

Multi performance optimization of electrochemical micro-machining process surface related parameters on machining Inconel 718 using Taguchi-grey relational analysis

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Due to several merits such as higher machining rate and high machining accuracy, electrochemical micromachining (ECMM) is used to machine high strength materials with complex shapes. In this experimental investigation, Inconel 718 specimens have been machined with brass electrode of 500 μm diameter using ECMM. Since electrochemical micromachining involves many responses, Taguchi method along cannot give to find out unique optimum parameter combination of the ECMM process. Therefore, an attempt has been made in the present study to identify the optimum combination of process parameter using grey relational analysis with Taguchi method. The experimental investigation of the process has been conducted with input process parameters such as applied voltage, electrolyte concentration, micro-tool feed rate and duty ratio on material removal rate (MRR), surface roughness (SR) and overcut (OC) with different process level using two electrolytes such as sodium chloride (NaCl) and sodium nitrate (NaNO₃). From the experimental results, it has been found that micro-tool feed rate is most influencing nature parameter for NaCl and applied voltage is most influencing nature parameter for NaNO₃ in ECMM process.

KEYWORDS: BRASS TOOL - ELECTROLYTE - TAGUCHI - GREY RELATIONAL ANALYSIS

INTRODUCTION

In the present scenario, the amount of using difficult-to-machine materials is being increased considerably such Inconel alloy, Titanium alloy etc. Inconel 718 is a family of nickel-based super

alloy which can able to retain their strength even after continuous exposure to high temperature. It is high strength, temperature resistant, corrosive resistance alloy with better welding characteristics. Owing its good tensile, fatigue, creep, and rupture strength, Inconel 718 alloy has wide range of applications such as components for liquid fueled rockets, rings, casings, various formed sheet metal parts for aircraft, land-based gas turbine engines, and cryogenic tankage[1]. Since Inconel 718 alloy has high toughness and high hardness, it is very difficult to machine such material using conventional machining process. Hence it is very essential to introduce unconventional machining processes. ECMM (Electro chemical micro machining) is one among such process, in which the material removal is happened due to the chemical energy [2-3]. Many problems such as higher surface roughness, heat affected zone and thermal stress are being happened while machining process such difficult-to-machine materials using conventional machining processes [4-6]. Owing to high tool wear and tool breakage, the conventional drilling process is unsuitable for performing micro-hole with a high aspect ratio in super alloys. Hence it is very essential to introduce unconventional machining process to machine hard materials. Non-conventional processes can be categorized as mechanical

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energy based process, thermal energy-based process, chemical energy-based process and electrochemical energy-based process. The main advantage of Electrochemical Machining (ECM) is high material removal rate, less heat affected zone, less tool wear and stress free workpiece specimens with fine surface finish. Due to these merits, ECM has been widely used in the production of turbine blades, high compression engines, artillery projectiles and parts for electronics and medical industries [7].

The material removal mechanism in electrochemical machining (ECM) process is based on an anodic dissolution during electrolysis. The principle of ECM is related to the work of Faraday i.e. if two electrolytic cell (workpiece as anode and micro-tool as cathode) are immersed in an electrolyte and supplied with a DC source, metal particles are removed from the anode and then deposited on the cathode. It has also been known that if the electrolyte is made to flow over the cathode at sufficient rate, it will flush them from the machining area instead of depositing on the cathode. Electrolytic action is responsible for the removal of metal ion. The shape of workpiece obtained after machining is always similar to the shape and size of tool and also based on the feed rate. The amount of material removed from workpiece is determined by the applied current density and the distance between workpiece and tool [8]. Since the process is stochastic in nature, it is very essential to discuss the influence of process parameters on performance measures to enhance the machining process in ECMM. The surface roughness of the machined workpiece can be reduced considerably by doing micro machining using ECM. While reviewing the literatures, it has been found that only little attention has been given on analyzing the influence of process parameters on machining Inconel alloy using ECM process in micro level based material removal rate. It is also important to find the optimum parameters combination in any machining process. Hence the present experimental investigation has been carried out to find influence of the process parameters and optimum combination for multiple performance measures using Taguchi-Grey analysis in ECMM process.

EXPERIMENTS AND METHODS

In the present study, an experimental investigation has been carried out to derive the optimal process parameters in ECMM process. Due to its inherent properties and importance in manufacturing industries, Inconel 718 alloy has been utilized as workpiece specimens in the present study with the dimension of 5 mm x 5 mm x 0.4 mm.

The micro tools which used for machining has been made up of brass with the diameter of 500µm. The micro tool has been insulated and coated with epoxy (Araldite AV 138 and Hardener HV 998) by spray epoxy coating for avoiding over cut in ECMM process. A fresh aqueous solution of sodium chloride (NaCl) and sodium nitrate (NaNO₃) has been chosen as an electrolyte for experiments conducted. The variable rectangular pulsed DC power supply has been chosen for applying electrical energy with variable pulse on and off time.

Material removal rate (MRR), surface roughness (SR) and overcut (OC) have been taken as performance measures in the present study owing to their predominant nature of ECMM process. Applied voltage (AV), electrolyte concentration (EC), micro-tool feed (MFR) and duty cycle (DC) have been considered as the input process parameters in ECMM process [9]. The process variables for applied voltage (AV), electrolyte concentration (EC), micro-tool feed rate (MFR) and duty cycle (DC) have been chosen as 8V, 9V, 10V ; 20g/l, 25g/l, 30g/l; 0.1 µm/s, 0.5µm/s, 1.0µm/s; 33%, 50%, 66% respectively. The weights of the specimens have been measured using electronic balance type aux 220. The micro tool and workpiece has been connected with negative and positive terminal of power supply respectively. The electrolyte has been flushed at a rate of 1 m/s over the electrodes side. Blind hole drilling of 25 mm depth has been done in all the experiments. The time taken for machining a hole has been computed using an electronic timer. The material removed rate has been calculated using the following Eq.1.:

$$MRR = \frac{\text{Initial weight of workpiece} - \text{Final weight of workpiece}}{\text{Machining time}} \quad (1)$$

Tab. 1 - Orthogonal array I₉ for responses

| S.NO. | AV (V) | EC (g/l) | MFR (µm/s) | DC (%) | Material removal rate (mm ³ /min) | | Surface roughness (µm) | | Overcut (µm) | |
|-------|--------|----------|------------|--------|--|-------------------|------------------------|-------------------|--------------|-------------------|
| | | | | | NaCl | NaNO ₃ | NaCl | NaNO ₃ | NaCl | NaNO ₃ |
| 1 | 8 | 20 | 0.1 | 33 | 0.022839 | 0.0214065 | 4.040 | 3.930 | 372.356 | 112.642 |
| 2 | 8 | 25 | 0.5 | 50 | 0.052409 | 0.0167397 | 2.820 | 1.930 | 302.934 | 146.502 |
| 3 | 8 | 30 | 1.0 | 66 | 0.084867 | 0.0102724 | 1.080 | 0.831 | 248.583 | 186.614 |
| 4 | 9 | 20 | 0.5 | 66 | 0.064464 | 0.0147514 | 2.930 | 2.750 | 308.422 | 156.505 |
| 5 | 9 | 25 | 1.0 | 33 | 0.079542 | 0.0789623 | 0.808 | 1.460 | 256.428 | 128.268 |
| 6 | 9 | 30 | 0.1 | 50 | 0.101355 | 0.0538920 | 3.360 | 0.535 | 338.424 | 188.614 |
| 7 | 10 | 20 | 1.0 | 50 | 0.069732 | 0.0557147 | 0.873 | 2.040 | 258.326 | 162.834 |
| 8 | 10 | 25 | 0.1 | 66 | 0.087057 | 0.0429439 | 3.510 | 1.060 | 364.728 | 226.575 |
| 9 | 10 | 30 | 0.5 | 33 | 0.119500 | 0.0984378 | 1.060 | 0.677 | 272.834 | 182.822 |

The surface finish has been measured in terms of roughness (μm) using TALYSURF CCI LITE non-contact surface roughness tester fitted with a small hole detector probe attachment to measure surface roughness inside the small holes. Overcut is the difference between the radius of the machined hole and the radius of the micro-tool. Since the shape of the machined hole may not be a perfect circle, the average radius of the machined hole has been considered for calculating the overcut. As the entry hole radius was found to be the larger compared to the exit hole radius, the entry hole has been considered for the overcut measurements. Using VMS, twelve points were located on the circumference of the hole to obtain the average radius of the entry hole. The surface topography of the machined hole in the workpiece specimens has been analyzed using micro graphs taken by scanning electron microscope (SEM). The influence of the parameters on performance measures has been analyzed using main effect plots obtained by Minitab software package.

TAGUCHI METHOD

In the present section, the design of experiments along with selection of quality characteristics level of process parameters in ECMM process has been discussed.

DESIGN OF EXPERIMENTS

Taguchi method is an effective tool for designing and conducting experiments in quality manufacturing system owing to its simplicity and ease applicability. Taguchi method can be utilized for optimizing the process variables in any process. This method provides the minimum number of experimentations that needed to be carried out for deriving optimum results. The least number of experiment can be calculated as per following Eq. 2

$$\text{DOF} = (L-1)(F) + (L-1)^2(Q) + 1 \text{ for the average} \quad (2)$$

where DOF is degree of freedom, F is number of independent variables, L is their levels, and Q is number of interactions. The number of trials should be greater than or equal to DOF for conducting experiments in any process. Since four input process parameters and with three levels have been taken without no considerations of interactions among process parameters, L_9 orthogonal array has been chosen based on Taguchi based design of experiments for conducting machining process[6].

SELECTION OF QUALITY CHARACTERISTICS LEVEL

The response of the each experiment has to be converted into S/N ratio to measure the quality characteristics which causes error from the desired value. The term signal indicates the desirable mean value of the output characteristics and the term noise indicates the undesirable value of the output characteristics. Since maximum MRR has been needed, larger the better type of quality characteristics has been selected for material removal rate[10]. Hence the S/N ratio for this response has been computed from the following Eq. 3

$$\text{S/N ratio} = -10 * \log (1/m) \sum (1/N_{ik}^2) \quad (3)$$

Surface roughness (SR) and Overcut (OC) are smaller the better type and their S/N ratios have been computed from the following Eq. 4

$$\text{S/N ratio} = -10 * \log (1/m) \sum N_{ik}^2 \quad (4)$$

where m is number of experimental replication and N_{ik} is response of i_{th} trial of K_{th} dependent level.

GREY RELATIONAL APPROACH

In the present study, the multiple performance characteristics have been investigated with grey relational approach. In this method, the multiple performance characteristics can be converted into single grey relational grade [10]. The following stages are done for this approach.

Stage 1:

The S/N ratios obtained from the Taguchi analysis have to be normalized in the range of 0 to 1 as per Eq. 5 and Eq. 6

For larger the better,

$$X_{ik} = (Y_{ik} - \min(Y_{ik})) / (\max(Y_{ik}) - \min(Y_{ik})) \quad (5)$$

For smaller the better,

$$X_{ik} = (\max(Y_{ik}) - Y_{ik}) / (\max(Y_{ik}) - \min(Y_{ik})) \quad (6)$$

Where X_{ik} is normalized S/N ratio, Y_{ik} is the S/N ratio obtained from the Taguchi analysis, $\min(Y_{ik})$ and $\max(Y_{ik})$ are respectively minimum and maximum values of S/N ratio.

Stage 2:

Grey relational grade in this analysis indicates the relational degree between every sequences of obtained values. The grey relational coefficient can be calculated as

$$GC_{ik} = (\Delta_{\min} + \Psi\Delta_{\max}) / (\Delta_{ik} + \Psi\Delta_{\max}) \quad (5)$$

Where GC_{ik} is the grey relational grade. Since multi response characteristics consist of both larger the better and smaller the better, Ψ is assumed to 0.5 in this case. Δ_{\min} and Δ_{\max} are the minimum and maximum absolute difference which is a deviation from target value and can be treated as quality loss.

Stage 3:

After averaging the grey relational coefficients, grey relational grade (G_i) can be calculated as

$$G_i = (1/m) \sum GC_{ik} \quad (6)$$

Where m is the number of response variables. The high value of grey relational grade indicates the stronger relational degree between ideal sequence and present sequence. Ideal sequence is the best response in the machining process. Higher grey grade indicates closer to the optimal response in the process[11].

Tab. 2. - S/N ratio with their normalized value for responses.

| S. No. | SODIUM CHLORIDE (NaCl) | | | | | | SODIUM NITRATE (NaNO ₃) | | | | | |
|--------|----------------------------|-------|---------------------|-------|---------|-------|-------------------------------------|-------|---------------------|-------|---------|-------|
| | MRR (mm ³ /min) | | R _a (μm) | | OC(μm) | | MRR (mm ³ /min) | | R _a (μm) | | OC(μm) | |
| | X1 | X2 | X1 | X2 | X1 | X2 | X1 | X2 | X1 | X2 | X1 | X2 |
| 1 | -32.826 | 0 | -12.127 | 1 | -51.419 | 1 | -33.389 | 0.324 | -11.887 | 1 | -41.034 | 0 |
| 2 | -25.611 | 0.501 | -9.004 | 0.776 | -49.627 | 0.489 | -35.525 | 0.216 | -5.711 | 0.643 | -43.316 | 0.376 |
| 3 | -21.425 | 0.793 | -0.668 | 0.180 | -47.909 | 0 | -39.766 | 0 | -1.607 | 0.220 | -45.418 | 0.722 |
| 4 | -23.813 | 0.627 | -9.337 | 0.800 | -49.782 | 0.533 | -36.623 | 0.160 | -8.786 | 0.820 | -43.890 | 0.470 |
| 5 | -21.988 | 0.754 | -1.851 | 0 | -48.719 | 0.076 | -22.051 | 0.902 | -3.287 | 0.503 | -42.162 | 0.185 |
| 6 | -19.883 | 0.900 | -10.526 | 0.885 | -50.589 | 0.763 | -25.369 | 0.733 | -5.432 | 0 | -45.511 | 0.737 |
| 7 | -23.131 | 0.674 | -1.179 | 0.048 | -48.243 | 0.095 | -25.080 | 0.748 | -6.192 | 0.671 | -44.234 | 0.527 |
| 8 | -21.203 | 0.808 | -10.906 | 0.912 | -51.239 | 0.948 | -27.342 | 0.632 | -0.506 | 0.342 | -47.104 | 1 |
| 9 | -18.452 | 1 | -0.506 | 0.168 | -48.718 | 0.230 | -20.136 | 1 | -3.388 | 0.118 | -45.240 | 0.692 |

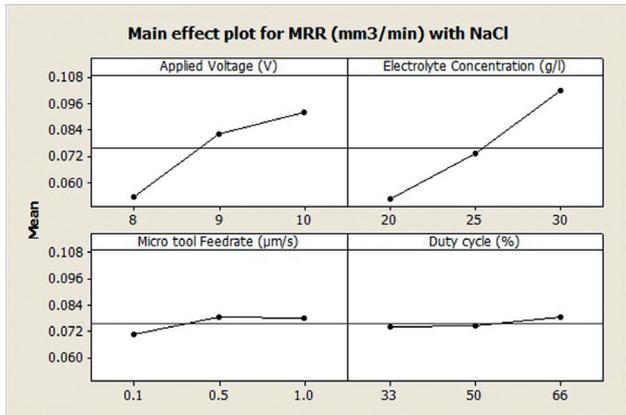
X₁ – S/N ratio, X₂ – Normalized S/N ratio

Tab. 3 - Grey relational co-efficient with their grade and rank.

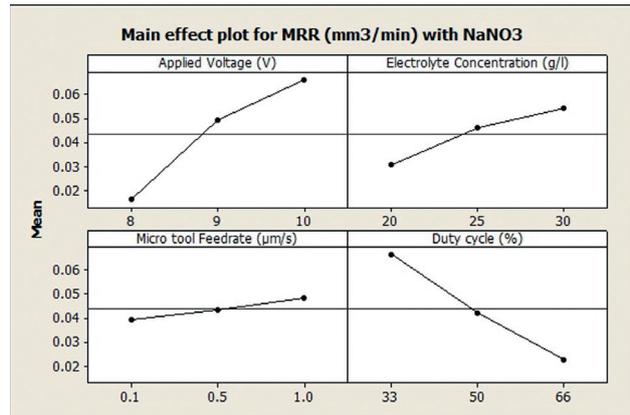
| S. No. | Grey relational co-efficient | | | | | | Grey relational grade | | Rank | |
|--------|------------------------------|----------|----------|-------------------|----------|----------|-----------------------|-------------------|------|-------------------|
| | NaCl | | | NaNO ₃ | | | NaCl | NaNO ₃ | NaCl | NaNO ₃ |
| | MRR | SR | OC | MRR | SR | OC | | | | |
| 1 | 1 | 0.333333 | 0.333333 | 0.606143 | 0.333333 | 1 | 0.555556 | 0.646492 | 5 | 2 |
| 2 | 0.499039 | 0.391658 | 0.505376 | 0.698251 | 0.437295 | 0.570727 | 0.465358 | 0.568758 | 6 | 4 |
| 3 | 0.386639 | 0.734988 | 1 | 1 | 0.693645 | 0.409046 | 0.707209 | 0.700897 | 3 | 1 |
| 4 | 0.443644 | 0.384497 | 0.483655 | 0.757432 | 0.378514 | 0.515154 | 0.437265 | 0.550367 | 7 | 5 |
| 5 | 0.398712 | 1 | 0.866709 | 0.356518 | 0.498286 | 0.728986 | 0.755141 | 0.52793 | 1 | 6 |
| 6 | 0.35702 | 0.360884 | 0.395716 | 0.405374 | 1 | 0.404004 | 0.371207 | 0.603126 | 8 | 3 |
| 7 | 0.425714 | 0.912284 | 0.840131 | 0.400594 | 0.426916 | 0.486708 | 0.726043 | 0.438073 | 2 | 9 |
| 8 | 0.38209 | 0.353952 | 0.345119 | 0.441328 | 0.5932 | 0.333333 | 0.360387 | 0.455954 | 9 | 8 |
| 9 | 0.333333 | 0.747754 | 0.684584 | 0.333333 | 0.808998 | 0.419118 | 0.588557 | 0.520483 | 4 | 7 |

Tab. 4 - Average grey relational grade for each input parameters.

| Factor Notation | Control Factor | Average grey relational grade | | | | | | Max-Min | |
|--|---------------------------------|-------------------------------|---------|--|-------------------------------------|---------|---------|---------|-------------------|
| | | Sodium Chloride(NaCl) | | | Sodium Nitrate (NaNO ₃) | | | NaCl | NaNO ₃ |
| | | Level 1 | Level 2 | Level 3 | Level 1 | Level 2 | Level 3 | | |
| V | Applied Voltage (V) | 0.57604 | 0.52120 | 0.55833 | 0.63872 | 0.56047 | 0.47150 | 0.0548 | 0.1672 |
| E.C | Electrolyte Concentration (g/l) | 0.57295 | 0.52696 | 0.55565 | 0.54497 | 0.51754 | 0.60816 | 0.0459 | 0.0906 |
| MFR | Micro-Tool Feed Rate (μm/min) | 0.42905 | 0.49706 | 0.72946 | 0.56852 | 0.54653 | 0.55563 | 0.3004 | 0.0122 |
| D.C | Duty Cycle (%) | 0.63308 | 0.52086 | 0.50162 | 0.56496 | 0.53665 | 0.56907 | 0.1315 | 0.0324 |
| Total mean grey relational grade (NaCl) = 0.5519 | | | | Total mean grey relational grade (NaNO ₃) = 0.5569 | | | | | |

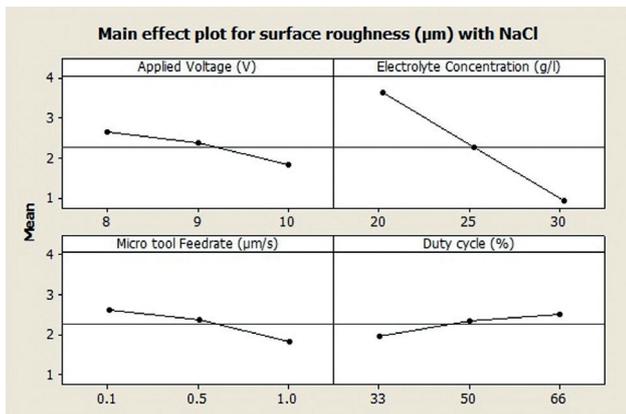


(a)

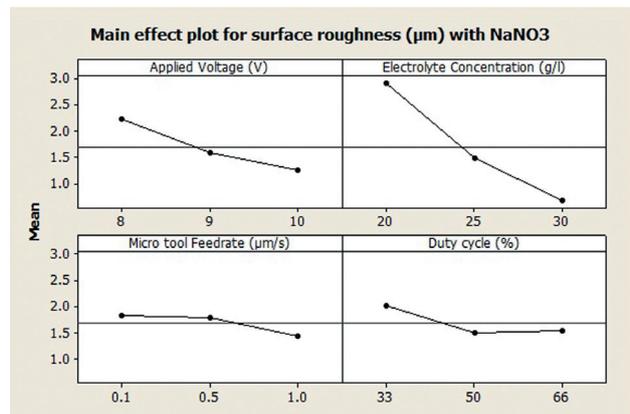


(b)

Fig. 1 - Influence of process parameters on material removal rate a) NaCl and b) NaNO₃

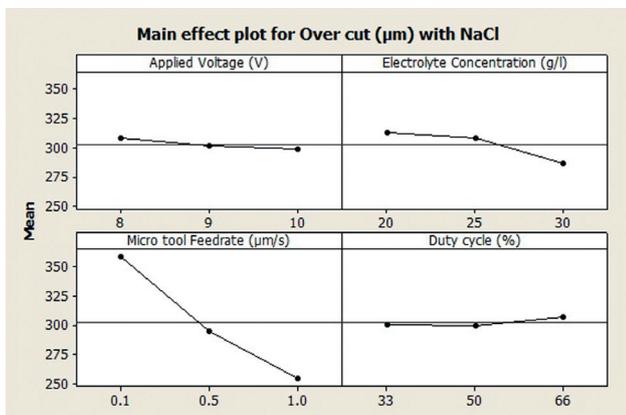


(a)

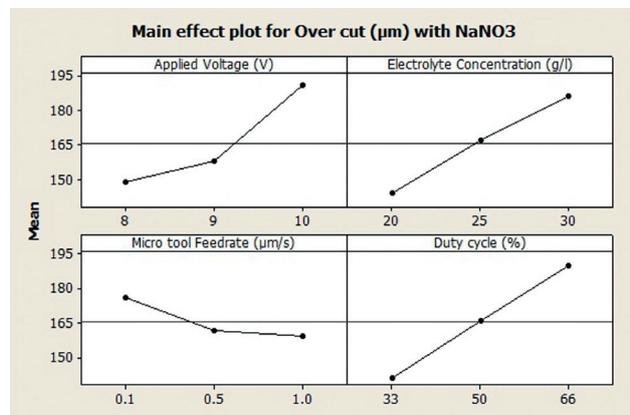


(b)

Fig. 2 - Influence of process parameters on surface roughness a) NaCl and b) NaNO₃



(a)



(b)

Fig. 3 - Influence of process parameters on overcut a) NaCl and b) NaNO₃

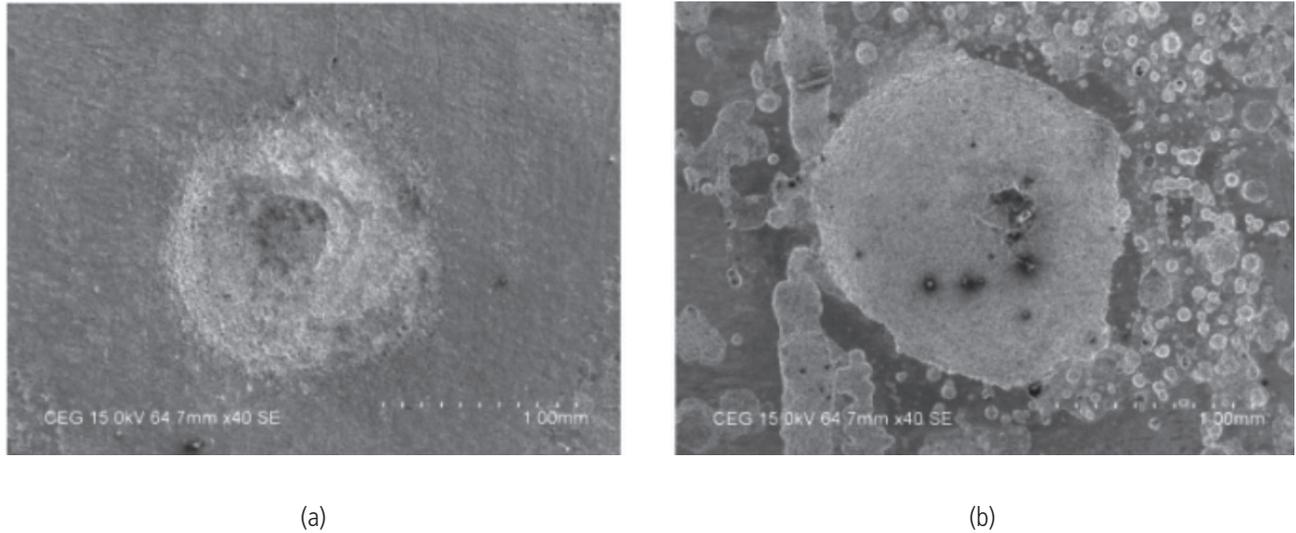


Fig. 4 - Microscopic image of brass tool (a) NaNO_3 and (b) NaCl

RESULTS AND DISCUSSION

In the present section, the obtained experimental results while machining the workpiece specimens has been discussed and analyzed. The optimal parameters combination of process parameters and influence of such parameters on performance measures has also been discussed in this section. Table 1 shows the experimental results on machining Inconel 718 alloy using ECMM process as per Taguchi design of experiments.

EFFECT OF PROCESS PARAMETERS ON MRR

Figure 1 shows the influence of the process parameters on MRR of ECMM process using main effect plot. In the main effect plot, the deviation from horizontal line indicates the more influence of process parameter on response variables. From the Figure 1, it has been clearly understood that applied voltage and electrolyte concentration has more influential nature on MRR. As per the Faraday's laws, it has been stated that the amount of material removal is directly proportional to the applied current. The current developed is mostly influenced by the applied voltage and electrolyte concentration. Inter-Electrode Gap (IEG) is not constant throughout the process so that the polarization voltage in-between the gap varies causes non-linearity. In order to get linear variation, IEG always should be less than 0.1 mm for Electrochemical Micro-Machining (ECMM) [12]. The overall machining characteristic shows that higher MRR is observed in NaCl electrolyte when compared to NaNO_3 electrolyte. NaCl is an aggressive electrolyte which causes metal ion to move free therefore more amount of material has been removed. Hence NaCl gives high MRR.

EFFECT OF PROCESS PARAMETERS ON SR

Figure 2 shows the influence of the process parameters on SR of ECMM process using main effect plot. From the Figure, it has been clearly understood that electrolyte concentration has more influential nature on SR. It has been cleared that SR decreases with increase in voltage, micro-tool feed rate and electrolyte concentration. The current density increases which causes stray current to minimize. This effect causes in decreasing the surface roughness. The pulse on time has increased material removal which has also resulted in higher surface roughness. The improper selection of duty factor

causes uneven or irregular surface finish which results in higher surface roughness. The higher surface finish has been observed while utilizing NaNO_3 as electrolyte when compared to NaCl electrolyte. NaNO_3 is a passive electrolyte which forms an oxide layer over the workpiece. It reduces the surface roughness which results in better surface finish.

EFFECT OF PROCESS PARAMETERS ON OC

Figure 3 shows the influence of the process parameters on OC of ECMM process using main effect plot. From the Figure, it has been clearly understood that all the process parameter has considerable amount influential nature on OC.

From the Figure 3, it has been observed that overcut has been decreased with increasing in applied voltage, electrolyte concentration and micro-tool feed rate while using NaCl as electrolyte. The electrolyte concentration has resulted in breakage of Na and Cl bond. This has needed more voltage which has resulted in current density. This has decreased slightly which has caused decrease in stray current. Hence there is no larger variation observed in Figure. From Figure, it has been cleared that overcut has been increased with the increase of voltage, electrolyte concentration and micro-tool feed rate. The increase of stray current flow has resulted in higher overcut. The hydrogen bubble has been broken easily during the electrolysis at higher voltage. It has resulted in the event of micro-sparking. Once micro-spark has been obtained while machining, then more material has been removed. Hence larger variation has been seen in higher voltage and electrolyte concentration. The lower overcut has been observed in NaNO_3 electrolyte concentration while compared to NaCl . The bond strength between Na and NO_3 has been high therefore higher current density has needed to break that bond thus has avoided free movement of metal ion.

SURFACE TOPOGRAPHY ANALYSIS

Figure 4 shows the surface topography of machined Inconel 718 alloy specimens using SEM. From the Figure, it has been observed overcut has been more in ECMM process. Since all the process parameter has considerable amount influential nature on OC, the higher overcut has been observed. The overcut has been reduced by doing machining

process with optimal process parameter combination. From the Fig.4 t has been well known that NaCl electrolyte has produced poor machining shape of machined specimens due to aggressive nature of ions. Whereas the machining accuracy has been better while utilizing sodium nitrate (NaNO_3) as electrolyte.

GREY RELATIONAL ANALYSIS

S/N ratio and grey relational grade

Table 2 displays the signal to noise ratio with their normalized value for various responses. MRR has been assumed to be larger the better whereas SR and OC has been chosen as smaller the better. The present investigation has been involved with both the quality characteristics, the co-efficient of distinguish has been considered to be 0.5 [10]. Table 3 shows the grey relational coefficient and grey grade for each response. The multi-response characteristics have been converted into single-response characteristics. The higher grey grade experimental value has give the better machining parameter i.e. 5th and 3rd experiment has produced the unique optimum solution with NaCl and NaNO_3 as electrolyte respectively. Table 4 shows the average of grade scale for all the factor level of input parameters.

Identification of significant process parameter

The average grey grade has been calculated by taking the average of grey grade for each corresponding factor level in the L_9 orthogonal array. The highest average grey relational level value indicates the optimum value for each parameter in the process [13]. The better optimal value of process parameters for NaCl has been observed as level 1 (applied voltage), level 1 (electrolyte concentration), level 3 (micro-tool feed rate) and level 1 (duty factor). Whereas the optimal combination has been found as level 1 (applied voltage), level 3 (electrolyte concentration), level 1 (micro-tool feed rate) and level 3 (duty factor) for NaNO_3 as electrolyte. The max–min indicated the level of most influencing nature among the input parameters on determining the machining characteristics [14]. It has noted that the micro-tool feed rate has most influent nature parameter for NaCl; whereas applied voltage has most influencing parameter for NaNO_3 .

CONCLUSION

In the present study, an experimental investigation has been carried out to find influence of process parameters on machining Inconel 718 alloy specimens. It has also been attempted to find the optimum combination of process parameters using Taguchi-grey methodology. From the experimental results and analysis, the following conclusions have been made.

- The micro-tool feed rate is the most influencing parameter for NaCl electrolyte; Applied voltage is the most influencing factor For NaNO_3 electrolyte.
- NaCl electrolyte can produce higher MRR whereas NaNO_3 can produce higher surface finish.
- The optimal parameters has been found for existing process variable levels as follows:
- NaCl: voltage = 9 V, electrolyte concentration = 25 g/l, feed rate = 1.0 $\mu\text{m}/\text{min}$ and duty ratio = 33 %
- NaNO_3 :voltage=8V,electrolyte concentration = 30 g/l, feed rate = 1.0 $\mu\text{m}/\text{min}$ and duty ratio = 66 %

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