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Modelling and Optimization of Magnetic Abrasive Finishing Process

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ABSTRACT

Increasing demand of high accuracy and high efficiency machining of difficult-to-machine materials is making the application of abrasive finishing technologies increasingly important. One of such process is magnetic abrasive finishing (MAF) process. It can produce surfaces with surface finish in range of 0.04-1.00 µm and dimensional accuracy up to 0.5 µm. In order to predict the effect of various machining parameters on material removal rate, tool wear rate and surface roughness value, it is important to model and optimise these machining parameters. In the present research work the process parameters of a MAF process are optimized using a very effective evolutionary algorithm termed as genetic algorithm (GA). Response Surface Methodology is applied for developing the models using the techniques of Design of Experiments and Central composite rotatable design was used to plan the experiments. The software used for design of experiments is Design Expert and that for implementing GA is MATLAB. The four input parameters under consideration are current to the electromagnetic coil (magnetic flux density),machining gap, grain size(mess no.) and number of cycles and two response variables are material removal(MR) and surface roughness value(ΔRa).

Keywords: *Alloy steel, Magnetic Abrasive Finishing, Response Surface Methodology, Surface Roughness, Analysis of Variance(ANOVA), Genetic Algorithm, GA Toolbox, MATLAB,DESIGN EXPERT.*

1.INTRODUCTION

1.1 Magnetic Abrasive Finishing

Finishing is final operation involved in the manufacturing of components and is most labour intensive, time consuming and least controllable area. The need of better finishing of complicated shapes made of advanced materials and high accuracy are the main factors responsible for using advanced abrasive fine finishing processes (Jain, 2002). MAF is an unconventional finishing process in which the cutting force is primarily controlled by the magnetic field. It reduces the possibility of microcracks on the surface of the workpiece, specially in hard brittle material, due to low forces acting on abrasive particles (Jain, 2002). This process is capable of producing surface roughness in the nanometer range on flat surfaces as well as internal and external cylindrical surfaces (Jain *et al*., 2001). The MAF process offers many advantages, such as self-sharpening, self-adaptability, controllability and the finishing tools require neither compensation nor dressing (Chang *et al*., 2002). In MAF, the workpiece is kept between the two poles of a magnet. The working gap between the workpiece and the magnet is filled with magnetic abrasive particles, composed of ferromagnetic particles and abrasive powder. Bonded or unbounded Magnetic abrasive particles can be used. In this process, usually ferromagnetic particles are sintered with fine abrasive particles (Al2O3, SiC, CBN, or diamond) and such particles are called ferromagnetic abrasive particles (Shinmura et al., 1986, 1990; Chang et al., 2002; Jain, 2009). Finishing pressure can be controlled via a magnetic field applications (Shinmura et al., 1993; Chang et al., 2002). Workpiece materials can be both magnetic (e.g., steel) as well as non-magnetic (e.g., ceramics) and the material removal can be adjusted based on the size of the magnetic abrasives. Thus, MAF is a multi-functional precise finishing method one can use to obtain quality surface finishes efficiently (Lieh-Dai et al., 2007). Jayswal et al. (2005) also proposed a mathematical model for mechanics of material removal and a model for surface roughness during the MAF process. They developed a finite element code to evaluate the distribution of magnetic forces, considering magnetic flux density, type and size of magnetic abrasive particles and the working gap as the main parameters. By considering the Gaussian distribution of the ordinates of the surface profile, (Jain et al., 2007) modelled and simulated the surface profile obtained after MAF. This model predicts centre-line average surface roughness value Ra obtained after MAF. Literature survey reveals that there are little contributions toward the simulation and modelling of the magnetic abrasive finishing process.

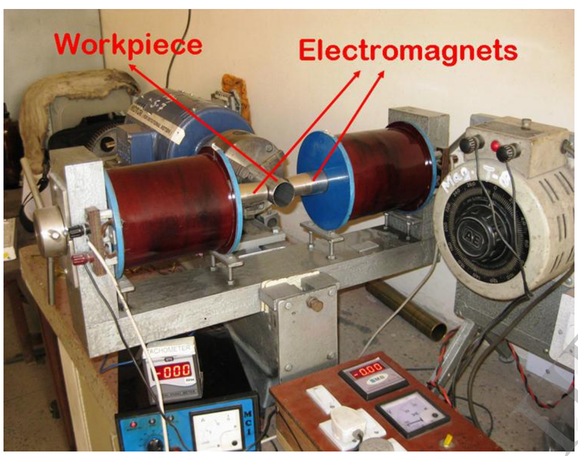

Figure1.1:Cylindrical work piece machining on magnetic abrasive finishing machine[1]

Common magnetic materials

- Iron and its oxides
- Cobalt
- Nickel
- Steel and Stainless Steel

Common Abrasive Materials

- Synthetic Diamond
- Cubic Boron Nitride CBN
- Aluminium Oxide Al2O3
- Silicon Carbide SiC

Common Magnetic Abrasive Materials

- White Alumina + Iron
- Diamond + Iron
- Tungsten Carbide + Cobalt

1.2 Formation of magnetic abrasive brush

Fig. 1.2 shows the configuration of magnetic abrasive brushes in which the magnetized abrasives spread in a row from the pole to the material. In considering only the magnetic field, a continuous function, it is estimated that the magnetized particles aggregate into bundles. However, the contact of the magnetized particles must be taken into account. Energy requirements in the production of magnetic abrasive brush using magnetic abrasives that are added little by little into the magnetic field are discussed as follows:

(1) Magnetization energy, Wm, required to magnetize the abrasives to form bundles.

(2) Repulsion energy, Wf , due to Faraday effect causes the bundles to repel from each other.

(3)Tension energy, Wt, needed to counter act the curved bundles due to repelling particles.

Therefore, in order to form the magnetic abrasive brush sum of these energies, W, is necessary:

$$W = Wm + Wf + Wt \qquad (1)$$

The brush is formed in a stable state when W Is minimum, that is, dW = 0.

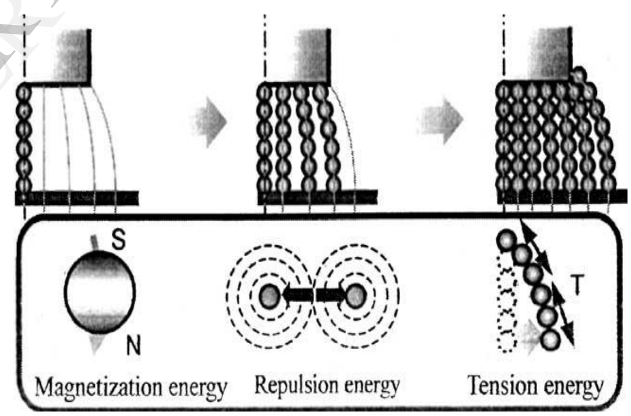

Figure 1.2: Configuration of magnetic abrasive brushes[2]

1.3 Applications

The process can be applied in many other fields,

i. Polishing of fine components such as printed circuit boards (PCB).
ii. The removal of oxide layers and protective coatings.
iii. Chamfering and deburring of gears and cams.
iv. Automatic polishing of complicated shapes.
v. Polishing of flat surfaces.

2.EXPERIMENTATION

2.1 Experimental setup

A schematic diagram of the plane MAF apparatus is shown in Figure 2.1. The flat-faced electromagnet has been designed such that the centre part of the magnet acts as a north pole and outer case as south pole. The reason of doing so that it concentrates magnetic force at the Centre of the magnet. The gap between the flat workpiece and the magnetic poles is known as working gap or machining gap and is filled with unbound magnetic abrasive particles. The iron particles are magnetized by the induced magnetic flux (by passing a current to the coil) and are coupled magnetically. These particles are concentrated in the machining gap. The finishing setup is attached to the main spindle of the machine through a holder. The current supplied to the coil of electromagnet is given by a device consisting of brass slip rings and electric carbon brushes.

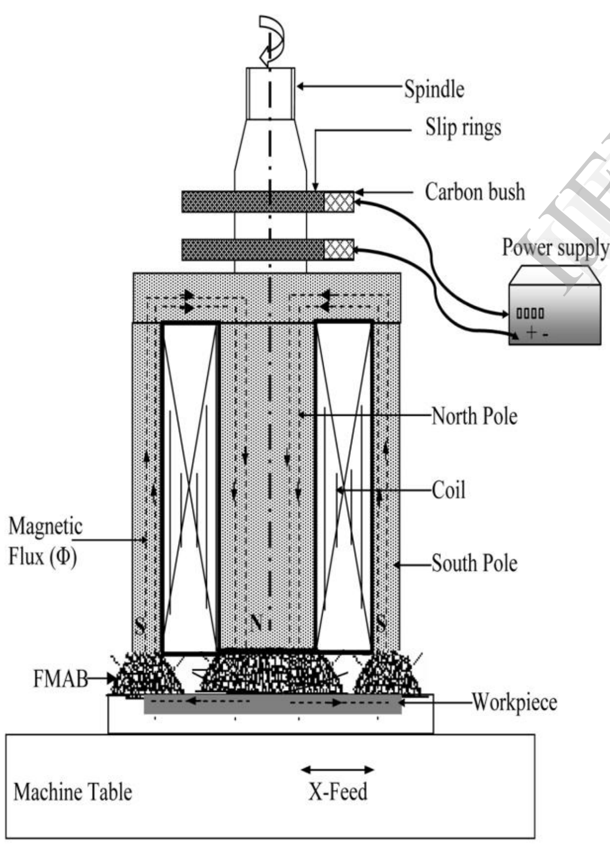

Figure 2.1: Schematic diagram of plane magnetic abrasive finishing setup. (Source D.K.Singh et. al.)

During the design of the setup, the parameters that have been considered are magnetic flux density (current), machining gap, and composition of ferromagnetic abrasive particles (ratio of iron particles and SiC abrasive particles in the gap).

2.2 Work piece composition

Alloy steel is considered as work piece for the experimental work.

Table 2.1: Workpiece Material composition (Alloy Steel)

Alloying elements	percentage
C	0.35-0.45
Mn 0.45-0.60	
Si	1.31-1.81
Cr	0.20-0.30
Ni	0.10-0.30
Iron	Rest

2.3 Experimental design

The various levels of machining parameters are selected based on the previous studies. The considered machining parameters and their coded levels are represented in table 2.2 Experiments have been planned using statistical technique to get useful inferences by performing minimum number of experiments. Design Expert software was used for designing of experiments.

Table 2.2: Machining Parameters and Their Corresponding Variation Levels.

Parameters(unit)	levels				
	-2	-1	0	1	2
current (amp)	0.5	0.63	0.75	0.88	1.0
Machining gap (mm)	1.25	1.50	1.75	2.00	2.25
Grain size(mesh no)	220	300	400	500	600
Number of cycles	5	7	9	11	13

TABLE 2.3: Table for Design of Experiments and Responses

INPUT PROCESS PARAMETERS					RESPONSES	
S.N	X1	X2	X3	X4	MR (mg)	ΔRa (µm)
1	0.75	1.75	400.00	9.00	79	0.24
2	0.75	1.25	400.00	9.00	101	0.26
4	0.63	2.00	500.00	11.00	78	0.24
3	0.88	1.50	500.00	11.00	96	0.28
5	0.75	1.75	400.00	9.00	67	0.17
6	0.75	2.25	400.00	9.00	52	0.14
7	0.75	1.75	400.00	13.00	98	0.22
8	0.88	2.00	300.00	11.00	91	0.21
9	0.63	2.00	300.00	7.00	40	0.12
10	0.88	1.50	300.00	11.00	90	0.23
11	0.50	1.75	400.00	9.00	53	0.12
12	0.63	1.50	500.00	7.00	66	0.17
13	0.63	1.50	300.00	7.00	77	0.17
14	0.75	1.75	400.00	5.00	52	0.17
15	0.63	2.00	300.00	11.00	70	0.17
16	0.88	2.00	500.00	11.00	110	0.24
17	0.75	1.75	400.00	9.00	89	0.24
18	0.75	1.75	400.00	9.00	82	0.23
19	0.75	1.75	600.00	9.00	99	0.26
20	0.75	1.75	400.00	9.00	90	0.24
21	0.75	1.75	400.00	9.00	71	0.19
22	0.88	1.50	500.00	7.00	95	0.28
23	1.00	1.75	400.00	9.00	99	0.24
24	0.75	1.75	400.00	9.00	76	0.18
25	0.75	1.75	220.00	9.00	53	0.18
26	0.63	1.50	300.00	11.00	58	0.19
27	0.88	1.50	300.00	7.00	89	0.23
28	0.63	2.00	500.00	7.00	48	0.16
29	0.88	2.00	300.00	7.00	62	0.17
30	0.63	1.50	500.00	11.00	82	0.22

Where X1 X2 X3 X4 are in actual levels values of current, machining gap, grain size and no of cycles. ,whose coded values are in table 2.2.

3.MODELLING OF PROCESS PARAMETERS

In the present work response surface methodology is used to model the process.A central composite design is adopted to develop model.

The statistical software (design expert) has been employed to analyse the experimental findings (Table2.3), and the following regression models have been evolved:

Equation for material removal is given by-

$$MR = 79.47 + 22.80\,X1 - 15.35X2 + 12.18X3 + 19.23X4 - 3.00X12 - 2.49X22 - 2.52X32 - 3.99X42 + 1.87X1X2 + 1.05X1X3 + 4.31X1X4 + 3.34X2X3 + 33.49X2X4 + 11.86X3X4 \quad (2)$$

And equation for surface roughness is given by-

$$\Delta Ra = 0.21 + 0.055X1 - 0.040X2 + 0.038X3 + 0.032X4 - 0.029X12 - 0.008963X22 + 0.009668X32 - 0.014X42 - 0.033X1X2 + 0.006102X1X3 - 0.031X1X4 + 0.011X2X3 + 0.034X2X4 + 0.013X3X4 \quad (3)$$

3.1 Analysis of variance (ANOVA) of regression

Analysis of variance (ANOVA) is a procedure for assigning sample variance to different sources and deciding whether the variation arises within or among different population groups. Samples are described in terms of variation around group means and variation of group means around an overall mean. If variations within groups are small relative to variations between groups, a difference in group means may be inferred. Hypothesis Tests are used to quantify decisions. ANOVA table for MR and Ra is shown in table 3.2 and table 3.3 respectively.

Table3.2:Analysis of variance(ANOVA) of regression for ΔRa

Sourcedofss f p percentage

Regression 14 0.0482 6.42 0.0003 84.9

Residual error 16 0.0086 --15.1

Total30 0.0568 - - 100

Table3.3:Analysis of variance(ANOVA) of regression for MR

Sourcedofss f p percentage

Regression 14 8758.70 6.59 0.0002 82.6

Residual error 16 1519.10- - 17.6

Total30 10277.80 - -100

significance at 95% confidence interval.

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F value for Ra is found to be 6.59 which is greater than standard f value(2.35),means our data is highly correlated and p value is almost found to be zero.

The analysis of variance (ANOVA, Table 4 and5) indicates that the variance ratio (F) is more than the standard value of F (¼2.35) at 95% confidence interval (a ¼ 0.05) for both the responses. Their P values come out to be zero .These statistical terms i.e., variance ratio (F) and P value are used tomeasure the significance of the regression under investigation. On the basis of these F and P values, it can be concluded that there is a good correlation between the predicted and the experimental values. Therefore, the regression Equation 2 for ΔRa and Equation 3 for material removal (MR) can be used to predict the responses of the MAF process.

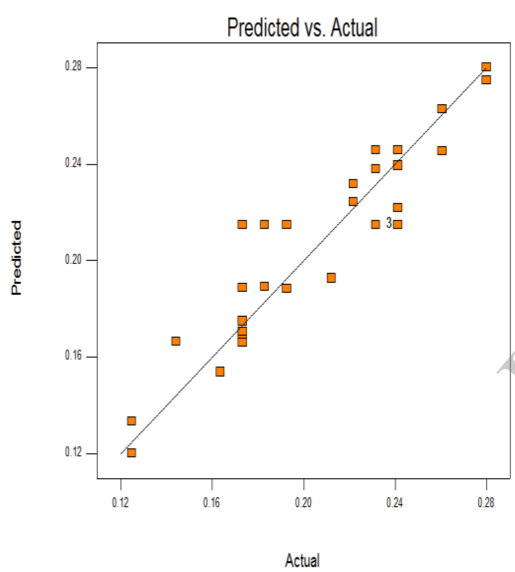

Fig 3.1 plot of actual vs predicted value for ΔRa

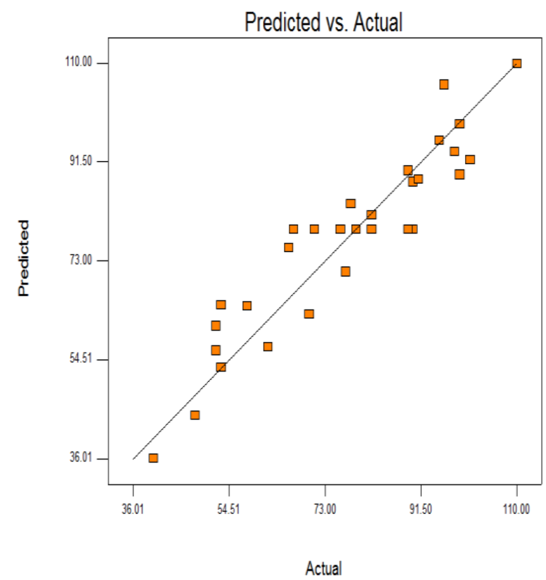

Fig 3.2 plot of actual vs predicted value for mr

Figure 3.1,3.2 shows the graphs between actual and predicted value.it clearly indicates a straight line which means our model responses mr and ΔRa are very close to the actual values.

3.2 Percentage contribution of factors

Table3.4for percentage contribution of factors in responses is also presented based on the result of anova. It clearly indicates the contribution of different factors in reduction in surface roughness value and amount of material removed.

Table3.4:Percentage Contribution Of Factors

Factors	MR (mg)	ΔRa (μm)
Current (Magnetic flux density) X1	30.63%	33.33%
Machining gap X2	14.01%	17.66%
Grain mesh number X3	9.69%	17.38%
Number of cycles X4	21.99%	11.40%
Error	23.68%	20.23%
Total	100	100

Error obtained is due to the negligence of higher order terms in the analysis of variance of regression. From the above table it can be concluded that material removal and reduction in surface roughness is affected mostly by current to the electromagnet.

4.OPTIMISATION WITH GA

4.1 Genetic algorithm

The EA holds a population of individuals (chromosomes), which evolve my means of selection and other operators like crossover and mutation. Every individual in the population gets an evaluation of its adaptation (fitness) to the environment. In the terms of optimization this means, that the function that is maximized or minimized is evaluated for every individual. The selection chooses the best gene combinations (individuals), which through crossover and mutation should drive to better solutions in the next population.

4.2 Basic steps of GA

- Generate initial population
- Calculation of the values of the function that we want to minimize of maximize.
- Check for termination of the algorithm
- Selection
- Crossover
- Mutation
- New generation

4.3 Fitness function

The fitness function is any function, which you want to optimize. For standard optimization algorithms, it is known as the objective function. GAs follows the ‘survival-of-the-fittest’ principle of nature to make a search process.

GAs are naturally suitable for solving maximization problems. All minimization problems are usually transformed into maximization problems by suitable transformations.

Fitness function for MR

function y = objective(x)

$$y(1) = -((307.80428) + (89.19921 * x(1)) - (172.1285 * x(2)) - (0.097110 * x(3)) - (29.64022 * x(4)) - (48.02137 * (x(1)^2)) - (9.96576 * (x(2)^2)) - (0.0000698313 * (x(3)^2)) - (0.24947 * (x(4)^2)) + (14.96249 * x(1) * x(2)) + (0.022038 * x(1) * x(3)) + (4.31306 * x(1) * x(4)) + (0.035112 * x(2) * x(3)) + (16.74442 * x(2) * x(4)) + (0.015611 * x(3) * x(4)));$$

Fitness function for ∆Ra

function ra =shukla(x)

$$ra(1) = ((-0.46892) + (1.60717 * x(1)) + (0.043693 * x(2)) - (0.00046892 * x(3)) + (0.010948 * x(4)) - (0.46689 * (x(1)^2)) - (0.035851 * (x(2)^2)) + (0.00000026781 * (x(3)\hat{}2)) - (0.000872671 * (x(4)\hat{}2)) - (0.26191 * x(1) * x(2)) + (0.000128469 * x(1) * x(3)) - (0.031227 * x(1) * x(4)) + (0.000114900 * x(2) * x(3)) + (0.016755 * x(2) * x(4)) + (0.000016887 * x(3) * x(4)));$$

These functions acts as the fitness functions for our problem. variation of factors for both the functions are as follows-

$0.5<x1<1.0$

$1.25<x2<2.25$

$220<x3<600$ and

$5<x4<13$

The above two fitness functions are used in GA toolbox in matlab.This toolbox can be easily accessed by simply typing GAtool in matlab command window.

S.N	CURRENT (amp)	MACH. GAP (mm)	GRAIN SIZE (Mesh no.)	No. Of Cycle	MR (mg)
1	0.50	1.25	220	5	84.5233
2	0.911	1.391	324.731	10.555	93.1472
3	0.692	1.25	220	5	99.3082
4	.999	1.787	385.298	10.807	106.6533
5	.824	2.055	551.59	11.04	109.8263
6	.865	1.25	510.798	7.808	107.0072
7	.932	1.25	461.009	7.602	110.6545
8	.688	1.507	591.371	10.132	91.6999
9	.677	2.232	462.717	12.983	108.3185
10	.972	1.25	531.048	5.364	113.0458

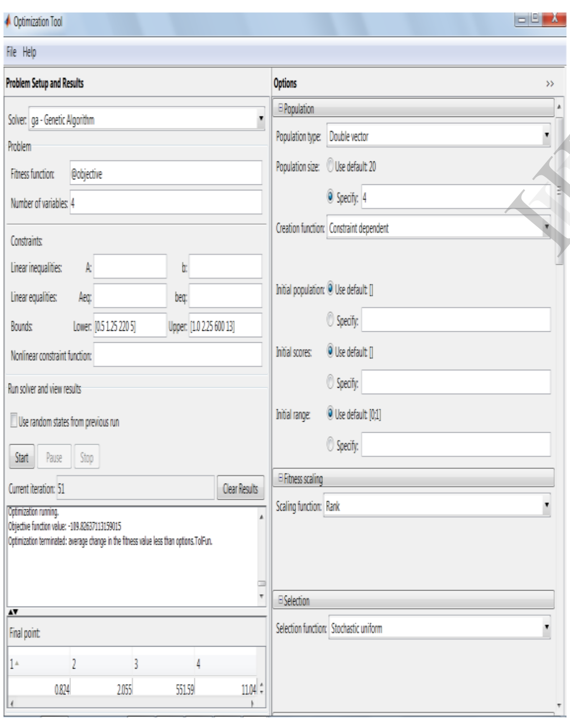

Fig 4.1:Snapshot of GA toolbox(matlab 2011a)

5.RESULTS AND DISCUSSION

5.1 Result for MR

TABLE 5.1 Result From Genetic Algorithm for MR

Based upon the result obtained from data the final optimized value of MR is found to be 109.8263 mg.

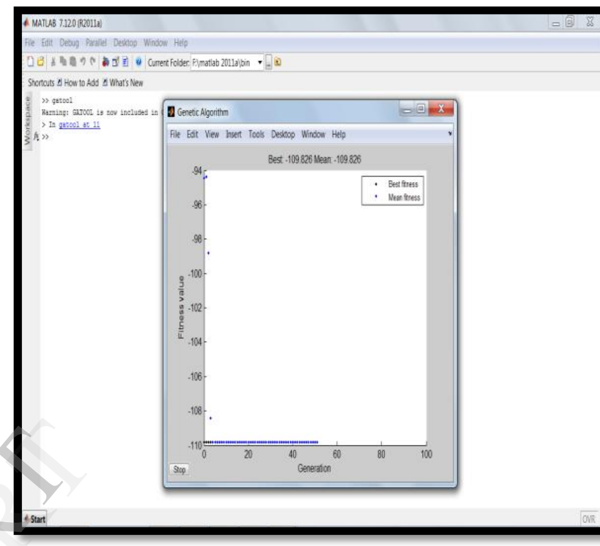

Fig5.1: Fitness curve for MR

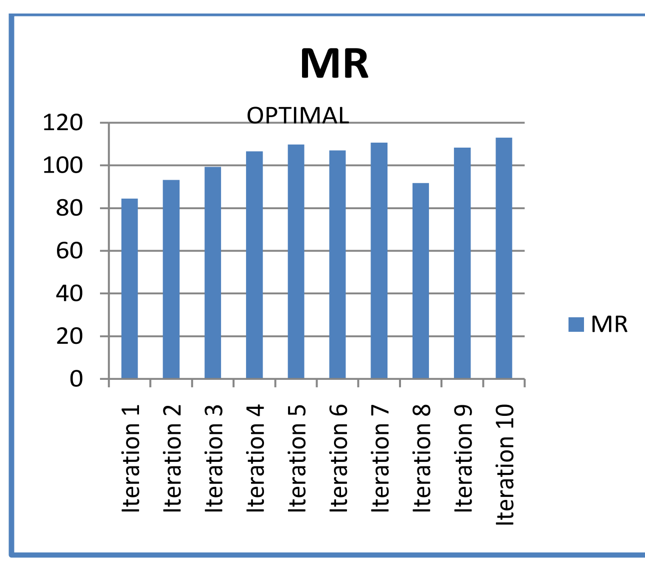

Fig5.2: Iterations vs MR

5.2 Result for ΔRa

TABLE 5.2: Result From Genetic Algorithm for ΔRa

S.N	CURRENT (amp)	MACH .GAP (mm)	GRAIN SIZE (Mesh no.)	No. Of Cycle	ΔRa (µm)
1	0.634	1.291	220	5	0.1655
2	0.880	1.962	330.791	11.962	0.2029
3	0.811	1.832	230.399	12.307	0.1932
4	0.511	1.908	327.37	9.476	0.1258
5	1.000	1.804	289.305	12.957	0.1905
6	0.569	2.083	417.661	7.689	0.1192
7	0.882	1.872	285.913	8.388	0.1939
8	0.574	1.647	471.117	6.449	0.1371
9	0.691	1.808	372.037	5.293	0.1389
10	0.566	2.209	558.993	8.164	0.1554

Based upon the result obtained from data the final optimized value of ΔRa is found to be 0.2029 µm.

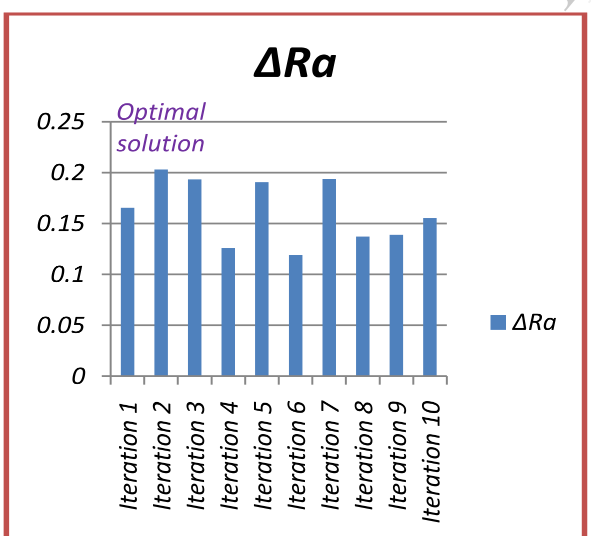

Fig 5.3:Iteration vs ΔRa

Based upon the result obtained from data the final optimized value of Ra is found to be 0.2058 µm and that for MR is 109.8263 mg. Corresponding values for parameters are shown in their respective rows. Some of the readings are found to be out of range so they are neglected. Current and machining gap are the most influencing parameters .These largely affect surface roughness value and material removal.

6.CONCLUSIONS

By completing the above work it can be said that response of magnetic abrasive finishing process can be controlled by controlling process parameter variables, which are current(magnetic flux density),machining gap, abrasive grain size (mesh no.) and no. of cycle. Table 5.1 and 5.2 shows the various optimized solutions of the problem for MR and ΔRa respectively. For optimising responses genetic algorithm is used.The result obtained by GA are very accurate.

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