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Original Article

Experimental Analysis for the Surface Roughness Improvement of Bearing Steel SAE 52100 Using Magnetic Abrasive Finishing Process

Rajendra E. Kalhapure[1], Gaurav Kumar Gugliani[2], Ravindra R. Navthar[3], Prashant N. Nagare[4]

[12]*Mechanical Engineering Department, Mandsaur University, Madhya Pradesh, India.*
[3]*Mechanical Engineering Department, DVVP COE Ahilynagar, Maharashtra, India.*
[4]*Mechanical Engineering Department, Amrutvahini COE Sangamner Ahilynagar, Maharashtra, India.*

[1]*Corresponding Author : rekalhapure@rediffmail.com*

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Abstract - *52100 bearing steel is mainly used in various applications, including seal rings, sleeves, bearings, balls, bearing races, rollers, guide bars, and knives, among others. Traditional finishing processes might be difficult to perform when making diverse components in varied forms and sizes. This aims to employ advanced fine machining and finishing procedures. Magnetic abrasive finishing is one of the precision fine-finishing approaches that yield exceptionally high-quality components. This process employs a flexible magnetic abrasive brush that is guided by a DC magnetized field to achieve desired results. The magnetized abrasives utilized in this fine-finishing process generally consist of two components: ferromagnetic material and abrasive particles, which must be interconnected. In this study, 52100 steel bars are fine-finished on a Magnetic abrasive finishing setup using multiple process variables. For this investigation, an Aluminum oxide (Al2O3) is used as an abrasive for this micro-finishing process. Variables such as magnetic density, workpiece rotating speed, and abrasive mixer can be easily varied to research greater surface finishes. The success of the process is determined by elements such as abrasive particle contents in mixing ratio, workpiece speed, and the input DC power source for magnetic flux density. The testing results reveal that the surface roughness of 52100 bearing steel rods improved with a high voltage of 36V and a rotational speed of 1026 rpm. Experiments demonstrate that raising the voltage and rotating speed improves surface roughness by a greater percentage.*

Keywords - *Flexible magnetic, Abrasive brush, Magnetic Abrasive Fine-finishing, DC electromagnet, Surface roughness.*

1. Introduction

Advanced fine/micro finishing approaches include lapping, honing, super finishing, buffing and polishing, Abrasive Flow Machining (AFM), Elastic Emission Machining (EEM), and Magnetic Abrasives Finishing (MAF), among others. Figure 1 depicts a schematic of the MAF process.

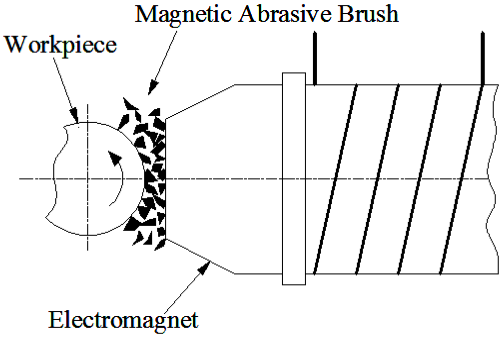

Fig. 1 Schematic of the MAF

The magnetic abrasive finishing technique is based on the principle of correlative motion of the workpiece and a mixture of ferrous and abrasive particles subjected to an electromagnetic field, resulting in a processing impact on the workpiece. In the Magnetic Abrasive Finishing (MAF) process, the magnetic field plays a crucial role in influencing the engagement between the workpiece and abrasive particles. The DC electromagnetic field influences both the surface of the workpiece and abrasive particles, and this interaction is what makes the process unique. The efficiency of the process of removing material is directly pertaining to the motion and force applied by the electromagnetic field on the Al2O3 particles. The rate of material removal increases with the rotational speed of the workpiece and the interaction of the abrasive particles with the workpiece. Additionally, as Al2O3 particles strike the workpiece, they carry out cutting or polishing actions, helping to smoothen the surface. The non-magnetic workpiece, composed of materials like stainless steel, aluminum, or ceramics, can typically be used in MAF, so the magnetic field doesn't directly affect the material of the workpiece itself in terms of magnetism. In earlier studies of MAF, Ik-Tae Im and colleagues have attained a surface roughness of just 0.06 µm and a circularity of 0.12 µm for workpiece by employing a diamond paste containing 1µm particles in the MAF process [1]. Baron et al. experimentally studied how MAF is utilized for the deburring of drilled holes [2, 3]. Zhen-Bing Hou and R. Komanduri have studied the thermal component of MAF for the given workpiece [4]. Another study by Deaconescu T. & Deaconescu A. developed MAF equipment for the finishing of roller bearing balls [5]. Jae-Seob Kwak has done simulation and experimentation of MAF for the finishing of nonferrous materials [6]. Kanish T C and et al experimentally investigated Magnetic Field Assisted Abrasive Finishing using Taguchi’s L27 orthogonal array [7]. Yuewu Gao and colleagues have conducted a study on the modeling of the removal of material in this abrasive finishing process by examining various process parameters [8]. In the study of authors Pandey and Mulik, it has been observed that both the normal force and final torque rise with increased voltage and decrease with a smaller finishing gap during MAF [9]. Rampal, Rohit, and Dr. Tarun Goyal have developed a MAF setup on a lathe machine to ensure a high level of precision in the finishing of the workpiece [10]. Among the various process parameters, voltage and finishing gap are the most influential factors impacting finishing torque and normal force. The utilization of nanoscale abrasive particles can lead to more precise and smoother finishes. These particles can be engineered to improve cutting efficiency while maintaining a high surface quality.

This paper deals with the percentage improvement in surface roughness during MAF using input DC voltage, workpiece rotating speed, and Al2O3 abrasive content (%) in mixing ratio as variables of the process. The statistical evaluation of this experimental data indicated that input DC voltage and the rotational speed of the component are the key process variables affecting the percentage enhancement in the roughness of the surface. This study investigated the effects of various process variables, including input DC voltage, workpiece rotational speed, and the concentration of Al2O3 abrasive in the mixing ratio. The analytical data were utilized to evaluate the characteristics of the MAF process.

2. Experimental Methodology

2.1. Experimental Configuration

For the purposes of this experimental study, the MAF setup is developed on a lathe machine (type of Lathe Machine: Centre Lathe Machine) using a DC power supply. The cutting tools, FMAB, consist of a mixture of abrasive particles (Al2O3) and ferromagnetic material (iron powder). The workpiece (Dimensions of workpiece: Ø25*25mm length) is gripped in a three-jaw chuck and adjusted between electromagnetic poles. An electromagnet is made up of two coils of copper wire, as shown in Figure 2, that are set to be mutually opposing. A DC current source (Specifications of DC power supply: 0 to 36V) from an AC to DC converter is utilized to power the electromagnet, which is coupled to a lathe slide. To prevent magnetic flux leakage onto the lathe slide, hardwood brackets and aluminium nuts and bolts are employed to clamp the electromagnet to the slide.

A Flexible abrasive brush is created by combining iron particles with Al2O3 particles, held together by the electromagnetic field generated by DC electromagnets, which provides the required finishing force.

The surface finish obtained is mirror-like since this technique is always carried out with very delicate forces.

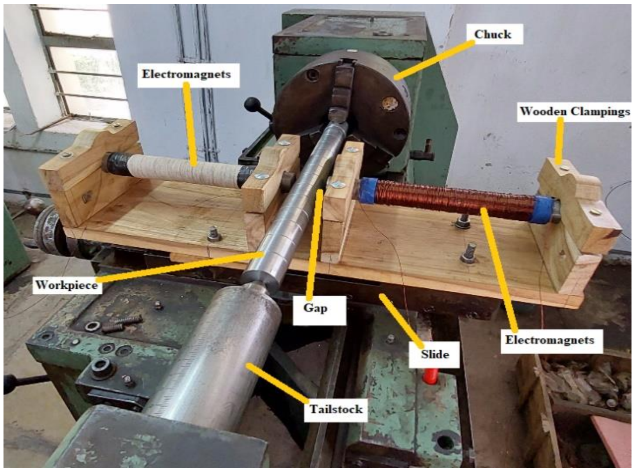

Fig. 2 Photograph of actual MAF Setup

Figure 3 shows a photograph that demonstrates how these particles align along magnetic field lines to generate a Flexible magnetic Abrasive Brush (FMAB). The same brush applies pressure to the workpiece's surface, generating finishing pressure that leads to micro indentations. The required tangential force produced by the FMAB serves as the primary cutting force that leads to micro-chipping. In this abrasive finishing method, the workpiece is positioned between two electromagnets and the required distance between the surface of the workpiece and the electromagnets must be set using properly sized slip gauges.

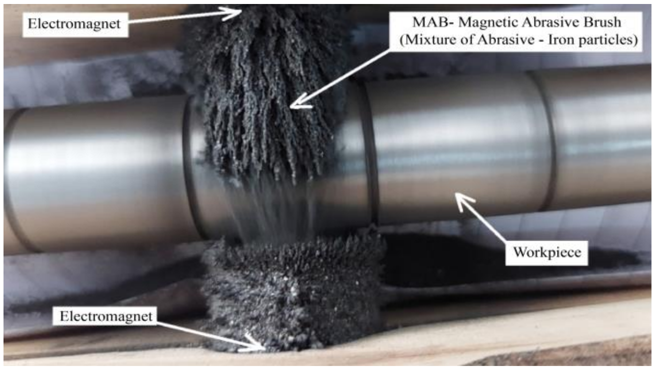

Fig. 3 Actual photograph of Flexible Magnetic Abrasive Brush (FMAB)

Al2O3 abrasive particles may be utilized in various forms: unbonded, lightly bonded and or fully bonded. A combination of Al2O3 abrasives and iron particles has been applied to 52100 steel bars in the finishing area, where the electromagnetic field generates a finishing force acting on the surface of the steel bars.

Throughout the process, a mixture of iron and abrasive particles placed on the surface of the workpiece are attracted to the electromagnetic field that presses against its outer surface. As the workpiece rotates and a DC voltage is applied to the electromagnet, a magnetized field is generated at the poles of the electromagnet. This magnetized field draws in a mixture of powders that have been applied to the workpiece. The same mixer is positioned within the gap of the workpiece, where electromagnets are employed to achieve a precise polishing of the surfaces.

2.2. Work Material

In this study, Al2O3-based magnetic abrasives were employed to polish cylindrical SAE 52100 steel rods, each measuring 25mm in diameter and 25mm in length, to achieve a fine finish. Prior to the final finishing of the MAF setup, the workpieces are initially ground, and their surface roughness is subsequently assessed.

2.3. Mixture of Abrasives and Iron Particles

A simply mixed mixture of magnetic abrasives was produced by combining Al2O3 and iron particles in different ratios, as illustrated in Figures 4 and 5.

Fig. 4 Weighing of Al_2O_3 = 50 gms powders for mixtures

Fig. 5 Weighing of Fe = 50 gms powders for mixtures

The content (%) of Al_2O_3 abrasives in mixing ratio was created by mixing Al_2O_3 and iron particles as per Table 1.

Table 1. Abrasive and iron powder proportions

Sr. No.	Abrasive: Iron powder	Proportion	Weight ratio (gms)
1	Al2O3:Fe	1:2	50:100
2	Al2O3:Fe	1:1	50:50
3	Al2O3:Fe	2:1	100:50

2.4. Selection of Process Parameters and Experimental Design

Actual experimentation was carried out using the design of experiments, Taguchi's orthogonal array L9 (3^3) (3 levels, 3 factors), to estimate the effects of factors as process variables that influence performance (finishing of the surface). Distance between the electromagnet and the workpiece is maintained at 2 mm using slip gauges, and a consistent fine finishing time of 20 minutes is applied across all experiments. For this study, 3 factors, speed in rpm, Input DC voltage and Mixing Ratios and the 3 levels, low, medium and high, were examined.

Table 2. Experimental conditions low medium high

Process Parameters	Levels		
	Low	Medium	High
Rotational speed of workpiece	226	649	1026
Input voltage	24	30	36
Abrasive content in Mixing Ratio (Abrasive: Fe)	1:2	1:1	2:1

2.5. Measurement of Response Variables

Table 3 shows respective input data and output measured data.

Table 3. Experimental input data and response

Expt. No.	W/p Rotational Speed	Input DC Voltage	Mixing Ratio	% Improvement	S/N
1	226	24	1:2	15.777	23.9605
2	226	30	1:1	22.317	26.9727
3	226	36	2:1	29.011	29.2513
4	649	24	1:1	18.325	25.2609
5	649	30	2:1	22.711	27.1247
6	649	36	1:2	28.361	29.0544
7	1026	24	2:1	20.461	26.2185
8	1026	30	1:2	26.123	28.3405
9	1026	36	1:1	33.231	30.4309

3. Results and Analysis

This section outlines the outcomes of the statistical analysis carried out on experimental data. Inferential statistical techniques are employed to assess the signal-to-noise ratio (S/ N ratio) and conduct an Analysis of Variance (ANOVA) to determine process variables that influence percentage improvement in surface finish.

3.1. S / N Ratio

To attain an increased percentage enhancement in surface finish (% change in Ra), the "Larger is better" quality feature was selected for this study.

Table 4. Response Table for S / N ratio of Percentage Change in Ra

Levels	W/P Speed	Input DC Voltage	Mixing Ratio
1	22.37	18.19	23.42
2	23.13	23.72	24.62
3	26.61	30.20	24.06
Delta	4.24	12.01	1.20
Rank	**2**	**1**	**3**

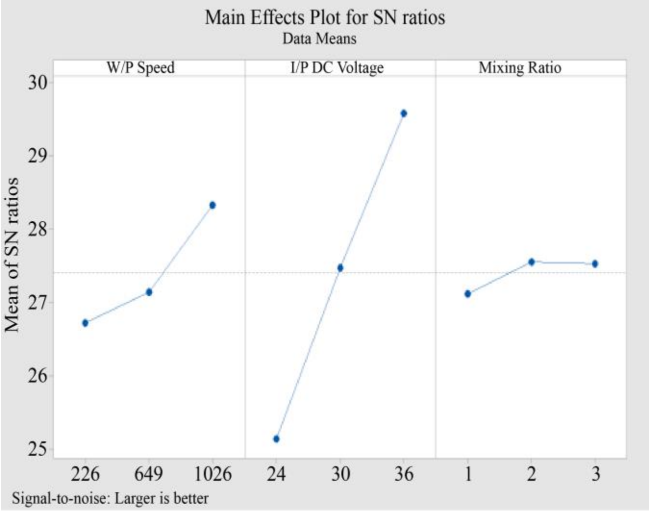

Fig. 6 Process parameters

To assess how individual process factors influence %ΔRa, the delta value is determined by calculating the signal-to-noise (S/N) ratios. Table 4 ranks parameters based on delta values found for %ΔRa. The factor with the greatest delta value was assigned the top ranking, and so on.

The figure illustrates the S / N ratios for process parameters in relation to the percentage enhancement in surface roughness, denoted as %ΔRa.

From Signal to Noise Ratio- Optimum levels are obtained, i.e. Best experiment levels to get maximum percentage Improvement: Workpiece input speed -1026 rpm, Input DC Voltage- 36 V, Mixing ratio- 1:1.

3.2. Analysis of Variance ANOVA

ANOVA was used to identify significant process characteristics influencing %ΔRa. Table 5 shows the ANOVA results for %ΔRa.

Table 5. Analysis of variance

Sources	DF	Adj. SS	Adj. MS	F - Value	P - Value
Regression	3	243.335	81.112	55.24	0.000
W/P Speed	1	26.239	26.239	17.87	0.008
I/P DC Voltage	1	216.480	216.480	147.42	0.000
Mixing Ratio	1	0.616	0.616	0.42	0.546
Error	5	7.342	1.468	-	-
Total	8	250.678	-	-	-

3.3. Percentage Contribution of Factors on the Process

Figure 7 illustrates the percentage contributions of various variables to the outcome of percentage change in Ra, highlighting that the DC voltage of the electromagnet has the most notable impact on the improvement in surface roughness of a given component.

Raising the DC voltage applied to the electromagnets enhances the magnetic flux density. Consequently, as the voltage rises, both the strength and the area of contact between the magnetized brush and the workpiece increase, resulting in greater indentation of the individual Al2O3 abrasive particles onto the workpiece. Additionally, the rotation speed of the workpiece has been recognized as a key factor.

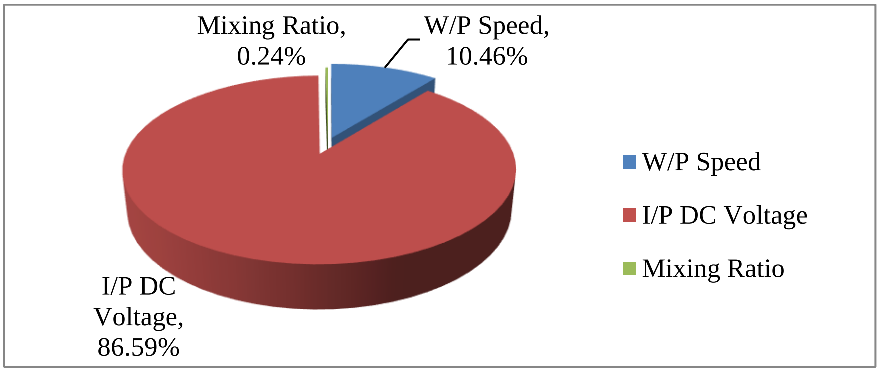

Fig. 7 Percentage contributions of process variables to %ΔRa

Table 6. Analysis of variance for percentage contribution

Term	DF	Adj. SS	Adj. MS	F - Value	P - Value	% Contribution
Regression	3	243.335	81.112	55.24	0.000	
W/P Speed	1	26.239	26.239	17.87	0.008	10.46
I/P DC Voltage	1	216.480	216.480	147.42	0.000	86.59
Mixing Ratio	1	0.616	0.616	0.42	0.546	0.24
Error	5	7.342	1.468	-	-	-
Total	8	250.678	-	-	-	-

Table 7. Coefficients

Terms	Coef.	SE Coef.	T-Value	P-Value	VIF
Constant	-9.95	2.81	-3.55	0.016	
W/P Speed	0.00523	0.00124	4.23	0.008	1.00
I/P DC Voltage	1.0011	0.0825	12.14	0.000	1.00
Mixing Ratio	0.320	0.495	0.65	0.546	1.00
		S 1.21181	R- sq 97.07%	R- sq (adj) 95.31%	R- sq (pred) 91.30%

The ANOVA results indicate that the input DC voltage supplied to the electromagnet, the rotational speed of the workpiece, and the mixing ratio all significantly influence the percentage improvement in surface roughness. These findings are consistent with the S/N ratio study. The P-Value suggests that input DC voltage and workpiece speed are less than 0.05. Therefore, they contribute to the process, and the mixing ratio is larger than 0.05; therefore, if they contribute to the process, they can be pooled.

3.4. Regression Equation

From the coefficients table, the following is the regression equation that was formed.

% Improvement in Surface Roughness = -9.95
+ 0.00523Workpiece Speed + 1.0011 Input DC Voltage
+ 0.320 Mixing Ratio

From Table 7, as R-Sq (Pred) is 91.30%, the regression model can be accepted statistically.

The regression model is best fitted as the R-squared value is 97.07% and the R-adjusted value is 95.31% under a 95% confidence level.

4. Conclusion

Optimizing the process parameters in Magnetic Abrasive Finishing (MAF) plays a crucial role in improving surface quality (%ΔRa). This research aims to develop an MAF process specifically for finishing 52100 bearing steel and to identify the optimal parameters that will enhance both surface finish and material removal. Through experimental investigations into the MAF process, This current study has led to the following conclusions:

The signal-to-noise (S/N) ratios and ANOVA analysis indicate that a high-level voltage of 36V and superior workpiece rotation speed of 1026rpm have a substantial impact on %ΔRa.

- Experiments show that increasing voltage and rotating speed have a favourable influence on %ΔRa.
- From Signal to Noise Ratio - Best Experiment Levels for Maximum% Improvement at W/p input speed -1026, I/p DC Voltage: 36, Mixing Ratio: 2 levels.
- The abrasive content in the mixing ratio has been shown to be affecting the least.

Future Scope

This process can be studied by using various grain sizes of abrasives under the various end shapes of electromagnets like conical, hemisphere, conical flat, etc.

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