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Optimization and prediction of sintering process parameters for magnetic abrasives preparation using response surface methodology

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A B S T R A C T

Magnetic abrasives are important parts of Magnetic Assisted Abrasive Finishing (MAF). Magnetic abrasives are prepared by many processes, but sintering is the one of the best processes to prepare magnetic abrasives. The objective of this paper is to optimize the sintering process parameters. To do that, Response Surface Methodology (RSM) is used for the optimization of process parameters, Abrasive concentration in ferromagnetic particles (AC)%, Compacting Pressure (CP) N/mm2 and Sintering Time(ST)min. To check the performance of magnetic abrasives Percentage Improvement in Surface finish (PISF) is considered as a response variable. Optimization and prediction are executed through RSM and Central Composite Design (CCD) is used to conduct the experiments. The optimized values of process parameters obtained are AC (19.29%), ST (15min) and CP (6.9 N/mm2) and also predicted values for the response variable are obtained.

1. Introduction

As abrasive machining is one of the suitable non-conventional machining processes. In the abrasive machining process, the main component is the abrasive particles. Shinmura et al. (1990) developed a new finishing process in which magnetic abrasive was used as the cutting tool and surface roughness change that was obtained from 0.45pmRa to 0.04pmRa. Kansal et al. (2007) made comparisons between the sintering process and mechanical alloying for the preparation of magnetic abrasives, experiments were conducted to check the surface finish change for both magnetic abrasive like mechanically alloyed magnetic abrasive and sintered magnetic abrasives, best results were obtained for mechanically alloyed magnetic abrasives with mesh size 52 and sintered magnetic abrasives with mesh size 130 and 180 comparable Technology and research developments in powder mixed electric discharge machining (PMEDM). Yamaguchi et al. (2011) studied the effect of temperature in which changes of tools were used for magnetic abrasive finishing. Work piece used 304 stainless steel tube at 2500 rpm, magnetic abrasive prepared by mixing of fe (80 %) and aluminium oxide (20 %) by weight. Feed Speed 0.59 mm/s, stroke length 26 mm, number of strokes 117 and processing time 174 min were used. Kim and Choi (1997) developed a new abrasive machining process magnetic-electrolytic-abrasive polishing (MEAP). Rampal

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(2012) studied the comparison of magnetic abrasives prepared by different methods. Abrasives were prepared by three different methods, by sintering, simple mixing and third one developed by using adhesive. The surface roughness improvement of the work piece (Approximately 49 %) for newly developed abrasives was introduced. The maximum percentage improvement in surface roughness for different types of abrasive was respectively 18 % for simply mixed, 42 % for Adhesive based and 49 % for sintered magnetic abrasives. Sharma and Singh (2013) studied the effect of parameters on MAF. The polishing of work piece was done by MAM using magnetic abrasives. The surface Roughness of work piece was changed from 0.257μm to 0.075μm Ra in a machining time of 3 minutes with 220 grit size aluminium oxide. Sooraj and Radhakrishnan (2014) used RSM using Central Composite Design (CCD) optimization technique to study the experimental work. Reddy et al. (2017) used RSM and ANN as the optimization tool for abrasive water jet machining process also Sahoo and Mishra (2014) used RSM to find the prediction and optimization of process parameters. Araujo et al. (1996) explained that the optimization term commonly is used as a mean of finding conditions in which the response yielded best value. RSM is one of the best optimization techniques to find the optimal solution in the field of abrasive finishing. RSM can be used when a response or a set of responses are effected by several variables. The objective is to optimize the levels of input variables to obtain the best performance. Box and Draper (2007) developed RSM in the 50s swots by Gilmour (2006). In RSM experimental values were obtained according to experimental design and an empirical fit model was obtained. Teofilo et al. (2006) stated that RSM is the mathematical and statistical techniques based on the fit empirical models. Toward this objective, linear or square polynomial functions were employed to describe the system studied and, consequently, to explore (modelling and displacing) experimental conditions until its optimization.

The purpose of this paper is to develop RSM-based optimization design for process parameter optimization of sintering process with the help of MAF. The experiments are performed based on the central composite design (CCD) design; the optimal combination of input parameters Abrasive concentration in ferromagnetic particles (AC)%, Compacting Pressure (CP) N/mm^2 and Sintering Time(ST) min is to be selected for response variable PISF.

2. Experimentation

2.1 Materials

In this study magnetic abrasive are prepared by the mixing Al2O3 and Iron oxide. Al2O3 and Iron oxide are taken in five different ratios and mixing of them was performed by the mechanical method. Then powder compact in the die and green compact is obtained. The green compact obtained were sintered and magnetic abrasives were prepared to use.

2.2 Design of experiments with RSM

Most of the engineering problems are solved by RSM because it is a useful for modelling and analysis as RSM is a collection of mathematical and statistical techniques (Öktem et al., 2005; Box & Behnken, 1960; Bruns et al., 2006)). This technique optimizes the response surface which is affected by various process parameters. RSM has been effectively applied to study and optimize the processes.

Table 1
Input parameters and their levels

Parameters	Notation	Unit	Level 1	Level 2	Level 3	Level 4	Level 5
Abrasive concentration	AC	%age	10	18	30	42	50
Sintering Time	ST	Time	15	24	37.5	51	60
Compacting Pressure	CP	N/mm^2	6.9	8.3	10.3	12.4	13.6
Constant Parameters							
Machining time	30 min						
Rotation of work piece	270 rpm						
Sintering temperature	1150 ºC						
Magnetic Abrasive particle Size	Al_2O_3 270 mesh size						
Work piece material	Brass						

In addition, RSM also reduces the number of experiments to evaluate several parameters and their interactions. RSM can be used for design and analysis of various processes parameters, model building, and gives optimum conditions to provide desirable responses (Oktem et al., 2005). In this study, independent variables such as AC, ST, and CP and RSM are used for optimization. The experiments are designed according to Central Composite Design (CCD) model with three factors and five levels given in Table 1. The results obtained from experimentation are analyzed, and the mathematical model has been established between sintering parameters and response variables.

2.3 Experimental procedure

In this experimentation, experimental runs are prepared by CCD design. Experimentation is done on the sintering furnace and MAF setup. For sintering of Al_2O_3 and iron oxide mixed compact three parameters are used which are listed in the Table 1. Sintering performed in the inert atmosphere by the use of argon gas to avoid formation of oxides of iron. Magnetic abrasive of mesh size 270 are used for the finishing of brass rod. Another parameters listed in table are kept constant during the whole process. The three independent parameters AC, ST, and CP were varied to check their effects on the response variables PISF. The experimental matrix given in Table 2 has been designed by the CCD and the observations are taken according to the prepared design. To achieve more correctness in the results, the average values of three experiments at a particular setting was taken. During the experimentation, surface roughness was measured at each parametric setting to calculate the Percentage in Surface Roughness (PISF). Then, PISF was calculated by measurement the surface roughness of the work piece before and after the experiment using surface roughness tester.

$$\text{PISF}=\frac{\text{Initial Surface Roughness - Final Surface Roughness}}{\text{Initial Surface Roughness}}\times 100 \tag{1}$$

3. Results and Discussion

The values of the response variables are obtained according to parametric conditions that are described in Table 2. The results obtained, the predicted model and the optimization of the process are described in this section.

Table 2
Experimental results

Run No.	Input parameters			Output Parameters
1	30	37.5	10.3	49
2	42	51	12.4	30.7
3	30	37.5	13.8	44.6
4	30	37.5	10.3	49
5	30	37.5	10.3	49
6	50	37.5	10.3	3.37
7	18	51	8.3	21.9
8	18	24	8.3	62.8
9	18	24	12.4	30.8
10	30	60	10.3	15.5
11	10	37.5	10.3	24.2
12	30	37.5	10.3	49
13	42	24	12.4	20
14	30	37.5	10.3	49
15	42	51	8.3	4.3
16	30	37.5	10.3	49
17	18	51	12.4	35.1
18	30	37.5	6.9	39.1
19	42	24	8.3	25.2
20	30	15	10.3	40

3.1 Determination of main effect on the response variable

The effect of input parameters on PISF has been determined using RSM model for the experimental PISF.

The mathematical relationship between the PISF and input parameters are obtained as the following expression.

$$PISF = 121.7 + 1.540\,AC - 1.770\,ST - 8.97\,CP - 0.08397\,AC\times AC - 0.03877\,ST\times ST - 0.469\,CP\times CP + 0.02037\,AC\times ST + 0.2022\,AC\times CP + 0.3473\,ST\times CP \tag{2}$$

In Table 3, ANOVA have been used to check adequacy and significance of the developed model with 95 % of confidence interval (CI).

Table 3

ANOVA table for PISF

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Remarks
Model	9	4967.46	551.94	68.63	0.000	Significant
Linear	3	212.85	70.95	8.82	0.004	Significant
AC	1	56.98	56.98	7.08	0.024	Significant
ST	1	91.70	91.70	11.4	0.007	Significant
CP	1	38.03	38.03	4.73	0.055	Non-Significant
R^2 =.9841	Adjusted R^2=.9697		Predicted R^2=.8723			

The statistical significance of process variables is shown by the P value and F values tell about the parameters influence. The statistical significance of process variables depends on the larger F values and having P values< 0.05. The R^2 values signifies the response variation which is expected by the model, also Adjusted R^2 value analyses the model fitness and adequacy. The values of R^2 are calculated to be .9841 for PISF, and it means by the 95 % confidence level that the experimental data was well-suited. The satisfactory model for the experimental data has been justified by the higher value of R^2. The high value of adjusted R^2 (.9697) supports a high correlation between the predicted and the experimental values.

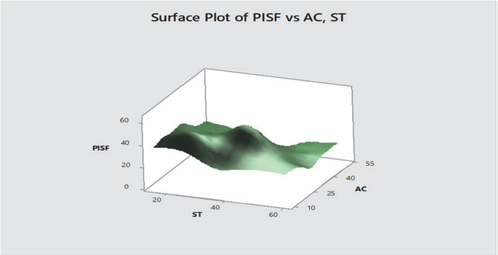

Fig. 1. Surface plot between for PISF vs AC, ST

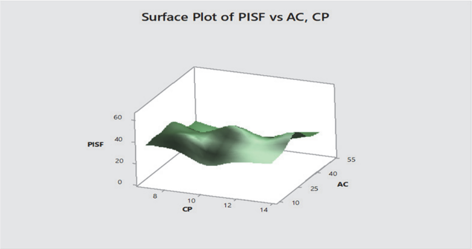

Fig. 2. Surface plot between for PISF vs CP, AC

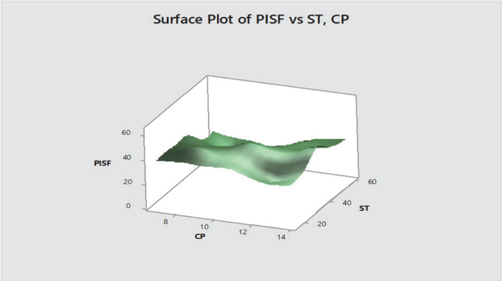

Fig. 3. Surface plot between for PISF vs CP, ST

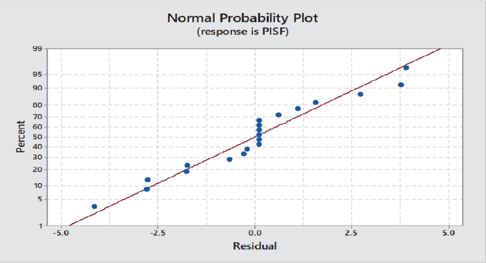

Fig. 4. Normal probability plot of the residuals

P values tells about the significance of the parameters as in ANOVA in Table 3. ST is prominent parameter followed AC and CP. Normality of data is shown by the Fig. 4., as data is closely distributed along the straight line shows that data is normally distributed. There are surface plots for different interactions of input parameters correspond to the response variable PISF which tells about the variation of response variable.

3.2 Prediction and optimization of process variable

In this section, prediction of the response values according to the fitted model Eq. (2) is discussed here. The optimization of the process parameters is performed through RSO (Response surface optimization) technique. In this technique first of all weights for each response (*w*) and individual desirability (*d*) are calculated. To determine the composite, or overall, desirability (*D*) these values are combined. The response parameter (*y*) to be optimized when composite desirability (*D*) obtains its maximum. The optimization goal is to maximize the PISF by setting the input parameters ST, AC and CP. The obtained optimize value of PISF is 69.4651 at the parametric conditions that are AC (19.29%), ST (15 min) and CP (6.90 N/mm^2). The predicted values for the experiments are compared with experimental values and corresponding errors are listed in the Table 4.

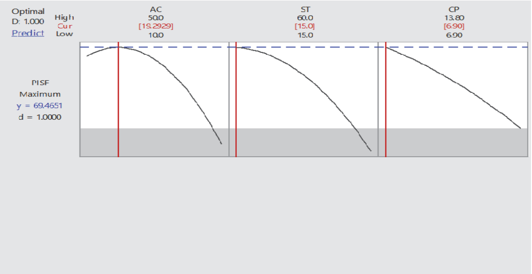

Fig. 5. Optimization of PISF by using desirability approach

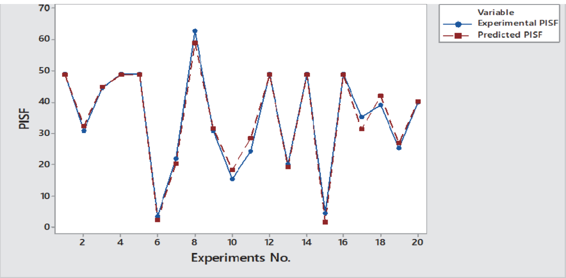

Fig. 6. Comparison between predicted PISF and experimental PISF

Table 4
Confirmation analysis

AC	ST	CP	PISF	Predicted PISF	Error
30	37.5	10.3	49	48.8972	0.10281
42	51	12.4	30.7	32.4682	-1.76817
30	37.5	13.8	44.6	44.7944	-0.19438
30	37.5	10.3	49	48.8972	0.10281
30	37.5	10.3	49	48.8972	0.10281
50	37.5	10.3	3.37	2.2637	1.10627
18	51	8.3	21.9	20.3269	1.57312
18	24	8.3	62.8	58.8895	3.91049
18	24	12.4	30.8	31.4432	-0.64322
30	60	10.3	15.5	18.267	-2.76702
10	37.5	10.3	24.2	28.3507	-4.15071
30	37.5	10.3	49	48.8972	0.10281
42	24	12.4	20	19.3802	0.6198
30	37.5	10.3	49	48.8972	0.10281
42	51	8.3	4.3	1.5707	2.72928
30	37.5	10.3	49	48.8972	0.10281
18	51	12.4	35.1	31.3312	3.76882
30	37.5	6.9	39.1	41.8904	-2.79036
42	24	8.3	25.2	26.9333	-1.73335
30	15	10.3	40	40.2774	-0.27742

Furthermore, the compression between the measured values of PISF and the predicted values of PISF through RSM model has been verified by plotting the experimental values versus predicated values and that are shown in Fig. 6. The confirmation analysis shows that the error between the predicted model and experimental values listed in the Table 4 is within the acceptable limit. Also, the prediction values from the RSM model display the high accuracy of modeling. Finally, it is concluded that the developed RSM model can be used to successfully predict the PISF values for any parametric combination of the AC, ST, and CP within the values that are used in this experimentation.

4. Conclusions

The conclusion of the paper is as follows,

1. The optimal combination for the process parameters yields the abrasive concentration of 19.29%, sintering time of 15 min and compacting pressure is 6.9 N/mm^2.

2. Model has been found to be significant as p-value is less than 0.05.
3. Higher R^2 value .9841 indicates the model fitness and statistical significant of the model.
4. Predicted values are near to the experimental values so the model is validated and also used for the prediction of PISF in the range of these selected input parameters.

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