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OPTIMIZATION OF THE MACHINING PARAMETERS IN THE ELECTROCHEMICAL MICRO-MACHINING OF NICKEL

OPTIMIZACIJA PARAMETROV ELEKTROKEMIJSKE MIKROMEHANSKE OBDELAVE NIKLJA

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Micro-machining is one of the basic technologies for the production of miniature parts and miso components. Electrochemical micro-machining (ECMM) is an emerging non-conventional technology for making micro-scale components. The main objective of this paper is to maximize the metal removal rate (*MRR*).The process parameters were considered such as electrolyte concentration, machining voltage, machining current, duty cycle and frequency. In this research, specimens for experimentation were 0.15-mm-thick nickel sheet, which is mainly in welded battery and gas turbine components. Taguchi's L_{18} orthogonal array was used for the experimentation. Analysis of variance (ANOVA) was used to estimate the contribution by each process parameters on *MRR*. Genetic algorithms (GAs) was used to optimize the process parameters. Based on the experimentations, it was observed that the machining current and frequency have contributed to a high *MRR* compared to other parameters. The *MRR* obtained using optimized process parameters was very closer to the value obtained from the validation experiment (2.9%). The optimum process parameters were obtained using the Taguchi method and a genetic algorithm to get the maximum *MRR*.

Keywords: electrochemical micro-machining, genetic algorithms, metal removal rate, Taguchi orthogonal array

Pričakuje se, da bo mikromehanska obdelava ena od osnovnih tehnologij izdelave miniaturnih izdelkov in mezokomponent. Elektrokemijska mikromehanska obdelava (ECMM, angl.: Electro Chemical Micro Machining) je prihajajoča nekonvencionalna tehnologija za izdelavo komponent mikronske velikosti. Osnovni cilj avtorjev tega članka je prikazati, kako doseči maksimalno hitrost odvzema kovine (*MRR*; angl.: Metal Removal Rate). V raziskavi so analizirali vpliv procesnih parametrov, kot so koncentracija elektrolita, napetost in tok mehanske obdelave, storilnost in frekvenca. V raziskavi so za testne vzorce uporabili nikljevo pločevino debeline 0,15 mm, ki se v glavnem uporablja v varjenih baterijah in komponentah plinskih turbin. Kot osnovo so za eksperimentiranje uporabili Taguchijevo L_{18} ortogonalno matriko. Za oceno prispevka vsakega od analiziranih procesnih parametrov na *MRR* so uporabili analizo variance (ANOVA) in za optimizacijo procesnih parametrov so uporabili genetske algoritme (GAs). Na osnovi preizkusov so ugotovili, da sta v primerjavi z drugimi parametri, tok in frekvenca ECMM največ prispevala k visoki *MRR*. Dosežena *MRR* z uporabo optimiziranih procesnih parametrov je bila zelo blizu tisti, ki so jo dosegli z ocenitvenim praktičnim preizkusom (2,9 %). Optimalne procesne parametre za doseganje maksimalne *MRR* so torej dobili s pomočjo Taguchijeve metode in genetskega algoritma.

Ključne besede: elektrokemijska mikromehanska obdelava, genetski algoritmi, hitrost odvzema kovine, Taguchijeva ortogonalna matrika

1 INTRODUCTION

Micro-machining is one of the important manufacturing processes for producing a large number of micro/miso components. Micro-machining refers to a small amount of material removal that ranges from 1 µm to 999 µm, B. Bhattacharyya et al.[1] Fabrication of parts made of hard and difficult-to-cut materials, finds applications in aerospace, biomedical engineering, electronics, etc. In ECMM process, the work piece is connected to an anode and the micro tool is connected to a cathode and they are placed inside the electrolyte with a small gap between them. On the application of adequate electrical energy, positive metal ions leave from the work piece and machining takes place. Electrolyte circulation removes the machined particles from the electrode gap. To continue the machining process, the electrode gap has to be maintained by moving the tool at the required rate. The ECMM process is capable of machining electrically conductive, tough and hard materials without inducing any residual stress, producing no tool wear, B. Bhattacharyya et al.[2] The process does not induce any deformation in the work piece because no force is acting on the work piece and there is no heat generation involved while machining, K. P. Rajurkar et al.[3] Monitoring method using radio frequency emission is given, which together with the current and voltage signals, identifies more clearly the events occurring within the gap, A. K. M. De Silva.[4] The ECMM system setup was developed for achieving satisfactory control of ECMM process parameters, B. Bhattacharyya et al.[5] The influence of key factors on the quality of hole produced by ECMM process, M. Sen et al.[6] The effect of machining voltage, pulse duration and pulse frequency on machining performance, S. H. Ahna et al.[7] The influence of the ECMM parameters machining voltage, electrolyte concentration, pulse period and frequency on *MRR*, accuracy and surface finish J. Munda et al.[8] Investigated the effective range of the process parameters for moderate *MRR* with lesser overcut, which is difference between the hole and tool sizes, J. Munda et al.[9] Developed a ECMM experimental setup with constant electrode gap control system and studied the influence of tool tip shape and machining gap on *MRR*, R. Thanigaivelan et al.[10] Electrochemical machining has no tool wear on machining hard materials and it does not leave a defective layer on the machined surface, R. J. Leese et al.[11] In ECMM the main disadvantage is poor accuracy, due to the dissolution that occur in the gap, generated by gas bubbles that increase the current density at the side gap. To prevent this drawback, it has been demonstrated that using ultra-short current pulses (100 ns and less) at high frequency (around the MHz), to improve the machining accuracy, N. Giandomenico et al.[12] The Taguchi method is used to find the optimal cutting parameters for surface roughness. L_9 orthogonal array, signal-to-noise (*S/N*) ratio and analysis of variance (ANOVA) is applied to synthesize the effect of Input parameters on the nickel-based alloy Inconel-718, O. G. Sonar et al.[13] The process parameters are optimized through the Non Dominated Sorting Genetic Algorithm-II (NSGA-II) approach to maximize the metal removal rate and minimize surface roughness, Chinnamuthu Senthilkumar et al.[14] From the literature study, it is observed that only a very few authors have investigated the performance of ECMM process. Further investigation is required for machining performance improvement for many newly developed difficult-to-cut materials. The objective of the present paper is to maximize the *MRR* by using ECMM process on selecting process parameters: electrolyte concentration, machining voltage, machining current, duty cycle and frequency. The Taguchi L_{18} orthogonal array is used for experimentation and to identify the most significant process parameter. Then analysis of variance (ANOVA) is used to verify statistical significance of these parameters. The process parameters were optimized by using genetic algorithm (GA) to maximize *MRR*.

2 EXPERIMENTAL PART

The ECMM set-up shown in **Figure 1** consists of various sub components: work holding platform, tool feeding device, control system, electrolyte flow system and power supply system.

The work-holding unit has two rectangular platforms to hold the work piece. The platforms were made up of acrylic because of its non-corrosive property. The work piece was placed between the two detachable plates which were fastened together by means of screws.

The machining chamber was filled with electrolyte and was clamped to the base. The platforms were immersed inside the electrolyte tank during machining. A tool feeding device was used to feed the tool towards the work piece at the required rate during the machining. The tool feeding device was actuated by a stepper motor, which moves the tool up or down based on the signals received from the control unit. The control system maintains the electrode gap at a desirable value either to avoid short circuiting or to avoid reduction in *MRR*. An ammeter was used to verify the electrode gap set between the tool and the work piece before machining. The tool can be moved according to the amount of inter-electrode gap required between the tool and the work piece. The rate of pulses given to the control unit maintains the tool feed.[15] For every pulse supplied to the stepper motor, the tool is moved for four microns.

A pumping system directs the electrolyte to the electrode gap with a medium velocity and drives out the material removed from the work piece. The electrolyte passes through two nozzles with the desired pressure into the machining chamber. The material removed from the work piece was dissolved in the electrolyte. The electrolyte was filtered before re-circulated into the machining chamber using a filter. During the machining operation hydrogen gas is evolved at the tool end. The gas bubbles formed act as a short circuiting medium creating micro sparks, which can erode the tool material. Hence, to avoid the micro spark generation, the electrolyte is pumped out at a moderate pressure, which removes the hydrogen gas generated. HCl or mixture of brine and H_2SO_4 is used as an electrolyte for machining of nickel. Non continuous pulsed DC supply was used in ECMM. The pulse current used in ECMM process improve electrolyte conductivity by flushing electrolyte in pulse off-time.[15] In ECMM the application of a voltage pulse at high current density in the anodic dissolution process improves the machining accuracy and surface finish.[16] It is observed that the maximum improvement in *MRR* with voltage and concentration were 100 % and 70 % respectively.[17]

In this study, Taguchi technique was used for the design and analysis of the experiments. The process para-

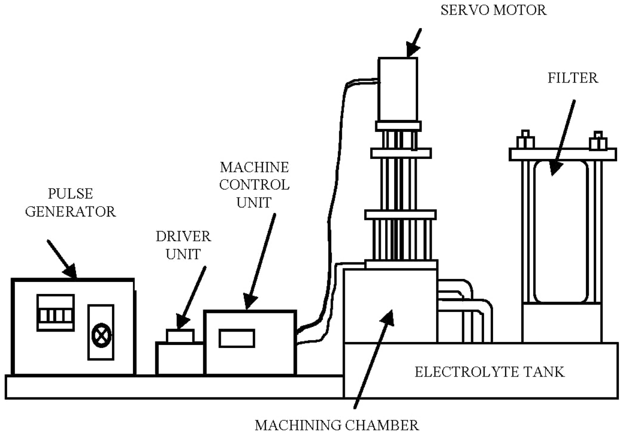

Figure 1: ECMM machining set-up

meters such as electrolyte concentration, voltage, current, duty cycle, and frequency were selected as factors. The levels of the parameters were determined based on tool material and work material used, and size of the hole to be machined. Based on the number of levels used, the total degrees of freedom were calculated and a suitable orthogonal array L_{18} was chosen. The parameters and their levels were given in **Table 1**. The experiments were carried out as per the orthogonal array. The signal-to-noise ratio (*S/N* ratio) was to be computed to get the optimized parameter levels. The S/N ratio for larger the better was used in this study to increase the *MRR*. ANOVA is conducted to identify the contribution of the individual parameter on *MRR*. Then a confirmation experiment was to be conducted using the optimal parameter levels combination.

Table 1: Factors and levels

Factor	(A)	(B)	(C)	(D)	(E)
Level 1	0.1	3.5	0.1	33.33	30
Level 2	0.2	5	0.3	50	40
Level 3	0.3	6.5	0.5	66.66	50

A. Electrolyte concentration (mol/lit.); B. Machining voltage (volts); C. Machining current, (amp); D. Duty cycle (%); E. Frequency (Hz).

2.1 Optimization using genetic algorithm

Genetic algorithms (GAs) were a nontraditional optimization algorithm based on the principles of natural genetics. The Genetic Algorithm was used to maximize the metal removal rate. The GA has been used for minimization problem by appropriately modifying the objective function.[18]

GAs evaluates the objective function using the basic elements of GAs consist of a chromosome and fitness value. The performance of GAs is mainly influenced by these three operator such as reproduction, crossover and mutation. The new population also goes through the same set of GAs operations: fitness evaluation, selection, crossover and mutation and to continue to develop best solutions which may maximize the objective function. This evolution continues until the convergence has criteria has reached.[21]

In this study, the objective is to maximize the *MRR* by optimally selecting the process parameters. In ECMM process, the *MRR* is controlled by the value of electrolyte concentration, current, voltage, duty cycle and frequency. The objective function, *MRR* is given as,

$$MRR = f\,(EC, C, V, DC, F) \tag{1}$$

The useful ranges of the ECMM process parameters are considered as the constraints for the above optimization problem. The constraints are stated as follows:

Bounds on electrolyte concentration (EC)

$$EC_L \le EC \le EC_H \tag{2}$$

where, EC_L and EC_H and are the least and highest values of electrolyte concentrations used, respectively, in the experiments.

Bounds on the machining current (C)

$$C_L \le C \le C_H \tag{3}$$

where, C_L and C_H are the least and highest values of machining current used respectively in the experiments.

Bounds on the machining voltage (*V*):

$$V_L \le V \le V_H \tag{4}$$

where, V_L and V_H are the smallest and highest values of machining voltage used, respectively, in the experiments.

Bounds on duty cycle (DC)

$$DC_L \le DC \le DC_H \tag{5}$$

Where, DC_L and DC_H are the smallest and highest values of duty cycle used, respectively, in the experiments

Bounds on frequency (F)

$$F_L \le F \le F_H \tag{6}$$

where, F_L and F_H are the smallest and highest values of frequency used, respectively, in the experiments.

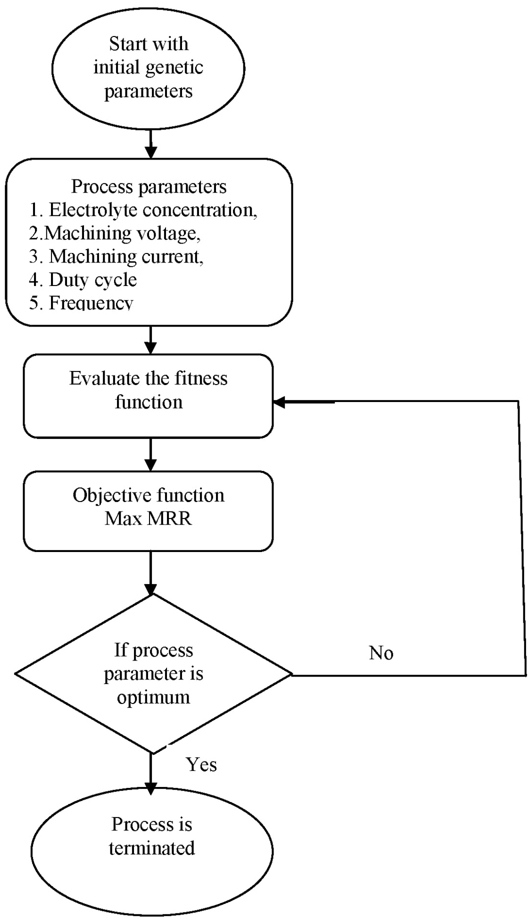

Figure 2: Modified genetic algorithm

3 RESULTS AND DISCUSSION

3.1 Experimentation

In this study, the specimen was made of 50 mm × 25 mm × 0.15 mm Ni. The tool electrode was made of brass with a diameter of 250 µm. The sidewalls of the tool electrode were coated with bonding liquid. The electrolyte used for the experiments was fresh HCL solution. Variable rectangular DC pulsed supply has been used for the experimentations. The experimental combinations of machining parameters were given in **Table 2**. During the experiments, pulse rectifier was switched on and the desired values of voltage, current, duty cycle and frequency are set before machining. The parameter levels set as per Taguchi L_{18} orthogonal array.[19] The interactions between the machining parameters were neglected in this study. The experiment with each combination of parameter level was repeated for three times to eliminate the random variations in the experimental results.

Table 2: Input parameters of orthogonal array and *MRR*

Exp. No	Inputs					Output
	(A)	(B)	(C)	(D)	(E)	(F)
1	0.1	3.5	0.1	33.33	30	0.001632
2	0.1	5	0.3	50	40	0.002123
3	0.1	6.5	0.5	66.66	50	0.006307
4	0.2	3.5	0.1	50	40	0.001839
5	0.2	5	0.3	66.66	50	0.004033
6	0.2	6.5	0.5	33.33	30	0.006703
7	0.3	3.5	0.3	33.33	50	0.002874
8	0.3	5	0.5	50	30	0.009577
9	0.3	6.5	0.1	66.66	40	0.003226
10	0.1	3.5	0.5	66.66	40	0.003724
11	0.1	5	0.1	33.33	50	0.001369
12	0.1	6.5	0.3	50	30	0.004675
13	0.2	3.5	0.3	66.66	30	0.004807
14	0.2	5	0.5	33.33	40	0.004402
15	0.2	6.5	0.1	50	50	0.00188
16	0.3	3.5	0.5	50	50	0.003931
17	0.3	5	0.1	66.66	30	0.003393
18	0.3	6.5	0.3	33.33	40	0.006546

A. Electrolyte concentration (mol/lit.); B. Machining voltage (volts); C. Machining current, (amp); D. Duty cycle (%); E. Frequency (Hz); F. *MRR* (mm^3/min).

Table 3: Ranking of Parameters, S/N Ratio (Delta)

Level	A	B	C	D	E
1	0.0033	0.0031	0.0022	0.0039	0.0051
2	0.0039	0.0041	0.0041	0.0040	0.0036
3	0.0049	0.0048	0.0057	0.0042	0.0033
Delta	0.0016	0.0017	0.0035	0.0003	0.0017
Rank	4	2	1	5	3

The *MRR* was determined by calculating the volume of material removed per unit time (mm^3/min). The average *MRR* calculated from each combination of parameter levels were tabulated in **Table 2**. Using Minitab software[22] *S/N* response table was created for larger was the better. The average value of *S/N* ratio (delta) for each combination parameter level used in experiments as given in **Table 3**. As inferred from **Table 3** the current is ranked as the most influencing process parameter, which was followed by voltage, frequency, electrolyte concentration and duty cycle.

3.2 Analysis of variance (ANOVA)

The ANOVA was performed to predict the statistical significance of the process parameters using Minitab software. It helps to determine the contribution of the individual input parameter on *MRR*. The result of ANOVA is presented in **Table 4**.

Table 4: ANOVA for *MRR*, using adjusted SS for tests

Source	DOF	Seq SS	Adj SS	Adj MS	F	P	#%
A	2	0.000008	0.000008	0.000004	2.18	0.18	10.12
B	2	9.3E-06	9.30E-06	4.70E-06	2.55	0.14	11.67
C	2	0.000042	0.000038	0.000019	10.37	0.00	53.14
D	2	0.000003	3.00E-07	2.00E-07	0.09	0.91	3.69
E	2	1.05E-05	1.05E-05	5.30E-06	2.88	0.12	13.28
Error	7	6.4E-06	1.28E-05	1.80E-06			8.10
Total	17	0.000079					100

Based on the results presented in **Table 4**, current is found to be the most influencing parameter, with a 53.14 % contribution to *MRR*, followed by frequency (13.28 %) and voltage (11.67 %). The main effects plot generated by Minitab software is shown in **Figure 3**. It can be inferred that a higher *MRR* could be obtained when the current and voltage are at higher levels.

3.3 Implementation of genetic algorithm

The *MRR* was maximized by optimizing the process parameters using Gas.[20, 21] The Minitab software was used to model the relationship between the input parameters and *MRR* using experimental results as input.[22] The objective function obtained from the software is,

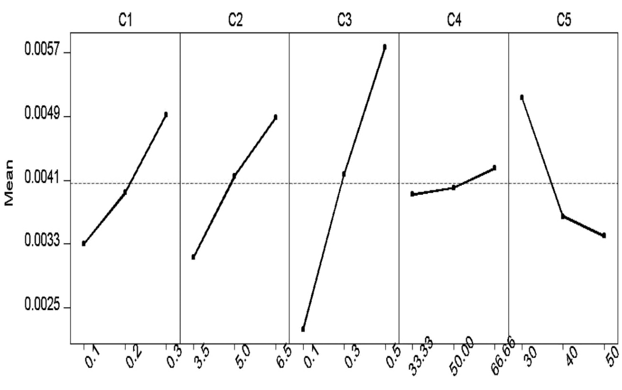

Figure 3: Main effects plot generated by Minitab software

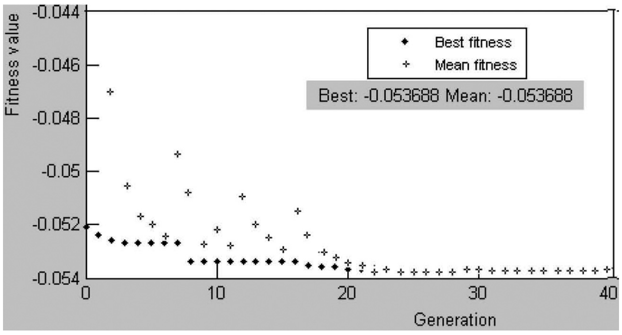

Figure 4: Convergence of GA result for 40 generations

$$MRR = -\,0.00018 + 0.00810EC + 0.000585C + 0.00888V + 0.000010DC - 0.000087F \quad (7)$$

Subject to the constraints,

Electrolyte concentration (EC): $0.1 \leq EC \leq 0.3$

Machining current (C): $0.1 \leq C \leq 0.3$

Machining voltage (V): $3.5 \leq V \leq 6.5$

Duty cycle (DC): $33.33 \leq DC \leq 66.66$

Frequency (F): $30 \leq F \leq 50$

The constrained optimization problem was solved using GAs module available Minitab software.[22] The GAs parameters used in this optimization problem are:

Population size = 100

Length of chromosome = 20

Selection operator = stochastic uniform

Crossover probability = 0.8

Mutation probability = 0.2

Fitness parameter = *MRR*

The optimized process parameters obtained for the maximum *MRR* is given in **Table 5**. **Figure 4** shows the reduction of fitness value as the number of generation increases. It shows that as the generation progresses the solutions are approaching optimum. A validation experiment was conducted using optimum process parameters. The *MRR* obtained from both the optimization process and validation experiments were given in **Table 5**. It was observed that the *MRR* obtained from validation experiment was closer to the optimized *MRR* obtained using GAs (2.9 %). This study demonstrates the practical applicability of the combined use of the Taguchi methodology and GAs for optimizing the ECMM process parameters to obtain the maximum *MRR*. **Figure 5** shows the optical microscope image of the machined micro hole.

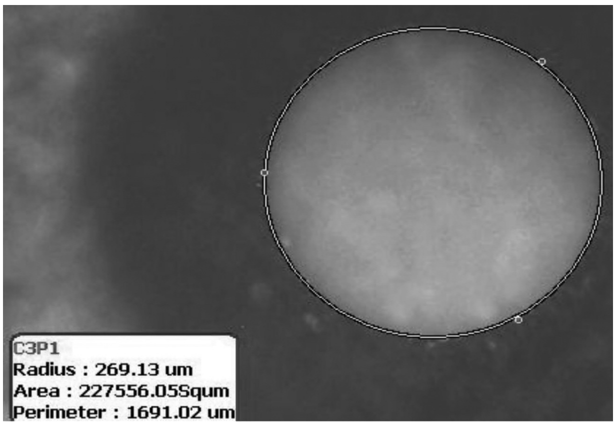

Figure 5: Optical microscope image of machined micro hole

Table 5: Optimized results

	(A)	(B)	(C)	(D)	(E)	(F)
GA	0.25	6.49	0.29	63.34	30.00	0.05
EV	0.25	6.50	0.30	66.66	30.00	0.05

GA-genetic algorithm, EV-experimental values

4 CONCLUSIONS

In this paper the Taguchi methodology and GAs were used together to optimize the ECMM process parameters for Ni machining. The Taguchi L_{18} orthogonal array was used and the statistical significance of the machining process parameters has been determined by ANOVA. The percentage contributions of the individual parameters on *MRR* have been found. The machining current makes the highest contribution (53.6 %) to *MRR*, followed by frequency (13.29 %) and voltage (11.72 %). The optimization of the process parameters has been carried out using GAs. The optimized value of electrolyte concentration, voltage, current, duty cycle and frequency on *MRR* are: 0.25 (mol/L), 6.49 (volts), 0.29 (amp), 63.34 (%), 30.00 (Hz). The maximum *MRR* obtained using the optimized process parameters is 0.05mm^3/min. The coherence between theoretically optimized values and the experimentally obtained values ensures the scope for using GAs to optimize the ECMM process parameters.

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