



## Multi-objective Optimization of Magnetic-field-assisted EDM Process using Non-dominated Sorted Genetic Algorithm

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**Abstract:** Electrical discharge machining is characterized by stochastic and time varying characteristics due to its complicated discharge mechanisms which make it difficult to optimize the process. Optimization of process parameters of electrical discharge machining is a multi-objective optimization task. In practice, the performance measures are conflicting in nature. Meta-heuristic technique such as genetic algorithm has been proven as one of the most popular multi-objective optimization techniques for the parametric optimization of conventional and non-conventional machining process. In this work, non-dominated sorted genetic algorithm has been used to optimize the process parameters. Experiments were carried out on die-sinking electrical discharge machine by taking AISI 4140 as workpiece material and copper as tool material. Experiments were designed using  $L_{18}(2^1 \times 3^3)$  Taguchi orthogonal array. Non-dominated sorted genetic algorithm has been employed to find out the optimal setting of process parameters that simultaneously maximize material removal rate, minimize surface roughness and maximize surface hardness. A set of pareto-optimal front is obtained which provides flexibility to choose the best setting depending on applications.

**Keywords:** Magnetic filed assisted EDM; Meta-heuristic; Genetic algorithm; AISI 4140; Taguchi approach

### I. Introduction

Electric discharge machining (EDM) is a non-conventional machining process in which material removal takes place by a series of electric sparks generated between the small gaps of two electrodes immersed in dielectric medium. The gap between the two electrodes, one workpiece and the other tool significantly affect the stability of machining process. The machining performance improves by removing the debris of already machined material from the machining gap quickly. Material removal rate (MRR) is a very important issue to be taken care of in EDM process. Powder mixed in dielectric fluid compliments EDM process in terms of high MRR. Externally applied magnetic field also helps in improving MRR in conventional EDM. Researchers have reported improvement in EDM output parameters with different powders mixed in dielectric under different conditions and different parametric settings. Similarly, a number of researches are being carried out on magnetic field assisted EDM process reporting improvement in EDM process with different types of magnets and different process parameters. Due to the very strong stochastic nature of electrical discharge machining process it becomes difficult to optimize the process. Optimization of process parameters of EDM is a multi-objective optimization task where in performance measures are conflicting in nature. Although, much work has been reported in literature to improve the process performance, yet proper selection of process parameters still remains a challenge. In the current trends of optimizing machining process parameters, various evolutionary or meta-heuristic techniques such as particle swarm optimization (PSO), genetic algorithm (GA), simulated annealing (SA), ant colony optimization (ACO) and artificial bee colony algorithm (ABC) have been used. GA is very different from most of the traditional optimization methods. GA finds applicability in the field of conventional and non conventional machining processes. It works with a random population of solution points and a set of Pareto-optimal solutions is obtained for the best performance measures. Lina et al. [1] studied the effects of magnetic force on EDM machining characteristics. The benefits of magnetic force assisted EDM were confirmed from the analysis of discharge waveforms and from the micrograph observation of surface integrity.

Bergaley and sharma [2] optimized the electrical and non electrical input parameters for optimal value of material removal rate and electrode wear rate. The research showed that the peak current has significant effect on material removal rate. Heinz et al. [3] developed a novel process and tested to improve material removal rate in magnetic-field-assisted  $\mu$ -EDM for nonmagnetic materials. Bhattacharya et al. [4] applied analytical hierarchy process for optimizing multiple responses in electrical discharge machining process. Seven different process parameters were tested to study their effect on MRR, TWR and SR using a specially designed Taguchi orthogonal array that could accommodate factors with varying number of levels. Dalai et al. [5] studied EDM of stainless steel in which best process environment (optimal) has been determined to satisfy productivity and quality requirements simultaneously. Sethy et al. [6] studied a new method to determine multi-objective optimal condition using principal component analysis (PCA) based on grey relational analysis (GRA) method for characteristics such as MRR, TWR and Ra during EDM of AISI P20 tool steel machine. Sahu et al. [7] had adopted response surface methodology to establish effect of various process parameters such as  $I_p$ , MRR, TWR, Ra and circularity of machined component. Padhee et al. [8] investigated the effect of silicon powder concentration in the dielectric fluid, pulse on time, duty cycle, and peak current on the material removal rate and surface roughness using response surface methodology and developed predictive models. Tarng et al. [9] and Yang et al. [10] employed SA technique for optimizing the parameters of EDM. Grey relation analysis has been employed successfully as a multi-objective optimization technique in EDM by many authors [11-13]. Bharti et al. [14] employed a new variant of GA i.e., controlled elitist NSGA to optimize the process parameters of EDM. In the present paper the aim is to develop empirical models for predicting material removal rate surface roughness and surface hardness in terms of magnetic strength, gap current, pulse on time and pulse off time using multiple regressions modeling method. Finally, non-dominated sorted genetic algorithm has been employed to obtain the pareto-optimal set of solutions. Simulation has been performed in MATLAB.

## II. Experimental Details

An electrical discharge machine, die-sink type, model C 400 x 250, make Electronica Machine Tools Limited with NC control in z-direction with servo head (constant gap) and positive polarity was used to conduct the experiments. Commercial grade EDM oil (specific gravity= 0.763, kinematic viscosity-23 cSt at 40 °C and dielectric strength 12 KV) was used as dielectric fluid. Side flushing pressure of 0.5 kg/cm<sup>2</sup> was kept constant. En 19 alloy steel was selected as the work piece material. Blocks of sizes 30 mm x 30 mm x 14 mm were prepared. These blocks were heat treated to a temperature of 820 °C for 30 minutes. Then they were oil quenched to obtain an average hardness of 45 HRc. Additionally, these parts were ground on surface grinding machine to acquire flat surfaces of surface finish 0.8  $\mu$ m. All experiments were carried out with electrolytic copper (99.9% pure) as tool electrode material. Work-pieces / tools were weighed by an electronic weighing balance of least count 0.001gm. Contact stylus type surface roughness tester was availed to measure centreline average surface roughness (SR). Experiments were designed using L<sub>18</sub> (2<sup>1</sup> x 3<sup>3</sup>) Taguchi orthogonal array. Table 1 shows the machining parameters and their levels.

Table I Machining parameters and their levels

| Levels | Magnetic field (T) | Gap current (A) | Pulse on time ( $\mu$ s) | Pulse off time ( $\mu$ s) |
|--------|--------------------|-----------------|--------------------------|---------------------------|
| 1      | 0                  | 2               | 8                        | 5                         |
| 2      | 0.124              | 4               | 23                       | 7                         |
| 3      | -                  | 6               | 38                       | 9                         |

After machining, the surfaces were washed with oil to remove any accumulated debris at the corners followed by acetone cleaning. All the machined surfaces thus obtained were subjected to micro-hardness testing using a load of 1000 g for a duration of 20 seconds. Before and after machining the micro-hardness was measured at five different places and average values were noted. Surface roughness (SR) of the machined surfaces was measured by Mitutoyo make of SJ-210 model surface roughness instrument. Material removal rate (MRR) was calculated using the following formula;

$$MRR = \frac{w_1 - w_2}{\rho \times T} \quad (1)$$

where  $w_1$  = initial weight of work-piece (gm),  $w_2$  = final weight of work-piece (gm),  $\rho$  = density of work-piece (gm/), T = machining time, 10 mins (kept constant).

## III. Results and Discussions

### A. Multiple regression model

The EDM experiments were conducted by using the parametric approach of the Taguchi's method as shown in table 2. Regression analysis has been performed to find out the relationship between input factors and responses

using Minitab 16 statistical software. During regression analysis it was assumed that the factors and the responses are linearly related to each other. General first order model was developed to predict the material removal rate surface roughness and hardness over the experimental region (equation 2 to 4).

$$\text{MRR} = -2.01483 + 34.7693 * \text{Magnetic Field} + 2.15977 * \text{Gap Current} + 0.0140835 * \text{Pulse on Time} - 0.443206 * \text{Pulse off Time} \quad (2)$$

$$\text{SR} = -0.133703 + 8.58244 * \text{Magnetic Field} + 0.6895 * \text{Gap Current} + 0.0433222 * \text{Pulse on Time} + 0.061375 * \text{Pulse off Time} \quad (3)$$

$$\text{HV} = 288.379 - 362.007 * \text{Magnetic Field} + 26.8583 * \text{Gap Current} + 4.02222 * \text{Pulse on Time} + 21.9125 * \text{Pulse off Time} \quad (4)$$

**Table II Taguchi orthogonal array with observed values**

| Sr. No. | Magnetic strength (T) | Gap current (A) | Pulse on time (μs) | Pulse off time (μs) | MRR (mm <sup>3</sup> /min) | SR (μm) | HV    |
|---------|-----------------------|-----------------|--------------------|---------------------|----------------------------|---------|-------|
| 1       | 0                     | 2               | 8                  | 5                   | 1.096                      | 1.298   | 593.1 |
| 2       | 0                     | 2               | 23                 | 7                   | 0.917                      | 2.758   | 609.7 |
| 3       | 0                     | 2               | 38                 | 9                   | 1.873                      | 3.868   | 762.9 |
| 4       | 0                     | 4               | 8                  | 5                   | 2.255                      | 2.845   | 294.4 |
| 5       | 0                     | 4               | 23                 | 7                   | 3.172                      | 5.035   | 658.9 |
| 6       | 0                     | 4               | 38                 | 9                   | 1.682                      | 3.416   | 605.9 |
| 7       | 0                     | 6               | 8                  | 7                   | 11.006                     | 5.535   | 876.4 |
| 8       | 0                     | 6               | 23                 | 9                   | 4.904                      | 5.458   | 682.2 |
| 9       | 0                     | 6               | 38                 | 5                   | 7.707                      | 6.24    | 691.9 |
| 10      | 0.124                 | 2               | 8                  | 9                   | 2.382                      | 2.99    | 454.2 |
| 11      | 0.124                 | 2               | 23                 | 5                   | 2.803                      | 4.283   | 351.6 |
| 12      | 0.124                 | 2               | 38                 | 7                   | 4.204                      | 4.335   | 785.1 |
| 13      | 0.124                 | 4               | 8                  | 7                   | 4.764                      | 2.852   | 443.3 |
| 14      | 0.124                 | 4               | 23                 | 9                   | 7.732                      | 5.998   | 714.7 |
| 15      | 0.124                 | 4               | 38                 | 5                   | 10.038                     | 6.726   | 671.8 |
| 16      | 0.124                 | 6               | 8                  | 9                   | 12.548                     | 7.083   | 663.9 |
| 17      | 0.124                 | 6               | 23                 | 5                   | 17.860                     | 5.948   | 755.1 |
| 18      | 0.124                 | 6               | 38                 | 7                   | 11.083                     | 5.816   | 531.7 |

### B. Multi-objective optimization

Pareto front is considered as two-dimensional where one objective is redundant. NSGA is used to get a pareto-optimal front to solve the three-objective optimization problems by considering the function as a two objective problem neglecting one objective in each run. To solve optimization problem using GA, fitness value is required. Fitness values, in fact, are the objective function values. In this work, multiple regressions modelling method has been employed to develop a mathematical model which establishes the relation between input and output. The developed mathematical model was converted into a MATLAB (R2009a) function. This function was input to the GA Toolbox of MATLAB 2009a as the objective function. Upper and lower bounds were specified as per the levels of the machining parameters and the number of variables was set at 4. The objective function values are obtained for maximization of material removal rate, minimization of surface roughness and maximization of surface hardness in EDM of AISI4140 alloy. Here, an initial population size of 100 is taken and optimization is carried out by setting simple crossover and bitwise mutation with a crossover probability  $P_c = 0.8$ , migration interval of 20, migration fraction of 0.2 and Pareto fraction of 0.35. According to the algorithm, ranking and sorting of solutions are done. The pareto-optimal sets of 72 solutions (along with corresponding performance measure values) are reported in table 3. Since the performance measures are conflicting in nature, surface quality decreases as MRR increases and the same behavior of performance measures is observed in the solutions obtained. Since none of the solutions in the pareto-optimal set is absolutely better than any other, any one of them is an acceptable solution. The choice of one solution over the other depends on the requirement of the process engineer.

**Table III Pareto optimal solutions**

| Machining parameters |         |       |                      |                       | Response parameters        |         |         |
|----------------------|---------|-------|----------------------|-----------------------|----------------------------|---------|---------|
| Solution No.         | M S (T) | I (A) | T <sub>on</sub> (μs) | T <sub>off</sub> (μs) | MRR (mm <sup>3</sup> /min) | SR (μm) | HV      |
| 1                    | 0       | 2     | 8                    | 5                     | 0.201                      | 1.899   | 483.836 |
| 2                    | 0.096   | 2.139 | 19.707               | 8.116                 | 2.629                      | 3.518   | 568.157 |
| 3                    | 0.001   | 2.043 | 12.919               | 8.779                 | 1.284                      | 2.380   | 587.278 |
| 4                    | 0.124   | 5.972 | 35.863               | 7.300                 | 12.454                     | 7.047   | 708.232 |
| 5                    | 0.002   | 5.981 | 37.365               | 8.639                 | 7.681                      | 6.159   | 787.766 |
| 6                    | 0.105   | 2.016 | 8.515                | 5.500                 | 3.676                      | 2.865   | 459.224 |
| 7                    | 0.054   | 5.936 | 36.410               | 8.101                 | 9.607                      | 6.498   | 752.203 |
| 8                    | 0.077   | 5.976 | 37.109               | 8.565                 | 10.312                     | 6.785   | 757.796 |
| 9                    | 0.013   | 2.448 | 14.832               | 7.101                 | 0.782                      | 2.743   | 564.718 |
| 10                   | 0.015   | 5.980 | 37.345               | 8.616                 | 8.126                      | 6.264   | 782.616 |
| 11                   | 0.112   | 2.016 | 8.124                | 5.025                 | 4.128                      | 2.880   | 444.693 |
| 12                   | 0.087   | 2.006 | 8.316                | 5.118                 | 3.192                      | 2.671   | 456.339 |
| 13                   | 0.121   | 5.835 | 30.554               | 6.550                 | 12.324                     | 6.654   | 667.699 |
| 14                   | 0.123   | 5.929 | 34.734               | 5.525                 | 13.122                     | 6.857   | 663.702 |
| 15                   | 0.088   | 2.469 | 11.123               | 6.041                 | 3.866                      | 3.179   | 499.845 |
| 16                   | 0.037   | 2.692 | 13.924               | 6.935                 | 2.225                      | 3.073   | 555.066 |
| 17                   | 0.004   | 2.070 | 11.914               | 5.523                 | 0.321                      | 2.184   | 511.428 |
| 18                   | 0.084   | 5.908 | 33.388               | 6.842                 | 11.120                     | 6.531   | 700.692 |
| 19                   | 0.104   | 5.537 | 32.616               | 6.014                 | 11.362                     | 6.361   | 662.315 |
| 20                   | 0       | 2.005 | 8.466                | 5.224                 | 0.120                      | 1.936   | 490.725 |
| 21                   | 0.044   | 3.293 | 10.703               | 5.134                 | 4.498                      | 3.292   | 516.476 |
| 22                   | 0.095   | 4.890 | 35.991               | 7.387                 | 9.084                      | 6.066   | 691.968 |
| 23                   | 0.110   | 2.367 | 10.407               | 5.207                 | 4.772                      | 3.216   | 467.954 |
| 24                   | 0.042   | 4.900 | 22.824               | 7.134                 | 7.183                      | 5.031   | 652.964 |
| 25                   | 0.001   | 2.013 | 8.977                | 6.434                 | 0.375                      | 2.042   | 519.344 |
| 26                   | 0.117   | 5.877 | 34.826               | 8.061                 | 11.677                     | 6.929   | 720.448 |
| 27                   | 0.001   | 2.037 | 12.577               | 7.975                 | 0.933                      | 2.315   | 568.043 |
| 28                   | 0.019   | 2.305 | 12.177               | 7.298                 | 0.554                      | 2.592   | 552.370 |
| 29                   | 0.040   | 2.023 | 8.610                | 5.299                 | 1.527                      | 2.305   | 478.862 |
| 30                   | 0.070   | 5.683 | 20.622               | 8.440                 | 9.236                      | 5.795   | 683.634 |
| 31                   | 0.035   | 3.701 | 25.309               | 5.983                 | 4.905                      | 4.183   | 607.975 |
| 32                   | 0.039   | 4.607 | 30.592               | 6.369                 | 6.910                      | 5.096   | 660.498 |
| 33                   | 0.004   | 2.046 | 11.010               | 7.705                 | 0.733                      | 2.257   | 555.181 |
| 34                   | 0.086   | 2.124 | 20.224               | 5.354                 | 3.466                      | 3.271   | 513.010 |
| 35                   | 0.001   | 2.655 | 9.050                | 6.294                 | 1.106                      | 2.487   | 533.513 |
| 36                   | 0.113   | 5.692 | 27.742               | 8.243                 | 10.958                     | 6.472   | 692.438 |
| 37                   | 0.123   | 5.977 | 37.114               | 6.599                 | 12.773                     | 7.057   | 698.211 |
| 38                   | 0.003   | 2.185 | 25.666               | 7.806                 | 0.281                      | 2.992   | 620.153 |
| 39                   | 0.089   | 3.392 | 31.903               | 5.933                 | 6.228                      | 4.716   | 605.568 |
| 40                   | 0.105   | 4.443 | 14.222               | 6.124                 | 8.715                      | 4.822   | 561.124 |
| 41                   | 0.097   | 3.150 | 24.032               | 6.653                 | 5.555                      | 4.321   | 580.255 |
| 42                   | 0.083   | 5.287 | 30.873               | 7.287                 | 9.499                      | 6.010   | 684.132 |
| 43                   | 0.117   | 5.975 | 37.110               | 8.639                 | 11.652                     | 7.128   | 745.100 |
| 44                   | 0.124   | 5.978 | 37.120               | 8.674                 | 11.879                     | 7.191   | 743.517 |
| 45                   | 0.123   | 5.953 | 31.305               | 5.334                 | 13.201                     | 6.711   | 646.501 |
| 46                   | 0.086   | 2.415 | 33.352               | 7.882                 | 3.182                      | 4.202   | 628.843 |
| 47                   | 0.023   | 4.473 | 18.976               | 7.262                 | 5.481                      | 4.412   | 635.765 |
| 48                   | 0.060   | 3.248 | 20.502               | 5.339                 | 5.025                      | 3.841   | 553.190 |
| 49                   | 0.062   | 2.436 | 27.870               | 6.204                 | 3.055                      | 3.668   | 579.293 |
| 50                   | 0.077   | 2.023 | 9.166                | 5.316                 | 2.819                      | 2.649   | 468.039 |
| 51                   | 0.002   | 2.056 | 12.713               | 7.068                 | 0.443                      | 2.290   | 548.737 |
| 52                   | 0.061   | 4.376 | 15.338               | 6.655                 | 6.809                      | 4.476   | 591.515 |
| 53                   | 0.070   | 3.258 | 22.933               | 5.745                 | 5.232                      | 4.059   | 568.692 |
| 54                   | 0.016   | 4.685 | 16.702               | 6.848                 | 5.848                      | 4.375   | 625.801 |
| 55                   | 0.042   | 2.012 | 8.433                | 6.236                 | 1.152                      | 2.364   | 497.688 |
| 56                   | 0.097   | 2.906 | 12.300               | 5.634                 | 5.311                      | 3.581   | 504.217 |
| 57                   | 0.060   | 2.608 | 32.888               | 6.314                 | 3.373                      | 3.993   | 607.322 |
| 58                   | 0.023   | 5.775 | 36.315               | 8.553                 | 7.963                      | 6.140   | 768.800 |
| 59                   | 0.094   | 5.934 | 33.918               | 8.032                 | 10.992                     | 6.728   | 726.131 |

|    |       |       |        |       |        |       |         |
|----|-------|-------|--------|-------|--------|-------|---------|
| 60 | 0.022 | 2.127 | 13.929 | 6.572 | 0.643  | 2.532 | 537.396 |
| 61 | 0.077 | 4.334 | 15.254 | 6.088 | 7.522  | 4.545 | 571.835 |
| 62 | 0.001 | 5.106 | 31.715 | 7.342 | 6.247  | 5.222 | 713.542 |
| 63 | 0.066 | 5.535 | 20.241 | 5.693 | 9.985  | 5.472 | 619.420 |
| 64 | 0.116 | 5.560 | 31.727 | 5.460 | 12.046 | 6.403 | 643.052 |
| 65 | 0.041 | 2.599 | 21.002 | 6.670 | 2.364  | 3.330 | 573.981 |
| 66 | 0.002 | 4.314 | 22.804 | 7.818 | 4.244  | 4.330 | 666.406 |
| 67 | 0.002 | 5.192 | 31.833 | 8.473 | 5.977  | 5.366 | 740.631 |
| 68 | 0.096 | 5.267 | 8.995  | 7.599 | 9.463  | 5.179 | 597.725 |
| 69 | 0.081 | 2.233 | 30.024 | 7.922 | 2.526  | 3.886 | 613.482 |
| 70 | 0.099 | 5.258 | 26.848 | 6.922 | 10.086 | 5.927 | 653.511 |
| 71 | 0.001 | 2.009 | 8.615  | 6.982 | 0.623  | 2.060 | 529.691 |
| 72 | 0.112 | 2.016 | 8.124  | 5.025 | 4.131  | 2.880 | 444.671 |

#### IV. Conclusions

In this study magnetic field assisted EDM of AISI4140 alloy steel was conducted by using the parametric approach of the Taguchi's method. Regression analysis has been performed to find out the relationship between input factors and responses using Minitab 16 statistical software. General first order model was developed to predict the material removal rate and surface roughness over the experimental region. A pareto-optimal set of 72 solutions has been obtained and reported by employing NSGA. The choice of any solution will actually depend on the working requirement. The research approach presented in this paper tremendously reduces the cost of experiments and allows EDM operator to set the parameters according to customer demand.

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