Experimental Investigation of MRR on Inconel 600 using Ultrasonic Assisted Pulse Electrochemical Machining

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Abstract. The non-traditional machining processes are commonly used for the materials which are hard and difficult to cut by conventional machining processes. One of the most commonly used non-conventional machining processes is electro chemical machining process. Electrochemical machining (ECM) is a modern machining process that relies on the removal of workpiece atoms by electrochemical dissolution (ECD) in accordance with the principles of Faraday. In electro chemical machining process, the tool and work piece don’t have any physical contact, resulting in negligible tool wear. Electrolyte in the process, which carries the current from the work piece to tool, removes the work piece material and generates the sludge. The electrolyte carries the sludge out of machining zone. Experiments are performed on developed setup to obtain optimized parameters of USAPEC for the maximum MRR and minimum overcut. The influence of 5 parameters specifically Voltage, Pulse on time, ultrasonic on time, ultrasonic off time and amplitude of vibration on MRR and overcut are studied. The experiments are conducted based on Taguchi technique with L²⁷ orthogonal array.

Keywords: Inconel 600, Taguchi, USAPEC, MRR

1. Introduction
All traditional methods of mechanical machining such as turning, milling and drilling etc. are usually carried out using the principal that tool of very hard material (e.g. Diamond) is used to remove the material from the work piece (soft material). During this process the tool has been continuously wear out or it get completely destruct due to extensive usage [1].

Due to the advancement in the technology use of high strength, hardened and heat resistance material increases tremendously in various application of automobile, aviation and space research technology. The requirement of tool material properties become nearly impossible to fulfill. As a consequence, Advanced Machining Technology (AMT) of metal removal has been investigated and developed.

Most offend used AMT’s are: Electrical Discharge Machining (EDM), Laser Beam Machining (LBM) and Electrochemical Machining (ECM). EDM and LBM are the thermal processes, where the material is removed by using high thermal energy to melt the material (i.e. creating electric spark in EDM and Laser in LBM). In these processes also there is no direct contact between
Workpiece (w/p) and tool. EDM and LBM create heat affected zones, residual stresses and surface cracks in the w/p [2].

Electrochemical machining is one of the AMT’s methods. The material is removed atom-by-atom by the controlled anodic dissolution process. Electrochemical Machining (ECM) is a high rate electrolysis process involving time dependent shape change of the workpiece (w/p). ECM found to be important technology in machining difficult to cut materials and to shape complicated contours [3]. Material is removed due to anodic dissolution as there is no direct contact between w/p and tool. ECM posses several advantages such as: no tool wear, w/p is not subjected to structural and thermal stresses, non rigid and open w/p can be produced, complicated geometrical shapes can be machined repeatedly and accurately, deep hole drilling or several holes at once can be made and fragile parts can also be machined using ECM [4].

In ECM current is passed through electrolyte in Inter Electrode Gap (IEG), however direction of current within the electrolyte cannot be precisely controlled or in other words it can’t be completely concentrated on the target w/p surface required to be machined. Analysis of mechanism of metal removal and analytical design of tool is complicated due to non uniform distribution of velocity of electrolyte flow, cavitation, change in valence, conductivity of electrolyte and electric field distortion [5]. Electrochemical Machining (ECM) as an anodic dissolution process has been widely used in the aerospace, automotive, defense, biomedical industries for its many advantages, such as superior machinability irrespective of material hardness, high metal removal rate without tool wear, good surface quality, ability to produce complex shapes, Stress (Thermal and Mechanical) free workpiece surface, high efficient production method [5,6,7].

2. Experimental specification

2.1. Workpiece with composition:
The experiments were conducted on INCONEL 600 alloy plate of 60*60*3mm, which has been used for applications that need high temperature resistance and corrosion. The chemical composition of INCONEL 600 alloy has been shown in Table 1.

Table 1. Chemical composition of INCONEL 600.

| Sr. No | Element | (% Chemical) | Sr. no | Element | (% Chemical) |
|-------|---------|--------------|-------|---------|--------------|
| 1     | Ni + Co | 72.0 min     | 6     | Mn      | 1.00 max     |
| 2     | Cr      | 14.0-17.0    | 7     | S       | .015 max     |
| 3     | Fe      | 0.0-10.0     | 8     | Si      | .50 max      |
| 4     | C       | 0.15max      | 9     | Cu      | .50 max      |

2.2. Experimental electrode:
Profile created on workpiece relies on tool profile. So the creation of tool is basic. The tool used in electrochemical machining should pose following properties viz; good electrical and thermal conductivity, chemically inert, corrosion resistance, good stiffness and machinability to withstand electrolyte pressure without vibration. Most common materials used for electrodes are platinum, titanium, tungsten, brass, copper alloys. Tool is comprised of copper material. Copper material is delicate and has less electrical resistivity as compared to titanium and tungsten. Due to good machinability and stiffness copper is used as tool material as brass limits this properties. To prevent undesirable overcut insulating layer is provided on the electrode.

In this experiment copper rod (100% Cu) has been used as a material for electrode because it is easy to machine it and can be die casted or extruded based on the application, hence making it the cheapest electrode material for ECM. In this experiment single hole copper tubular electrode of diameter 3 mm and length 158 mm were used as a tool.
2.3. Experimental details:
The experimental was carried out on ECM machine. The ECM setup has been shown in fig 2. Tool act as cathode while the work piece act as anode. Sodium nitrate was used as electrolyte.

For measuring the diameters of the holes optical video measuring machine was used and the equipment used for calibration was QVI Sprint MVP 250 with Measure-X software designed for fast, accurate and repeatable automatic measurements. Specifications of the machine are given in Table 2.

In the said examination 5 factors at 3 levels (i.e., $3^5$experiments), were chosen. The experimentation started with screening tests including all factors at three levels to decide the impact of each factor on machining performance. The screening experiments were conducted utilizing copper tool with pulse power supply. The factors and level combinations are specified in Table underneath

Table 2. Technical specification of experimental set-up

| Parameter                  | Value         |
|----------------------------|---------------|
| Power rating               | 3KVA          |
| Vertical tool travel       | 120mm         |
| Table travel               | 120mm         |
| Pump capacity              | 12lit/min     |
| Electrolyte tank capacity  | 175lit        |
| Machining chamber          | 25lit         |
| Workpiece material         | Ni based super alloys |
| Electrolyte                | NaNO3         |
| Tool material              | Cooper        |

Table 3. Process parameters and levels for USAPECM

| Sr. No. | Parameter            | Unit | Abbreviation | Level 1 | Level 2 | Level 3 |
|---------|----------------------|------|--------------|---------|---------|---------|
| 1       | Voltage              | Volt | A            | 16      | 18      | 20      |
| 2       | Pulse On Time        | µs   | B            | 100     | 250     | 500     |
| 3       | Ultrasonic On Time   | Sec  | C            | 2       | 3       | 4       |
| 4       | Ultrasonic Off Time  | Sec  | D            | 8       | 9       | 10      |
| 5       | Amplitude            | µ     | E            | 16      | 18      | 20      |

Fig. 1 Copper Electrode
For measuring the weight, a precision weighing machine has been used.
3. Methodology

The Taguchi method is a powerful approach that provides a simple, efficient and systematic approach to determine the optimum process parameters, which drastically reduces the number of experiments that are required to model response functions. It is a method based on orthogonal array (OA) experiments, which provide the much-reduced variance for the experiment resulting in the optimum setting of process control parameters. The selection of an efficient experimental design helps to optimize the process and determine factors that influence the variability.

The steps involved in Taguchi method are:

1) Identify the response functions and process parameters.
2) Determine the levels of process parameters and possible interactions between them.
3) Select the appropriate orthogonal array and conduct the experiment accordingly.
4) Analyze the experimental results and select the optimum level of process parameters.
5) Verify optimum process parameters through confirmation experiment.

For the present work L27 Taguchi OA was selected that was shown in Table 4. Total 27 experiments were performed using copper electrode. An electronic balance having an accuracy of 0.0001 g was used to measure the weigh work-piece after each experiment. After collecting the experiment data based on Taguchi L27 OA. The signal to noise ratios which are log function of desired output serves
as objective function for method of optimization which helps in data analysis and finding the optimal result. The optimization problems which involve selection of best levels of parameters in order to get a desired output are called as “static problem”. There are three signal-to-noise ratios of common interest for optimization of static problems: 1) Smaller-The-Better \( n = -10 \log_{10} \left[ \text{mean of sum of squares of measured data} \right] \) this is usually the chosen S/N ratio for all undesirable characteristics for which the ideal value is zero. But when the ideal value is zero, then the difference between measured data and ideal value is expected to be as small as possible. The generic form of S/N ratio becomes: \( n = -10 \log_{10} \left[ \text{mean of sum of squares of } \left( \text{measured} - \text{ideal} \right) \right] \)

2) Larger-The-Better \( n = -10 \log_{10} \left[ \text{mean of sum squares of reciprocal of measured data} \right] \) By taking the reciprocals of measured data and taking the value of S/N ratio as in smaller-the-better case, we can convert it to smaller-the-better case.

3) Nominal-The-Best \( n = 10 \log_{10} \left( \text{square of mean/ variance} \right) \) this case arises when a specified value is most desired, meaning that neither a smaller nor a larger value is desirable.

The calculation has been made to determine the performance parameters of ECM process for each set of experiment.

The value of performance parameters has been calculated by Eq. (1) and Eq. (2)

\[
\text{MRR} = \frac{\text{Initial Weight} - \text{Final Weight}}{\text{Machining Time}} \quad (1)
\]

\[
\text{Overcut} = \text{Diameter of hole produced} - \text{Diameter of the tool electrode} \quad (2)
\]

| Exp. No | A | B | C | D | E |
|---------|---|---|---|---|---|
| E1      | 1 | 1 | 1 | 1 | 1 |
| E2      | 1 | 1 | 1 | 1 | 2 |
| E3      | 1 | 1 | 1 | 1 | 3 |
| E4      | 1 | 2 | 2 | 2 | 1 |
| E5      | 1 | 2 | 2 | 2 | 2 |
| E6      | 1 | 2 | 2 | 2 | 3 |
| E7      | 1 | 3 | 3 | 3 | 1 |
| E8      | 1 | 3 | 3 | 3 | 2 |
| E9      | 1 | 3 | 3 | 3 | 3 |
| E10     | 2 | 1 | 2 | 2 | 1 |
| E11     | 2 | 1 | 2 | 3 | 2 |
| E12     | 2 | 1 | 2 | 3 | 3 |
| E13     | 2 | 2 | 3 | 1 | 1 |
| E14     | 2 | 2 | 3 | 1 | 2 |
| E15     | 2 | 2 | 3 | 1 | 3 |
| E16     | 2 | 3 | 1 | 2 | 1 |
| E17     | 2 | 3 | 1 | 2 | 2 |
| E18     | 2 | 3 | 1 | 2 | 3 |
| E19     | 3 | 1 | 3 | 2 | 1 |
| E20     | 3 | 1 | 3 | 2 | 2 |
| E21     | 3 | 1 | 3 | 2 | 3 |
| E22     | 3 | 2 | 1 | 3 | 1 |
| E23     | 3 | 2 | 1 | 3 | 2 |
| E24     | 3 | 2 | 1 | 3 | 3 |
| E25     | 3 | 3 | 2 | 1 | 1 |
| E26     | 3 | 3 | 2 | 1 | 2 |
| E27     | 3 | 3 | 2 | 1 | 3 |
4. Result and discussions

4.1. Result for MRR:

Table 5. Experimental result table for MRR

| EXPERIMENTAL RUN | Replicate 1 | Replicate 2 | Average MRR |
|-----------------|-------------|-------------|-------------|
| 1               | 0.005500    | 0.006500    | 0.006000    |
| 2               | 0.007500    | 0.005500    | 0.006500    |
| 3               | 0.008000    | 0.007500    | 0.007750    |
| 4               | 0.006500    | 0.007500    | 0.007000    |
| 5               | 0.007000    | 0.006500    | 0.006750    |
| 6               | 0.008000    | 0.006000    | 0.007000    |
| 7               | 0.007500    | 0.007500    | 0.007500    |
| 8               | 0.007000    | 0.007000    | 0.007000    |
| 9               | 0.004000    | 0.008500    | 0.006250    |
| 10              | 0.005000    | 0.008500    | 0.006750    |
| 11              | 0.005500    | 0.006000    | 0.005750    |
| 12              | 0.006000    | 0.006500    | 0.006250    |
| 13              | 0.006000    | 0.006500    | 0.006250    |
| 14              | 0.006000    | 0.007500    | 0.006750    |
| 15              | 0.004500    | 0.005000    | 0.004750    |
| 16              | 0.006000    | 0.005000    | 0.005500    |
| 17              | 0.009000    | 0.005500    | 0.007250    |
| 18              | 0.007000    | 0.006500    | 0.006750    |
| 19              | 0.006000    | 0.007000    | 0.006500    |
| 20              | 0.007000    | 0.007500    | 0.007250    |
| 21              | 0.005250    | 0.005250    | 0.005250    |
| 22              | 0.006000    | 0.007500    | 0.006750    |
| 23              | 0.006000    | 0.007000    | 0.006500    |
| 24              | 0.006500    | 0.007000    | 0.006750    |
| 25              | 0.007000    | 0.005000    | 0.006000    |
| 26              | 0.007000    | 0.005500    | 0.006250    |
| 27              | 0.007000    | 0.006500    | 0.006750    |

Table 6. Experimental result table for MRR

| Experiment No. | Avg. MRR | S/N ratio |
|----------------|----------|-----------|
| E1             | 0.006000 | -44.437   |
| E2             | 0.006500 | -43.7417  |
| E3             | 0.007750 | -42.214   |
| E4             | 0.007000 | -43.098   |
| E5             | 0.006750 | -43.4139  |
| E6             | 0.007000 | -43.098   |
| E7             | 0.007500 | -42.4988  |
| E8             | 0.007000 | -43.098   |
| E9             | 0.006250 | -44.0824  |
| E10            | 0.006750 | -43.4139  |
| E11            | 0.005750 | -44.8066  |
| E12            | 0.006250 | -44.0824  |
| E13            | 0.006250 | -44.0824  |
| E14            | 0.006750 | -43.4139  |
| E15            | 0.004750 | -46.4661  |
It can be observed that from the experimental results for MRR in USA-PECM, the average MRR ranges from 0.006000 - 0.007750 gm/min. The Third combination of levels of process parameters, A1B1C1D1E3 gave maximum MRR of 0.007750 gm/min. At this combination, the machining performance is better. Hence this combination proved to be the optimum process parameter to produce the maximum MRR on INCONEL 600.

- Main effect plot of voltage vs MRR shows that the out of three voltage (16, 18, 20V), the material removal rate is maximum when working voltage is 16V.
- Main effect plot of pulse on time vs MRR shows that the material removal rate is high if the pulse on time is 500µs.
- Main effect plot of ultrasonic off time vs MRR shows that the material removal rate decreases as ultrasonic off time increase. So the material removal rate is high when the ultrasonic off time is 8sec.
- Main effect plot of ultrasonic on time vs MRR shows that the, when the ultrasonic on time is 2sec, then the material removal is high compare to 3sec.
- Main effect plot of amplitude of vibration vs MRR shows that, MRR is higher when the amplitude on vibration is 16µ.
4.2. Result for Overcut:

Table 7. Experimental result table for overcut

| Experimental run | Overcut 1 | Overcut 2 | Avg. Overcut |
|------------------|-----------|-----------|--------------|
| 1                | 1.3085    | 1.3262    | 1.31735      |
| 2                | 1.3888    | 1.4661    | 1.42745      |
| 3                | 1.3001    | 1.4437    | 1.3719       |
| 4                | 1.0788    | 1.464     | 1.2714       |
| 5                | 1.2834    | 1.3194    | 1.3014       |
| 6                | 1.4411    | 1.4189    | 1.43         |
| 7                | 1.3851    | 1.5655    | 1.4753       |
| 8                | 1.3831    | 1.1626    | 1.27285      |
| 9                | 1.2289    | 0.8414    | 1.03515      |
| 10               | 1.2623    | 1.3428    | 1.30255      |
| 11               | 1.2734    | 1.3876    | 1.3305       |
| 12               | 1.3717    | 1.4686    | 1.42015      |
| 13               | 1.3809    | 1.4738    | 1.42735      |
| 14               | 1.2669    | 1.191     | 1.22895      |
| 15               | 1.0841    | 1.1553    | 1.1197       |
| 16               | 1.2407    | 1.2297    | 1.2352       |
| 17               | 1.253     | 1.2753    | 1.26415      |
| 18               | 1.2623    | 1.2171    | 1.2397       |
| 19               | 1.2058    | 1.2214    | 1.2136       |
| 20               | 1.3361    | 1.396     | 1.36605      |
| 21               | 1.3454    | 1.2958    | 1.3206       |
| 22               | 1.1814    | 1.3539    | 1.26765      |
| 23               | 1.0708    | 1.3685    | 1.21965      |
| 24               | 1.3801    | 1.3228    | 1.35145      |
| 25               | 1.2575    | 1.2921    | 1.2748       |
| 26               | 1.4245    | 1.3599    | 1.3922       |
| 27               | 1.4917    | 1.511     | 1.50135      |
Table 8. Experimental result table for overcut

| Sr. No | Avg. Overcut | S/N Ratio |
|--------|--------------|-----------|
| 1      | 1.31735      | -2.39402  |
| 2      | 1.42745      | -3.09122  |
| 3      | 1.3719       | -2.74645  |
| 4      | 1.2714       | -2.08564  |
| 5      | 1.3014       | -2.28822  |
| 6      | 1.43         | -3.10672  |
| 7      | 1.4753       | -3.37761  |
| 8      | 1.27285      | -2.09554  |
| 9      | 1.03515      | -0.30007  |
| 10     | 1.30255      | -2.29589  |
| 11     | 1.3305       | -2.4803   |
| 12     | 1.42015      | -3.04668  |
| 13     | 1.42735      | -3.09061  |
| 14     | 1.22895      | -1.79068  |
| 15     | 1.1197       | -0.98203  |
| 16     | 1.2352       | -1.83475  |
| 17     | 1.26415      | -2.03597  |
| 18     | 1.2397       | -1.86633  |
| 19     | 1.2136       | -1.68151  |
| 20     | 1.36605      | -2.70933  |
| 21     | 1.3206       | -2.41543  |
| 22     | 1.26765      | -2.05999  |
| 23     | 1.21965      | -1.7247   |
| 24     | 1.35145      | -2.616    |
| 25     | 1.2748       | -2.10884  |
| 26     | 1.3922       | -2.87403  |
| 27     | 1.50135      | -3.52964  |

Fig. 7 Main effect plot for overcut

- Main effect plot of voltage vs overcut shows that the out of three voltage (16, 18 and 20V), the overcut is minimum when working voltage is 18V.
• Main effect plot of pulse on time vs overcut shows that the overcut is minimum if the pulse on time is 250µs.
• Main effect plot of ultrasonic off time vs overcut shows that the overcut is minimum at off time 9 sec.
• Main effect plot of ultrasonic on time vs overcut show that, when the ultrasonic on time is 4sec, then the overcut value is minimum.
• Main effect plot of amplitude of vibration vs overcut a show that, overcut is lower when the amplitude of vibration is 20µ.

5. Analysis of variance
The ideal condition is recognized by analyzing the primary impacts of each of the process parameters. The principle impacts show the general patterns of impact of every parameter. The information about individual parameters and its contributions is a key in choosing the way of control to be established on a production procedure. The analysis of variance (ANOVA) is a statistical treatment most regularly connected to the results of the investigations in deciding the percentage contribution of every parameter against an expressed level of certainty. Investigation of ANOVA table for a given examination decides which of the parameters require control.

In the present examination, the S/N data analysis has been performed. The impacts of the chose USA-PECM process parameters for maximum MRR have been explored through the plots of the main effects. The ideal condition for maximum MRR has been set up through S/N data. No outer array has been utilized and rather, experiments have been performed two times at each trial condition.

| PARAMETERS     | DOF | SS     | MS     | F-value |
|---------------|-----|--------|--------|---------|
| A voltage     | 2   | 0.000002 | 0.000001 | 1.73    |
| B pulse on time | 2   | 7.2e-7  | 3.6e-7  | 0.08    |
| C ultrasonic on time | 2   | 2.34e-6 | 1.17e-6 | 0.26    |
| D ultrasonic on time | 2   | 3.42e-6 | 1.71e-6 | 0.38    |
| E amplitude   | 2   | 2.97e-6 | 1.48e-6 | 0.33    |
| F error       | 16  | 0.000009 | 0.000001 |         |
| Total         | 26  | 0.000012 |         |         |

| PARAMETERS     | DOF | SS     | MS     | F-value |
|---------------|-----|--------|--------|---------|
| A voltage     | 2   | 0.008405 | 0.004202 | 0.30    |
| B pulse on time | 2   | 0.013118 | 0.006559 | 0.48    |
| C ultrasonic on time | 2   | 0.034106 | 0.017053 | 1.24    |
| D ultrasonic on time | 2   | 0.012054 | 0.006027 | 0.44    |
| E amplitude   | 2   | 0.000019 | 0.000010 | 0.00    |
| F error       | 16  | 0.220821 | 0.013801 |         |
| Total         | 26  | 0.288523 |         |         |

6. Confirmation test for MRR and Overcut

| Prediction | Experiment |
|------------|------------|
| Parameter combination | A1B3C1D1E2 | A1B1C1D1E3 |
| MRR(gm/min) | 0.0770 | 0.07750 |

The optimum combination of process parameters calculated statistically for Inconel 600 is A1B3C1D1E2 which is very similar to the experimental values. The optimum combination of process parameters for maximum MRR obtained with confirmation test for Inconel 600 is first level of
voltage(A1), first level of pulse on time(B1), first level of ultrasonic on time(C1), third level of ultrasonic off time(D3), third level of amplitude(E3).

| Parameter combination | Prediction | Experiment |
|------------------------|------------|------------|
| A2B2C3D2E3             | 1.1505     | 1.03515    |
| Overcut (mm)           |            |            |

The optimum combination of process parameters for Minimum overcut obtained with confirmation test for Inconel 600 at voltage(A1), third level of pulse on time(B3), third level of ultrasonic on time(C3), third level of ultrasonic off time(D3), third level of amplitude(E3).

7. Conclusion
The material removal rate of Inconel 600 is mostly influenced at higher values of amplitude, ultrasonic on time, ultrasonic off time and voltage for the selected ranges while pulse on time has negligible effect. As voltage increased, the machining current in the IEG also increased, which leads to increase in MRR. During USA-PECM, at Voltage (16V), Pulse on time (500 µsec), Ultrasonic on time (2sec), Ultrasonic off time (8sec), Amplitude (18µ) the maximum MRR was obtained. Minimum overcut obtained at Voltage (18V), Pulse on time (250 µsec), Ultrasonic on time (4sec), and Ultrasonic off time (9sec), Amplitude (20µ).

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