Parametric Optimization of Ball End Magneto Rheological Finishing Process on EN-31

Shashikant Pandey, Suman Kant, Vinod Mishra, Neha Khatri, Sarepaka.V.Ramagopal

Abstract*— This work is concerned to explore the effect of process parameters of the ball end magnetorheologial finishing on the magnetic work piece to achieve nanofinishing. Magnetizing Current, working gap and Nozzle speed have been considered as input parameters; however percent improvement in surface roughness considered as an outcome of the process. In Present work the experiments have been carried out with above mentioned input process parameters with the help of the standard L9 orthogonal array of Taguchi .The measurement of the surface roughness is taken with the help of contact type Contact Mechanical Profiler PGI 120. Experimental data has been analyzed by using pooled anova for finding the contribution of input parameters, and further searching best input values to obtain optimal/near optimal output value. In the end a generic input-output relation has been developed using regression analysis to predict output value for newer input values.

***Index Terms*— Magneto rheological finishing, Surface roughness, Taguchi method, ANOVA, Regression model**

I. INTRODUCTION

With the current trends in developing the advanced processing technologies, manufactured components/products are expected to demonstrate superior quality and enhanced functional performance. Material removal processes continue to dominate among all manufacturing processes. The functional performance of components from material removal processes is heavily influenced by the quality and reliability of the surfaces produced. The surface roughness plays an important role in product quality, precision fits and high-strength applications. Bad surface feature of engineering components can create many problems during operations, such as malfunctioning, excessive wear, corrosion and oxidation, geometric inaccuracy, power loss, poor aesthetic appearance etc.[1]

Finishing processes are essential to meet the necessities of high surface finish, accuracy, and least surface defects.[2] In past few years, to overcome the boundaries of conventional finishing processes and accurate control of finishing forces throughout operation, a number of magnetic fields supported finishing processes have been developed. To name a few, these techniques are magnetic abrasive finishing (MAF), magnetic float polishing (MFP), magnetorheological jet finishing (MRJF),magnetorheological abrasive flow finishing (MRAFF), and magnetorheological finishing (MRF).[3]

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Magnetorheological finishing (MRF) is a novel polishing process that was invented and developed by an international group of collaborators at the center for optics manufacturing (COM) in the mid-1990s and commercialized by QED technologies, Inc. in 1997 [4]. The MRF Process depends on "smart fluid", known as magnetorheological (MR) fluid. MR fluids shows active field strength of 50-100 kPa for applied magnetic field of 150-250 kA/ m[5]. MR fluids contain magnetic carbonyl iron particles (CIPs), and nonmagnetic polishing abrasives in water or other carrier fluid like mineral oil. Very important properties of MR fluid is its rheological properties. Normally, MR fluid is free flowing liquid and shows Newtonian behavior. On activation of external magnetic field, the resistance to motion is considerably increased which can stand against external force. Since energy is required to deform and rupture the particles chains, this micro-structural transition is responsible for the onset of a large, "tunable" finite yield stress. [6]

Jain V.K. et al. had done Experimental investigation in to surface roughness and yield stress in MRF base Nano-finishing process carried experimental study to see the effect of process parameters with the help of the Response surface metodology. They developed a predictive model for the surface roughness after conducting their experiments on brass and stainless steel material. [7] An experimental study of finishing process on MRF has been carried out by Wan Li Song et al. Magnetic field strength, normal load, and rotating speed were input variable and the surface roughness and material removal rate considered as output variable. [8] Although several authors contributed their work in magnetorheological finishing, but in case of ball end magnetorheological finishing process very few researches have been found out. Further no work has been reported to find optimal/near optimal solution with Fractional Factorial experiments (i.e Reduction in experiments with orthogonally suggested). Keeping these views an attempt has been made by authors to find the best output value through Taguchi L-9 FFE (Fractional Factorial experiments). It is quite interesting to see the results after using this technique. It is needless to be mentioned that originally designed 27 numbers of experiments would have led to increment in time and cost as compared to L-9 FFE (Fractional Factorial experiments). Taguchi methods have been widely utilized in engineering analysis and consist of a plan of experiments with the purpose of obtaining data in a controlled way, in order to gain information about the behavior of a given process. [9]For the present work EN-31 is chosen as the work piece material. EN-31 steel is widely used in various engineering application.

But use of EN-31 steel can be explored with achieving high surface finish with the highly precise dimension (minimum profile deviations). This material is most suitable for the fabrication of the mold for the injection molding machine which is used in the optical lenses manufacturing, human implants, cryogenic application, ball bearing used in precision machining and in automobile industry. Due to its good strength, the life and performance of the components will increase.

But achieving nano level surface finish in the steel is not very easy. Diamond tool are worldwide popular for nano level finishing of the metallic object. But in case of steel material they cannot be use due to heavy diffusion wear of the diamond tool while machining of steel. Diamond turning is a costly machine and diamond tools are also costly so this method is not applicable for this job. Sometime tool of titanium carbide can be used in the computer numerical controlled machine but with the help of carbide tool the surface roughness cannot decrease up to desired level. Researchers proved the capacity of the BE MRF process can achieve the surface roughness in the ferromagnetic material up to 16.6 nm. It is relatively economic, efficient and highly capable process to achieve varies good surface finish in very short time. The performance of the BE MRF process is highly dependent of the process parameters.

In this study, the settings of BEMRF process parameters were determined by using Taguchi's experimental design method. Orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA), and regression analyses are employed to find the optimal levels and to analyze the effect of the BEMRF process parameters on change in the surface roughness values. A regression model is developed and confirmation test is conducted to validate the mathematical regression equation.

II. EXPERIMENT DETAILS

A. Preparation of component for BEMRF process

Ball end magneto rheological finishing is a nano finishing process. It removes the material in the form of very small nano or micro size of chips and can finish the components up to 15-20 nm so for better performance of the process the initial surface of the component should be as minimum as possible so that a significant good surface can be achieve at the of the finishing process in short time. In this study initially a rod of 20 mm diameter is taken and then it is cut down in to various disks of 20 mm thickness and 20 mm diameter by handhexa. Then with the help of facing operation in the conventional lathe machine using carbide tool surface is improved. Then next the grinding process is applied on these work pieces. After the grinding process the surface finish is achieved up to 800 nm. Then Component is taken for the lapping operation. Lapping is done in three stages by using alumina oxide as abrasive and water as a base medium. At three stages of lapping operation three size of alumina oxide is taken first 302(mA2) with 22 µm size then 303(mA3) having 15 µm size and then finally 303.5(mA3) with 11 µm size is used. After the lapping the surface finish is measured at every stage. After lapping with 303.5(mA3) the final surface roughness is around 210- 290 nm. Finally 27 samples are prepared for the MRF polishing .The surface roughness of all the components is not same initially so change in surface roughness is taken as output in this study. The image of the final component is shown in figure.

Fig: 1.1 Image of the component before BE MRF

B. Taguchi Experiment Design

Essentially, conventional experimental design techniques are too complex and not easy to use. A huge number of experimental works have to be carried out when the number of process parameters increases. To resolve this problem, the Taguchi method uses a unique design of orthogonal arrays to study the entire parameter space with only a small number of experiments [8]. Taguchi's robust design method is a powerful tool for the design of a high-quality system. In addition to the S/N ratio, a statistical analysis of variance (ANOVA) can be employed to indicate the impact of process parameters on the change in surface roughness values. The steps applied for Taguchi optimization in this study are as follows. [10]

- Select quality characteristics
- Select noise and control factors
- Select Taguchi orthogonal array
- Conduct Experiments
- Analyze results
- Predict optimum performance
- Contribution of each factor
- Regression equation
- Confirmation experiment

Factors which affect the surface quality are basically divided into two major types: Controllable and uncontrollable parameters Machine vibration, ambience and metrology practice are considered to be the uncontrollable parameters and the nozzle speed, feed rate, gap between nozzle and work piece, current (magnetic field), types of fluid, abrasives, time are considered to be the controllable parameters. We cannot have our hands on the uncontrollable parameters. One has to pay attention in selecting the best combination which fails would result in very rough surfaces. Thus the greatest challenge the optimum combination of the process parameters to get the best surface quality. The parameters with their level chosen for optimization are given in the table1.1:

Table 1.1-BEMRF process parameters with their level

Parameter	Code	Levels		
		1	2	3
Magnetizing current	A	0.8	1.1	1.4
Working gap	B	0.75	1	1.25
Speed of tool core	C	300	400	500

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C. Preparation of MR fluid and Experimentation

MR fluid is prepared with 20 vol% of CIP (Carbonyl Iron Powder) of grade CS of average particle size of 19µm, 20 vol% Silicon Carbide powder and 60 vol% of viscoplastic base medium (20 wt% AP3 grease and 80 wt% of heavy paraffin liquid)

First the base fluid medium is prepared by mixing of AP3 grease and heavy paraffin liquid and then the suspension is prepared by mixing abrasive and iron particles into the base medium and stirring with the help of multiple blade stirrers in the funnel. This results in the uniform dispersion of iron of iron and abrasive particles in the base medium. Thus required MRP-fluid has been prepared for conducting the experiments. Table 1.2 shows the composition of synthesized MR polishing fluid.

Table 1.2-Composition of Synthesized MR polishing fluid.

S.No.	Constituents	%Volume Concentration
1	Carbonyl Iron Powder of CS grade	20
2	Silicon Carbide of mesh size 800	20
3	Base fluid medium	60

In the BEMRF process is controlled through computer controlled programs. The process can finish the work piece surfaces similar to the machining of 3D surfaces by CNC ball end milling process. In this process the tool is design in such a way that flow of pressurized MR fluid through center of the tool core and get stiffed controlled ball end shape of MR polishing at the tip surface of the tool. The stiffness of ball end shape was controlled by the magnetizing current. The complete setup and process can be visualized as similar to ball end milling cutter 3 axis vertical CNC machine. Fig.1.2 shows the schematic of experimental set-up.

Table1.3- Fixed experiment conditions

S.No.	Parameters	Conditions
1	Each finishing cycle time	30 min
2	Abrasive Silicon Carbide (SiC) powder mesh number	800
3	Work piece Material	Ferro magnetic

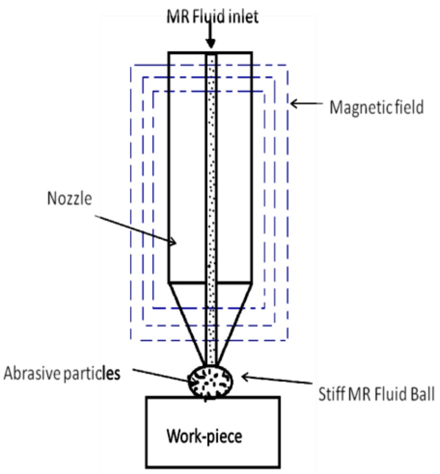

Fig. 1.2 schematic of experimental set-up

The workpiece was kept in a rectangular slot of work piece holder and precision vice holds the work piece holder tightly along with the workpiece. The reciprocating motion of the workpiece was given by Y movement of linear slide which is driven by computer controlled stepper motor. During the experiment the prepared MR fluid is continuously staired for proper mixing and to avoid sedimentation of the various particals. Experimental parameter and condition are given in the table 1.3

III. RESULTS AND DISCUSSION

After experiment each sample is measured by contact type profilometer. Measurement data is collected for stastical analysis.

The responses in terms of absolute value of surface roughness (Ra) and percentage change in roughness value (%ΔRa) are presented in Table. The response percentage change in Ra value is analyzed and given in the table. (%ΔRa) is given by the equation. Where Ra is the initial surface roughness before BE MRF and Raf is the final surface roughness after BE MRF.

$$\%\nabla Ra = \frac{(Rai - Raf)}{Rai} \times 100$$

The summery of response is given in the table 1.5

A. Pre BEMRF results

As the efficiency of any finishing process depends on conditions of experiment samples. Generally we have to finish the samples at certain level to provide suitable conditions for nano finishing. In current experiment lapping was used for pre- finishing. Results of lapping and MRF experiment are shown in table no. 1.4

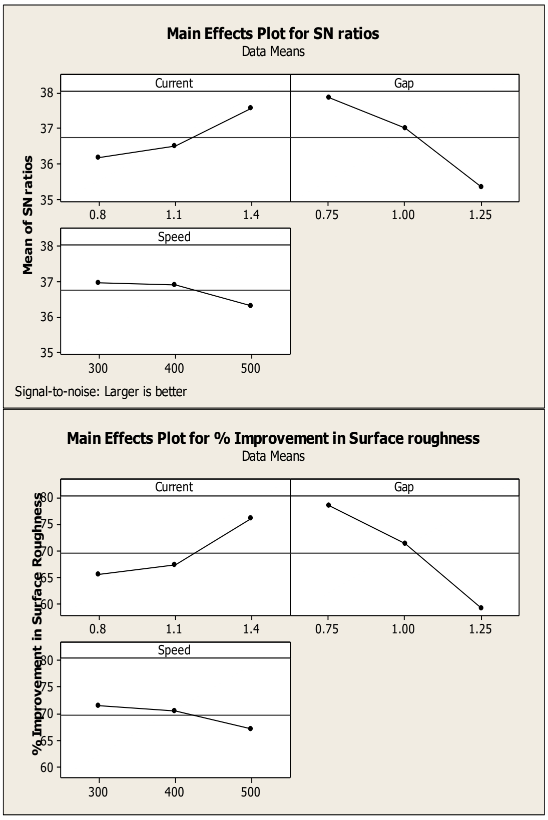

Figure 1.3: Main effects plot

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Table 1.4 – Result of surface roughness before and after BEMRF

Sr. no.	Set 1		Set 2		Set 3	
	After MRF Ra (μm)	Before MRF Ra (μm)	After MRF Ra (μm)	Before MRF Ra (μm)	After MRF Ra (μm)	Before MRF Ra (μm)
1	0.070	0.292	0.075	0.290	0.059	0.283
2	0.074	0.225	0.067	0.245	0.081	0.234
3	0.13	0.267	0.145	0.277	0.113	0.276
4	0.056	0.254	0.059	0.251	0.060	0.247
5	0.067	0.217	0.081	0.226	0.074	0.228
6	0.124	0.277	0.118	0.287	0.113	0.296
7	0.048	0.281	0.051	0.292	0.049	0.284
8	0.051	0.239	0.044	0.246	0.055	0.247
9	0.067	0.221	0.081	0.225	0.074	0.224

Analysis of the S/N Ratio

In this study our aim is to maximize the improvement in the surface roughness in the ball end magneto- rheological process. Larger percentage change in Ra values represents better or improved surface finish. As There are three types of quality characteristics in the Taguchi methodology, such as nominal the best, larger the better and smaller the better [49]. In this study larger the better quality characteristics of S/N ratio is used which is given by following equation.

$$S/N = -10 \log [(1/y1^2 + 1/y2^2 + \ldots + 1/yn^2)/n]$$

In this equation, y is the value of measured response for each test, and n is the number of repetitions of each test (in this study was 3). Calculated the S/N ratio for each level of each variable by using the equation is given in the table 1.5

Based on average response (% improvement in surface roughness) and SN ratios, plots are taken with the help of Minitab software. As shown in figure1.3, Percentage improvement in Surface roughness and its S/N ratio for each level of input factor was taken and plotted to check their effects on process.

Based on mean of % improvement and SN ratio analysis it was found that at Current 1.4A, percentage change in surface roughness is higher as compare to other levels of current. As viscosity of fluid depends on the magnetic field which further depends on selection of current. From trend of graphs it is clear that by increasing current percentage improvement is more.

Rpm of nozzle with ball end MR tool also affect the surface finish and finishing mechanism. From the plots of Rpm vs. % improvement in roughness, it was observed that low rpm leads to good improvement. Higher RPM leads to higher centrifugal forces at periphery of ball end tool. Due to centrifugal forces abrasive particles has a tendency to move outwards and reduces the efficiency of process.

Gap between surface to be finish and nozzle having MR fluid is very important factor. In current study it was found that by increasing the gap % improvement will be less. By increasing gap, effective particles which are in contact with surface for finishing will be less hence reduces the % improvement.

Table No. 1.5: - Percentage improvement table with s/n ratio and mean response

Sr. no.	Current (Amp)	Gap (mm)	Speed (rpm)	Average. % Improvement in surface roughness			S/N (db)	Mean response (% Improvement)
				Set 1 (% improvement)	Set 2 (%Improvement)	Set3 (%Improvement)		
1	0.8	0.75	300	75.9247	73.9340	78.8563	37.6344	76.2383
2	0.8	1.00	400	66.9036	72.4490	65.1282	36.6442	68.1603
3	0.8	1.25	500	49.1779	47.8230	59.0580	34.2119	52.0196
4	1.1	0.75	400	77.9394	76.3347	75.5870	37.6848	76.6204
5	1.1	1.00	500	68.8940	63.8938	67.2807	36.4682	66.6895
6	1.1	1.25	300	55.2233	59.0135	61.9400	35.3476	58.7256
7	1.4	0.75	500	82.7402	82.2260	82.6648	38.3336	82.5437
8	1.4	1.00	300	78.3264	82.0065	77.6071	37.9794	79.3133
9	1.4	1.25	400	69.4570	63.7333	66.6964	36.4572	66.6289

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IV. PROFILE IMAGES OF SURFAES ROUGHNESS

Surface roughness graphs for before BE MRF is shown in Figure 1.4 and after BE MRF process is shown in Figure 1.5

A. *Analysis of variances and regression modeling*

Analysis of variances is performed to check the significance and contribution of input parameters on % improvement in surface quality. In current analysis pooled way ANOVA is applied. In one way ANOVA the contribution of error is less than 10% so the effect of interaction of parameters very much less. The interactions are pooled to the error and pooled one way ANOVA is applied for the analysis of the results. Further contribution of each input factor on output was calculated and it is observed that gap is most significant factor responsible for improvement in surface finish having contribution 66.59%, followed by current 22.65% and Nozzle speed is having least contribution only 3.63%. All these parameters are found to be significant at 95% confidence level. ANOVA analysis is shown in table no. 1.6

With the help of the input parameter and the response of the process first order regression equation is generated. This will help to create an input output relationship which helps to predict the close response of the process. This is useful to select appropriate process parameters to the operator for desired output. The regression equation is as follows.

$$\% Ra_{Improvemen} = 95.1 + 13.3C - 32.9G - 0.0157S$$

Where C is current, G is Gap between component surface and nozzle and S is Nozzle speed.

Table no. 1.6: ANOVA Table

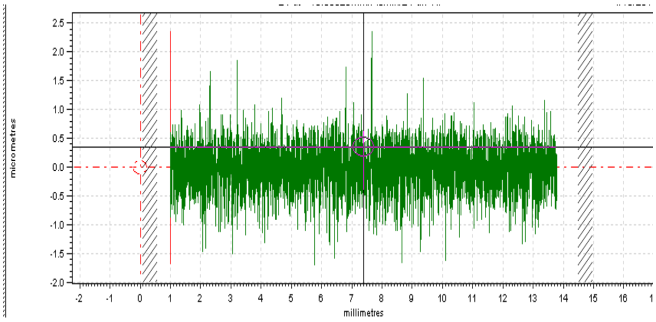

Fig: 1.4initial surface roughness profile before BE MRF (Ra 246nm)

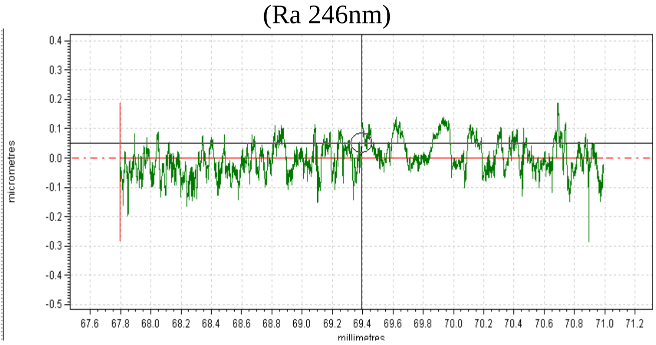

Fig: 1.5 Initial surface roughness profile after BE MRF (Ra 44nm)

Source	Sum of Square	DOF	MSE	F-Ratio	F-Ratio Table	Pooling	Contribution in %
Current	586.51	2	293.25	31.78576	3.4928	significant	22.65698
Gap	1723.94	2	861.97	93.42884	3.4928	significant	66.59634
Nozzle speed	93.67	2	46.84	5.076665	3.4928	significant	3.618661
Error	184.52	20	9.23				7.128028
Total	2588.63	26					

D. Validation trials

To validate the developed regression equation 3 MR finishing trials are performed and the results are compared with the output response values of equation for same input values on which validation experiments are performed. The parameter set and the output of the validation test is given in the table no.1.7. Results of experiment are found close to predicted values by regression equation. Percentage error is calculated between expericemental results and predicted results. Comparative graph of predicted and experimental results are shown in figure 1.6 in this fig the % improvement in surface roughness is shown in Y- axis and in the X –axis represent the experimental sets.

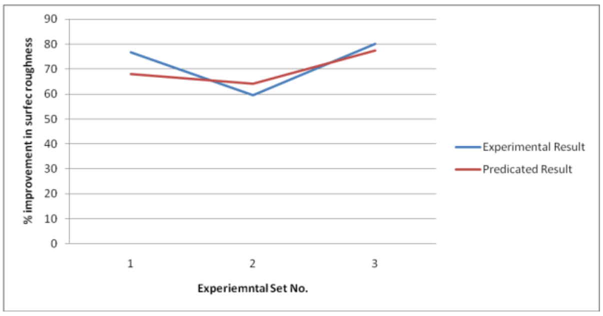

Fig: 1.6 Validation of result of BE MRF Process

Table No: 1.7: Validation trial results

Sr. no.	Process parameters			Experimental result	Predicted result	Error (%)
	Current	**Gap**	**Nozzle speed**			
1	1.4	1.25	300	76.71	68.15	12.56
2	0.61	1	400	59.43	64.15	-7.825
3	1.6	1	400	80.07	77.52	3.28

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V. CONCLUSION

With the help of Taguchi L-9 FFE (Fractional Factorial experiments) experimental study was carried out. Very exciting improvement in the surface finish is achieved. All tree parameters taken in the study working gap, magnetizing current and nozzle speed is found to significant at the 95% confidence level. On the bases of above experimental study optimum process parameters for BEMRF for finishing of EN- 31 steel are Current 1.4amp, Nozzle rotation speed 300rpm and Gap between work surface and nozzle tip is 0.75mm. Surface finish of 44nm is achieved on En -31 sample in just 30 minutes. An empirical model is developed which is capable enough to predict the percentage improvement in surface roughness. Current study may helpful to understand the finishing behavior of EN-31 steel by BEMRF process

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