Fuzzy logic optimization of process parameters affecting surface temperature in MAF

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Abstract. Magnetic abrasive finishing process was introduced to boost surface quality of super-alloys, composites and ceramics. This process erode material from the surface of workpiece in micro-nano range. Surface texture achieved from this process was very excellent. Thermal stability of finishing surface of workpiece is vital aspect during the finishing of MAF process because it affects the surface texture, surface integrity, finishing accuracy and material removal. In present study, experimentation had been performed to measure the surface temperature of finishing surface of mild steel using MAF process. Taguchi L₉ orthogonal array had been employed to design the experiment. Current, working gap, abrasive weight and rotational speed were important process parameters that had been selected for analysis. Fuzzy logic had been used to develop Artificial intelligent based predictive model to predict surface temperature during finishing operation in MAF process. Surface temperature model built on Fuzzy logic had been validated.

Keywords. Magnetic Abrasive Finishing, Surface Temperature, L₉ orthogonal array, Fuzzy logic.

1. Introduction

Magnetic abrasive finishing was introduced to boost surface quality of advance and harder materials [1]. Finishing was achieved in this process by moving magnetic abrasive particle which were homogenous mixture of large ferromagnetic particles with small abrasive particles (Silicon carbide) mixed in specified ratio with help of strong magnetic field. These magnetic particles were positioned into working gap which lies between top surface of workpiece and magnetic poles [2]. Due to strong magnetic field present in working gap, magnetic particles aligned with magnetic forces forming flexible magnetic abrasive brush. Finishing of surface was achieved by relative motion between workpiece and flexible magnetic abrasive brush [3]. Flexible magnetic abrasive brush acted as multi-point cutters responsible for material removal from top surface of workpiece. Material removal was done in form of microchips which were created by tangential cutting force of magnetic brush [4]. This process causes substantial amount of heat on the surface of workpiece when finishing was performed. This happens due to deformation in material, fracture and friction when top surface of workpiece interacts with magnetic abrasive brush.

In past, two theoretical temperature analyses were done using Silicon nitride ceramic (Si₃N₄) as workpiece and Chromium oxide (Cr₂O₃) as abrasive particles. First was done by Komanduri et al. in which they derived analytical thermal solution by using standard moving heat theory of Jaeger. This model substantially calculated flash temperature produced during machining and flash time at interaction point [5]. Other attempt was made by Kumar et al. and they developed Finite element model to study the thermal behaviour of surface temperature. Conclusions of these studies were that temperature elevated due to escalation in magnetic particle velocity & magnetic potential [6]. So far, experimental work on temperature analysis was done by Mulik et al. on the workpiece magnetic brush interface during Ultrasonic MAF process (UMAF) and they took ferrous alloy as workpiece for conducting experiment. Key finding of their study was that, temperature directly depends on voltage, weight of abrasive particles and pulse on time [7].
Literature review enlighten that so far, few experimental study had been performed for temperature analysis using MAF process. Present study focuses on surface temperature analysis of MAF process using Mild steel and compare it with artificial intelligent based fuzzy logic model developed for the surface temperature prediction [8]. In this research work, experiment had been performed on MAF set-up to measure surface temperature between mild steel workpiece and magnetic abrasive brush. Taguchi L9 orthogonal array had been used to design the organized experiments. The main process parameters that considered were working gap, abrasive weight, current and rotational speed. Artificial intelligent based modelling had been done using Fuzzy logic for the surface temperature prediction. Finally, validation of predictive model had been done by comparing it with experimental work which was performed to study surface temperature effect on the surface of top surface of workpiece.

2. Experimentation of surface temperature of mild steel using MAF process
In this section detailed reporting had been done about the experimental set-up which had been fabricated in-house, about selection of workpiece material and important process factors on which surface temperature depends, how temperature measurement had been done and finally, thorough experimental procedure had been discussed.

2.1 Experimental setup of MAF process
The MAF set up was comprised of flat faced electromagnets having 1000 turn of copper wire wounded around iron core. This two-poled electromagnet was mounted on pillar drilling machine. Pillar drilling machine was used to provide rotational motion to electromagnet with speed range between 100-300 rpm. Direct current (3A – 6A) was provided by DC power supply which provided static direct current to electromagnet. Static direct current generated 0 - 1.02 T of magnetic flux density in working gap of 1.00 -2.00 mm. A digital gaussmeter (model EMF-PORTABLE, range 0-2.0 T) was used to measure magnetic flux density in the working gap and variation in the strength of magnetic flux density was done by varying the input current. Formation of magnetic abrasive brush in working gap took place when current was supplied to electromagnet. Mechanical mixture of iron powder (300 mesh number) and silicon carbide (400 mesh number) were used to create magnetic abrasive brush and magnetic abrasive particle used for magnetic brush was Unbounded in nature. The process parameters were based on preceding works conducted in this field and range of input parameters listed in table (1) were selected on basis of setup constrained.

![Fig.1 k-type thermocouple](image)

| Sr no | Process parameter                  | Range    |
|-------|-----------------------------------|----------|
| 1     | Working gap (mm)                  | 1.0-2.0  |
| 2     | Abrasive weight (gm)              | 20-30    |
| 3     | Current (A)                       | 3.0-6.0  |
| 4     | Rotational speed of magnet (rpm)  | 100-300  |
2.2 Experimental procedure for surface temperature
The mild steel workpiece was fastened on tool vice mounted on the table of pillar drill machine. The required working gap between bottom electromagnet pole and top surface of mild steel workpiece was measured by using slip gauges. Unbounded magnetic abrasive particles were used to form the magnetic abrasive brush in working gap. Weight of total magnetic abrasive particles was 100 gm and silicon carbide were mixed in required proportion i.e. 20 gm to 30 gm in iron powder. For measuring temperature for present thermal experiment K-type thermocouple made of chromel and alunel had been used as shown in figure (1) [9]. For measuring surface temperature of mild steel, through holes have been drilled into the workpiece. In these holes K-types thermocouples have been inserted and actual position of holes were obtained by measuring variation in magnetic flux density in the working gap using magnetic flux meter at different position [10]. Literally, no feed had been provided to the workpiece and its value has been kept to zero. While performing pilot experiment, it was seen that raise in temperature had become constant after 20 odd minutes. Hence the experiments were conducted for 20 minutes only. The maximum surface temperature in mild steel was found to be 41°C while the ambient temperature was 23°C as shown in table (2).

| Trail no | Working gap (mm) | Abrasive weight (gm) | Current (A) | Speed (rpm) | Maximum Temperature (°C) |
|----------|------------------|----------------------|-------------|-------------|--------------------------|
| 1        | 1.0              | 20                   | 3.0         | 100         | 30                       |
| 2        | 1.0              | 25                   | 4.5         | 200         | 35                       |
| 3        | 1.0              | 30                   | 6.0         | 300         | 41                       |
| 4        | 1.5              | 20                   | 4.5         | 300         | 32                       |
| 5        | 1.5              | 25                   | 6.0         | 100         | 37                       |
| 6        | 1.5              | 30                   | 3.0         | 200         | 34                       |
| 7        | 2.0              | 20                   | 6.0         | 200         | 33                       |
| 8        | 2.0              | 25                   | 3.0         | 300         | 30                       |
| 9        | 2.0              | 30                   | 4.5         | 100         | 31                       |

2.3 Regression Analysis using Taguchi L9 Orthogonal Array for surface temperature
Minitab software was used for Regression analysis using Taguchi L9 Orthogonal Array for obtaining the significant process parameters and the rank of process parameters. Rank of temperature analysis of different input parameters has been shown in table (3). The current had largest contribution in the temperature of workpiece surface. Followed by working gap and abrasive weight. Speed of the magnetic abrasive brush had least impact on surface temperature.

| Level | Gap | Weight | Current | Speed |
|-------|-----|--------|---------|-------|
| 1     | 35.33 | 31.67 | 31.33   | 32.67 |
| 2     | 34.33 | 34.00 | 32.67   | 34.00 |
| 3     | 31.33 | 35.33 | 37.00   | 34.33 |
| Delta | 4.00 | 3.67  | 5.67    | 1.67  |
| Rank  | 2    | 3      | 1       | 4     |

ANOVA was done to obtain the percentage contribution of the process parameters to the maximum temperature of mild steel in MAF process. Table (4) maximum contribution was of current which had 48.16% of total contribution. Then working gap with 24%, abrasive weight with 20.16% and least contribution was made done by speed with 4.16%. Finally, table (5) shows the value of coefficient which had been obtained by the regression analysis. These coefficients were used to form the regression equation of the surface temperature of mild steel.
Table 4 - Analysis of Variance

| Source    | DF | Adj SS   | Adj MS  | F-Value | P-Value |
|-----------|----|----------|---------|---------|---------|
| Regression| 4  | 96.500   | 24.125  | 12.87   | 0.015   |
| Weight    | 1  | 20.167   | 20.167  | 10.76   | 0.031   |
| Current   | 1  | 48.167   | 48.167  | 25.69   | 0.007   |
| Speed     | 1  | 4.167    | 4.167   | 2.22    | 0.210   |
| Gap       | 1  | 24.000   | 24.000  | 12.80   | 0.023   |
| Error     | 4  | 7.500    | 1.875   |         |         |
| Total     | 8  | 104.000  |         |         |         |

Table 5- Coefficients

| Term   | Coef | SE Coef | T-Value | P-Value |
|--------|------|---------|---------|---------|
| Constant | 20.33 | 3.86   | 5.27    | 0.006   |
| Weight  | 0.367 | 0.112  | 3.28    | 0.031   |
| Current | 1.889 | 0.373  | 5.07    | 0.007   |
| Speed   | 0.00833 | 0.00559 | 1.49   | 0.210   |
| Gap     | -4.00 | 1.12   | -3.58   | 0.023   |

Regression Equation:

Temperature = 20.33 + 0.367 Weight + 1.889 Current + 0.00833 Speed - 4.00 Gap

3. Fuzzy logic modelling of surface temperature of mild steel.

Fuzzy logic was systematic methodology introduced by Lotfi Zadeh in year 1965 to solve problem which had incomplete, ambiguous, noisy values and it provided an easy means to attain a conclusion [11]. Fuzzy logic’s tactics was synonymous to a human making decisions, but in a faster mean. This System consisted of five vital parts, that were - Fuzzifier, Membership functions, Rules, Inference System, De-fuzzifier [12].

Fig.2: Fuzzy logic model

The modelling of surface temperature of mild steel workpiece in MAF process had been done by using fuzzy logic interface system of MATLAB. For present modelling, Mamdani fuzzifier had been used as shown in figure (2). Fuzzy model consisted of four process parameters (working gap, abrasive weight, current and rotational speed) as input to Mamdani fuzzifier and one response parameter i.e. Surface Temperature as output to Mamdani fuzzifier.

3.1 Membership functions option

The triangular membership functions were used for defining the range of input process and output response parameters. Range for process parameters were taken as follows, Working gap between 1.00-2.00 mm, Abrasive weight between 20-30 gm, Current between 3.0-6.0 A and Rotational speed between 100-300 rpm. Three membership functions were created for every input process parameters (working gap, abrasive weight, current and rotational speed). These three-membership function were assigned as Low, Medium and High.
Membership functions for output response surface temperature of the workpiece temperature had been shown in figure (3). The range was taken between 30\(^\circ\)C-41\(^\circ\)C for surface temperature. Again, three-membership function were allocated as Low, Medium and High.

3.2 Defining Fuzzy Rules sets
To model surface temperature in fuzzy system, rules had to be properly defined in the Mamdani fuzzifier. For obtaining optimized solution, rules had been defined by using Taguchi L\(_9\) orthogonal arrays of experimental results. Total nine rules were defined as per fuzzy rules and these rules were fed to Mamdani fuzzy inference system in fuzzy logic toolbox, MATLAB 2014Ra. The set of rules along with membership function was seen in rule viewer of fuzzy model. Rule viewer revealed that after the devising of rules, the optimum value of surface temperature at any set between low and high bounds of the process parameter could be easily predicted.

Figure (4) is bar chart comparison between different process parameters of experimental values to different process parameters values that had been predicted by Fuzzy logic model for same sets of process parameters. The closest predict was done by fuzzy model was at trail number 8 with error around 1.29% and farthest prediction was at trail number 5 with error -7.02%.

3.3 Validation of fuzzy model
Validation of the predictive fuzzy model had been done by conducting confirmatory test and the process parameters were taken different from Taguchi L\(_9\) experimental test. From table (6) shows that surface temperature was 34 \(^\circ\)C in confirmatory test. And fuzzy logic model predicted 35.5 \(^\circ\)C and error between confirmatory test and predictive model was 4.5%. Therefore, artificial intelligent based fuzzy logic was found to be good accordance with experiment test.
Table 6- Validation of fuzzy surface temperature model

| Working gap | Abrasive weight | Current | Speed | Experimental temperature | Predicted temperature |
|-------------|-----------------|---------|-------|--------------------------|-----------------------|
| 1.0         | 25              | 3       | 200   | 34                       | 35.5                  |

4. Results and discussion

Experimental investigation of surface temperature of mild steel at ambient temperature was 23°C had been performed using MAF process. It revealed that finishing of mild steel generated low surface temperature because thermal conductivity of mild steel good. The maximum temperature was found to 41°C when process parameters were at working gap 1mm, abrasive weight 30gm, Current 6 A and speed 300 rpm.

Taguchi experimental analysis exhibited the effect of working gap on surface temperature is shown in figure (5). With increase in working gap surface temperature decreases because magnetic flux in the working gap becomes weaker. But surface temperature increases with increase of SiC abrasive weight, Current and Rotational speed of electromagnet.

The most significant process parameters that affected the surface temperature were current and abrasive weight. When current increases, Magnetic abrasive brush becomes stiffer with increase of magnetic flux leading to increase in normal magnetic force on magnetic abrasive particles. Further, Rotational speed and working gap had less significant.

Figure (4) gives the assessment between the performed experimental results and predicted results using fuzzy logic model. Closest experimental value to predicted fuzzy logic model was found to be 1.29% for surface temperature. Thus, the predictive model gave more than 90% accuracy. Hence, there is excellent agreement between fuzzy logic model and experimental results in all cases.

Fig 5. Taguchi mean plot of process parameters

5. Conclusions

1. The maximum surface temperature of mild steel in MAF process in present case is found to be low and the maximum temperature gained in experiment was of 41°C. Reason for low surface temperature can be understand that mild steel has fair thermal conductivity which swiftly dissipate heat from the finishing surface of the workpiece.

2. Regression analysis is done to find the most significant process parameters that affect the surface temperature are Current and Working gap of magnetic brush. Abrasive weight and Rotational speed are found to be less influential factors.
3. ANOVA tells the percentage contributions of process parameters on the surface temperature. Current has 48.16% of total contribution then follow by working gap with 24%, abrasive weight with 20.16% and speed with 4.16%.

4. Artificial intelligent based fuzzy logic model had been developed for prediction of surface temperature. Fuzzy logic model was simpler to evaluate and successfully predicted the surface temperature.

5. Predictive Fuzzy logic model of surface temperature has been validated with experimental results and there has been good accordance with experimental results. The overall error was in range of -7% to 5%.

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