefore, Eqs (5) and (6) estimate approximate values. Δ Ra increases with increase in magnetic and cutting force as shown in Figs. (5a) and (5b). The magnetic force is responsible for microindentation into the workpiece. The increased magnetic force enhances the strength of FMAB and indentations into the workpiece leading to increased cutting force. As a result, more will be the abrasion and more microchips will be formed resulting in better surface finish (or lower value of Ra after MAF and higher Δ Ra).

Conclusions

Following inferences have been derived on the basis of above results and discussion:

Regression models for magnetic force and tangential cutting force indicate that both forces increase with increase in current. Further, ANOVA indicates that there is a good correlation between predicted and experimental data (87.73%-96.7%) (Fig. 3). It is also observed that calculated variance ratio (F) is more than the standard F value in all cases hence the proposed modes are adequate. It is also concluded that the process repeatability is good (Table.3).

Correlation between the normal magnetic force and tangential cutting force with change in Ra is comparatively weak. It needs further investigation.

Acknowledgement

The authors acknowledge the support of Department of Science and Technology, Government of India for the project on Investigations into Magnetic Abrasive Finishing (MAF) of Plane Surfaces.

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Table 3 Experiments for reproducibility

S.N.	Fm (N)	Fc (N)	Δ Ra (μm)
1	46.64	34.22	0.26
2	48.58	35.82	0.21
3	43.53	34.91	0.2
4	41.59	34.22	0.21
5	50.54	34.68	0.19
6	52.40	35.13	0.28
S.D	3.640	0.66	0.027

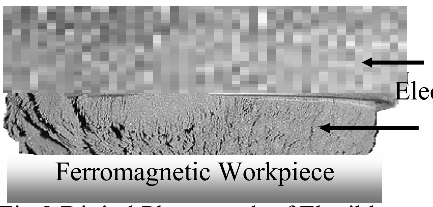

Fig.2 Digital Photograph of Flexible Magnetic Abrasive Brush (FMAB)

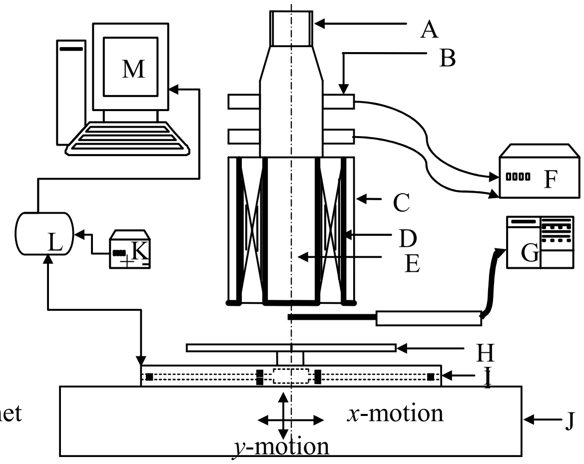

Fig.1 Schematic View of Plane Magnetic Abrasive

A: Main Spindle of Vertical Milling Machine; B: Slip Rings; C: Outer Pole (South Pole); D: Coil; E: Central Pole (North Pole); F: DC Power Supply; G: Digital Gauss Meter; H: Workpiece Fixture; I: Ring Dynamometer; J: Table of the Machine; K: 6.0 Volt DC Supply for Signal Conditioning Unit; L: Signal Conditioning Unit; M: PC for recording force data

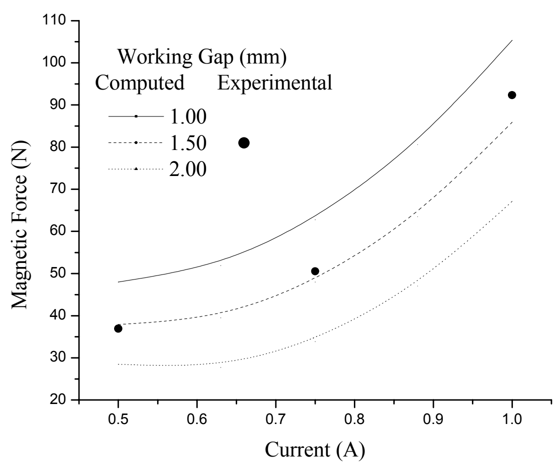

Fig.3 Effect of current on magnetic force for different gap at %oil = 3, RPM = 125, Time = 45min

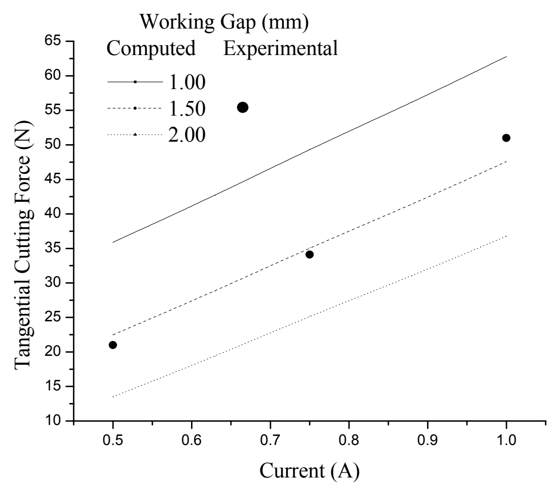

Fig.4 Effect of current on Tangential cutting force for different gap at %oil = 3, RPM = 125, Time = 45 min

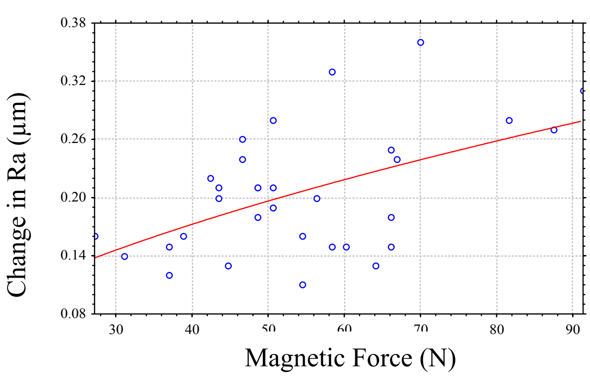

Fig.5a Correlation between Magnetic Force and Change in Ra

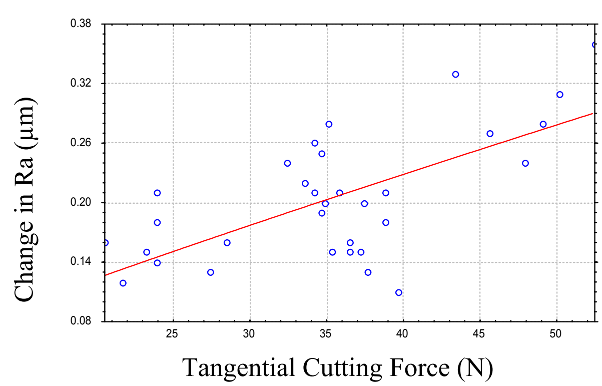

Fig.5b Correlation between Tangential Cutting Force and Change in Ra