Ultrasonic vibration assisted Electro-jet machining for Macro to Micro grooving applications of metal sheets/foils

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Submitted by

D Krishna Vamsi
17ME02028

Under the Supervision of
Dr. Suvradip Mullick, Dr. Gaurav Bartarya
Assistant Professor, SMS

School of Mechanical Sciences
Indian Institute of Technology, Bhubaneswar
Argul, Jatni, Bhubaneswar – 752050
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1. Introduction

For the process of macro to micro-grooving applications we need tools of small size with dimensions as small as few millimeters, manufacturing industries which make precision instruments related to medical, aerospace needs to manufacture devices which have small dimensions, this can be tedious and expensive. Conventional manufacturing techniques have some limitations like the tool risks either breaking or distorting, especially with difficult-to-machine materials so to fabricate micro parts, several unconventional manufacturing methods like electrical discharge machining (EDM), laser beam machining (LBM), micro ultrasonic machining (USM) and micro-electrical chemical machining (ECM) etc. can be used as an alternate to conventional methods. These unconventional methods have some advantages over traditional microfabrication techniques, but these unconventional methods are expensive. Hence, we can say that the manufacturing of micro-sized components is a tedious and costly procedure traditionally.

Wang et al. 2016 modified jet-ECM to fabricate deeper grooves for milling micro-grooves. it was seen that the radial overcut decreases with the increase of machining speed, and the overcut is larger for holes fabricated without Ultrasonic vibrations than with Ultrasonic vibrations. **Ebeid** et al. 2014 by plotting a graph between feed rate and overcut, it was concluded that the feed rate has a significant effect overcut value at different vibration amplitudes. By plotting a graph between the applied voltage and overcut values, it was seen that the overcut value increases non-linearly with the increase in applied voltage for every vibration amplitude. It was concluded that the amplitude of tool vibration is the most effective parameter affecting ECM. **Heiwdy** et al. 2018investigated the effect of tool vibration on the material removal rate in ECM. The analytical model suggests that with an increase of vibration amplitude, frontal gap size decreases, which leads to an increase in the current density, so ultimately, MRR increases. In tool vibration case sparking and tool damage can occur, so in order to avoid it, feed rate has to be restricted.

Rusraz et al. 2018 investigated the effects of ultrasonic vibration of the electrode on surface finish in the electrochemical micromachining process. As from the results ultrasonic vibrations help to decrease the surface roughness parameter Ra in comparison to the classical electrochemical process. **Bhattacharya** et al. 2015 Investigated into micro-milling of microgrooves on titanium alloy by electrochemical micromachining & concludes that by increasing machining voltage, width overcut & length overcut increases and by increasing pulse frequency width overcut and length overcut can be decreased **Dalbehra** et al. 2020 the effect of various parameters on the overcut were discussed Effect of voltage: As the voltage increases, the overcut also increases. (Current density increases), Effect of IEG: With the increase in IEG, the overcut keeps on increasing, Effect of Ultrasonic vibration: the Inter electrode gap between the tool and the workpiece changes periodically, MRR and flushing rate improves. As frequency of vibration increases, Width of cut decreases resulting in less overcut.

2. Objectives

There are three major objectives of the project:

1. To develop analytical model towards calculation of MRR and overcut in ultrasonic assisted electro jet drilling, by giving ultrasonic vibrations to the workpiece.
2. To study the effect of the process parameters, specifically the pulse frequency, duty cycle and the ultrasonic vibration frequency on the machining performances.
3. To perform regression analysis by using Response Surface Methodology, to predict the effects of the independent variables like pulse frequency, duty cycle and ultrasonic vibration frequency on the dependent ones like MRR, Overcut and Hole diameter.

Experiments are conducted in the next step and the results are analyzed and compared with the results of analytical model.

3. Model development

ECM is based on Faraday's law of electrolysis.

When there is continuous DC, the amount of material removed during µECM can be determined by combining Faraday's first law and Ohm's law which can be stated as:

As MRR in ECM = $\frac{V_0 E}{RF\eta\rho_m} = \frac{V_0 E}{\frac{rh}{A}F\eta\rho_m} = \frac{V_0 EA}{Frh\eta\rho_m}$ [3.1]

MRR under continuous DC = $\frac{V_0 EA}{Frh\eta\rho_{m.}}$ [3.2]

MRR under ultrasonic vibrations = $\frac{V_0 EA}{Frh\eta\rho_m[\, hc \pm a \sin(\omega t + \phi)]}$ [3.3]

Let, MRR be the material removal rate, at be the area of cross-section and dx be the depth of the hole that needs to be cut.

So, MRR= Area of cross-section x depth of hole, => dx = MRR / π/4 (dt)^2

But here the hole is not cylindrical, because of overcut, we get an approximate shape of a frustum of cone.

Actual dx = MRR / $\frac{\pi}{4}(\mathrm{dt} + \mathrm{Overcut})^2$

Actual dx = MRR / $\frac{\pi}{4}(\mathrm{dt} + (\mathrm{Overcut\ Top} + \mathrm{Overcut\ Bottom})/2)^2$ [3.4]

Here, MRR = $(k\ Vo\ E\ A\ \eta)$ / $(\rho mF$ [hc ± a sin (ω t + ϕ)]),

hc = $(Vo$ Mx) / $(\rho mF$r)

Actual dx = $(k\ Vo\ E\ A\ \eta)$ / $(\rho mF$ [hc ± a sin (ω t + ϕ)]) / $\frac{\pi}{4}(\mathrm{dt} + (\mathrm{Overcut\ Top} + \mathrm{Overcut\ Bottom})/2)^2$ [3.5]

4. Experimental Details

A setup is arranged to give ultrasonic vibrations to the workpiece, this can be achieved by using ultrasonic transducers and generator setup.

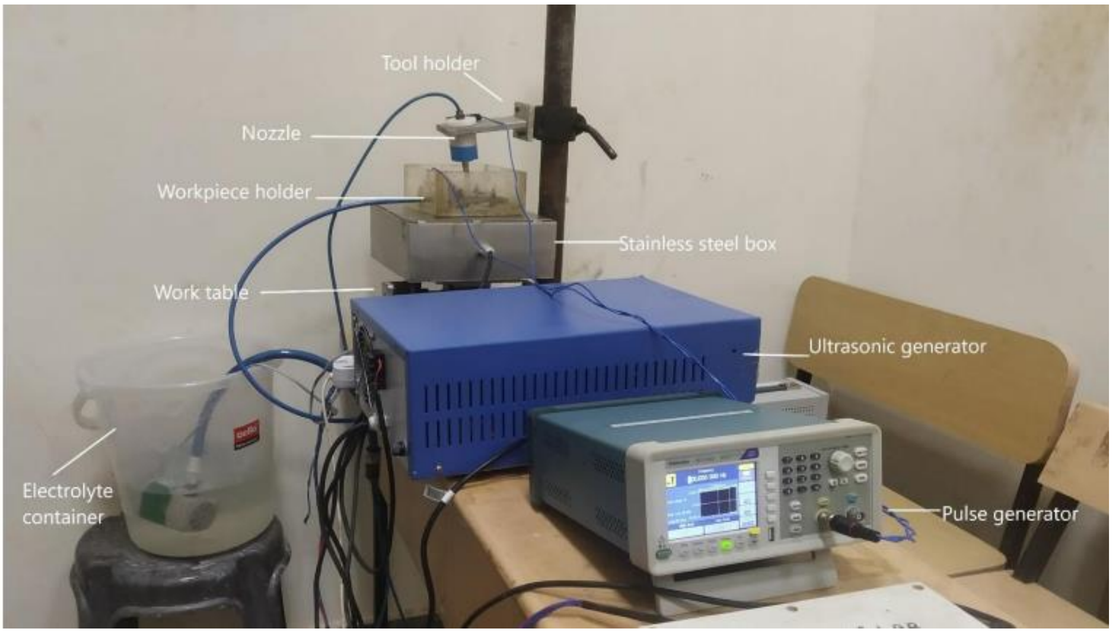


Fig1: Complete Experimental Setup

The whole EJMM setup can be categorized in four sub-systems: Power supply system, Electrolyte circulation system, Tool assembly.

In addition to develop EJMM assisted with ultrasonic vibration two more sub systems are added with respect to EJMM setup: Ultrasonic transducers and Ultrasonic vibration generator. The experiment was performed on ECM setup and Ultrasonic vibrations were given to the workpiece by placing the workpiece holder on the Stainless-steel box.

The experiment is carried out in Pulsed DC mode and the experimental parameter like Voltage, inter electrode gap and the electrolyte concentration are kept constant, and the parameters like

Pulse Frequency, Duty cycle and Ultrasonic vibrations frequency is varied and the outputs MRR, Hole diameter and Overcut are measured.

Ultrasonic generator was use for getting vibrations in the transducers which were placed in a stainless-steel box. Here the frequency range of ultrasonic generator lies between 28-34 kHz. Here, the input power supply was given as AC power supply.

Frequency of vibration was controlled by ultrasonic generator. Here in this setup four ultrasonic transducers are placed inside a stainless-steel box and on the top of the stainless-steel box machining tank was placed on which aluminium workpiece was mounted with the help of workpiece holder as shown in the Fig.18. So, by applying ultrasonic vibration IEG changes so MRR improves, and also better flushing occurs due to vibration

4.1 Experimental Observations to find the effect of single factor on Machining.

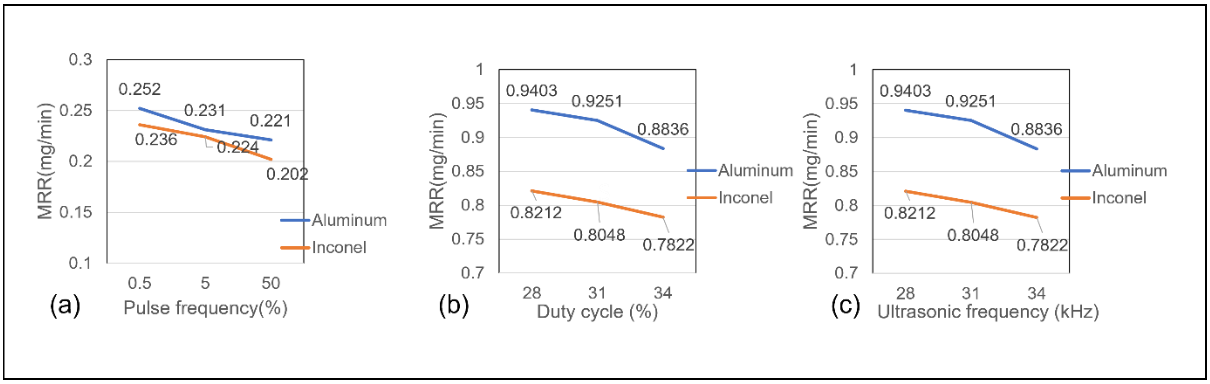


Fig 2: Effects of the individual parameters on the MRR

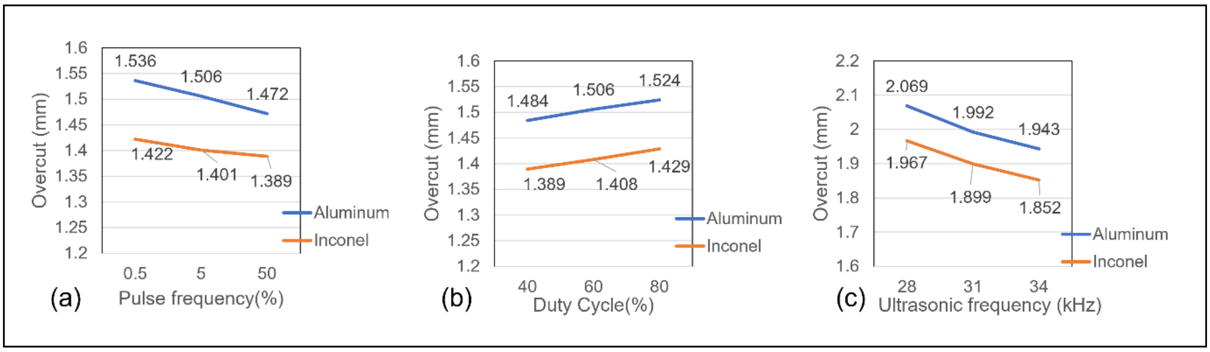


Fig 3: Effect of individual parameters on Overcut

The Theoretical MRR in the range of 1.02 to 1.17 mg/min for Aluminium sheet and in the range of 0.81 to 0.98 mg/min for Inconel sheet using the equation derived above. The percentage of change in MRR between aluminium and Inconel sheet in Experimental MRR is 6% to 9 % and the percentage change in Theoretical MRR is 8% to 12%.

4.2 Optimization of drilling process using Response surface methodology

Optimization by Response Surface methodology was done, it involved three major steps, firstly statistically designed experiments, secondly, estimate the coefficients in a mathematical model and finally predicting the response and checking the adequacy of the model within.

Box-Behnken designs are used to generate higher order response surfaces using fewer runs than a normal factorial technique.

The experimental results have also been analyzed using analysis of variance (ANOVA). The results of ANOVA for MRR, Hole diameter and Overcut are tabulated in below table. The values of all deterministic constant (R2) for all the responses are above 90%. The term lack-of-fit is non-significant for all responses as it is desired.

For Response surface designs the perturbation plot shows how the response changes each factor moves from the chosen reference point. The lines represent the behaviors of each factor, while holding the others constant at the reference value. Design-Expert sets the reference point default at the middle of the design space (the coded zero level of each factor). In the perturbation plots, each process parameters are represented in coded units, where the low, middle and high levels of each parameter are coded as -1, 0 and +1 respectively.

Process parameters and Experimental design levels:

Table1: Levels of selected Input Variables for both the materials.

FACTORS	Units	Level 1	Level 2	Level 3
Pulse Frequency	khz	0.5	5	50
Duty Cycle	%	40	60	80
Ultrasonic Frequency	khz	28	31	34

Table2: Abstracted ANOVA table for all responses

Material	Response	Significant terms	SS Model	DF	Lack of Fit	R^2	Adj-R^2	Pre-R^2	Adequate Precision
Aluminium	MRR	A,B,C,AB,AC ,BC,A^2,B^2,C^2	0.0094	9	Not sig	0.9967	0.9924	0.9771	50.68
	Hole Dia	A, B, C, AC , BC, A^2, C^2	0.1780	7	Not sig	0.9793	0.9632	0.8925	25.70
	Overcut	A, B, C, AC , BC, A^2, C^2	0.0622	7	Not sig	0.9810	0.9663	0.9240	25.75
Inconel	MRR	A,B,C,AB,AC ,BC,A^2,B^2,C^2	0.0033	9	Not sig	0.9938	0.9858	0.9443	36.98
	Hole Dia	A,B,C,AB,AC ,BC,A^2,B^2,C^2	0.1536	9	Not sig	0.9993	0.9984	0.9901	55.25
	Overcut	A, B, C, AC, A^2, C^2	0.0619	6	Not sig	0.9716	0.9546	0.9051	23.17

Design Expert software has been used to analyze the measured responses. Model significance test, significance test for each of the model terms and lack of fit test were carried out. A step wise regression method was selected to find out the significant model terms automatically and the resultant ANOVA tables for reduced quadratic model summarizing the analysis of variance for each response.

4.2.1 Analysis of variance for drilling in Aluminum Sheet

Analysis of variance of all the three output quality parameters has been studied for Aluminium sheet, which shows that for MRR the effects of Pulse frequency (A) and Duty cycle (B), Ultrasonic vibration frequency (C), interactions (AB), (BC) and (AC), and the quadratic effects of A^2, B^2 and C^2 are the significant model terms. Whereas for Hole diameter the effects of all the three process parameters, interaction (AC) and (BC) the quadratic effects of (A^2) and (C^2) are the significant model terms. The analysis of Overcut indicates that all the three main effects and Interaction effects of (AB) and (AC) and the quadratic effects of (A^2) and (C^2) are significant model terms. The abstracted ANOVA table for all the three responses in Aluminium sheet are presented in Table. Individual reduced ANOVA tables for each output variable are given in Appendix B. The final regression models in terms of actual factors are given by

MRR = $0.715293 + 0.000191*A + 0.001639*B – 0.033366*C – 0.000465*AB – 0.00090*AC + 0.000461*BC + 0.00053*A^2 + 0.00021*B^2 + 0.000469*C^2$

Hole Diameter = $6.05609 – 0.008005*A – 0.006152*B – 0.262558*C – 0.000312*AB + 0.000408*BC + 0.000326*A^2 + 0.003664*C^2$

Overcut = $2.52525 – 0.000579*A + 0.0004246*B – 0.11228*C – 0.000019*AB – 0.000218*AC + 0.000151*A^2 + 0.001734*C^2$

4.2.2 Analysis of variance for Drilling in Inconel Sheet

Analysis of variance of all the three output quality parameters has been studied for Inconel sheet, which shows that for MRR the effects of Pulse frequency (A) and Duty cycle (B), Ultrasonic vibration frequency (C), interactions (AB), (BC) and (AC), and the quadratic effects of (A^2), (B^2) and (C^2) are the significant model terms. Whereas for Hole diameter the effects of all the three process parameters, interaction (AB), (BC) and (AC) the quadratic effects of (A^2), (B^2) and (C^2) are the significant model terms. The analysis of Overcut indicates that all the three main effects and Interaction effect of (AC) and the quadratic effects of (A^2) and (C^2) are significant model terms. The abstracted ANOVA table for all the three responses in Inconel sheet are presented in Table. Individual reduced ANOVA tables for each output variable are given in Appendix B. The final regression models in terms of actual factors are given by

MRR = 0.513014 + 0.000132*A + 0.00054*B – 0.023115*C – 3.95597E-06*AB – 0.00058*AC + 0.000036*BC + 0.000034*A^2 – 5.12500E-0.6*B^2 + 0.000328*C^2

Hole Diameter = 4.58569 – 0.006818*A – 0.002699*B – 0.208778*C – 0.000035*AB – 0.000084*AC + 0.000233*BC + 0.000202*A^2 – 0.000026*B^2+ 0.002981*C^2

Overcut = 2.43186 – 0.001914*A + 0.003963*B – 0.118089*C – 0.000218*AC + 0.000155*A^2 + 0.001827*C^2

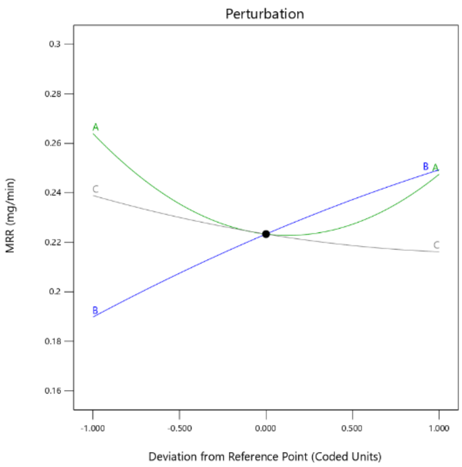
4.3 Experimental results

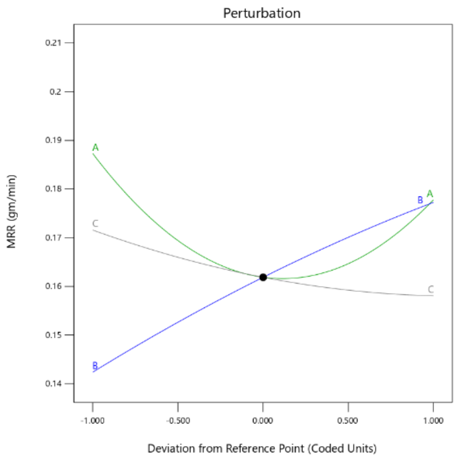
Voltage = 20V, IEG = 0.2 mm, Electrolyte concentration = 30 gm/lit, Pulse frequency = 5 khz, Duty cycle = 60, Ultrasonic vibration Frequency = 31 kHz, Top hole diameter = 1.744 mm, Bottom hole diameter = 0.972 mm, Overcut = 0.929 mm, MRR= 0.252 mg/min.

Groove images	
 (a)	 (b)

Fig2: (a) top view and (b) bottom view in drilled samples

The perturbation plots for MRR for Aluminum and Inconel sheets are shown below.





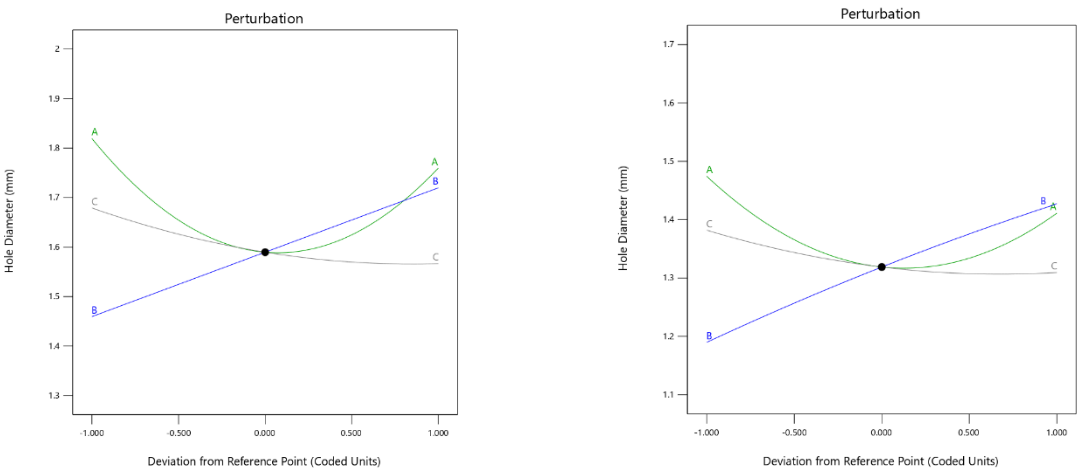
a. Aluminium sheet

b. Inconel sheet

Fig5: Perturbation plots

For both Aluminum and Inconel sheets, the MRR follows the same trend with all the three factors. MRR first increases with increase in pulse frequency but then after a certain point MRR decreases with the increase in pulse frequency. MRR increases as the Duty cycle increases.

4.4 The perturbation plots for Hole diameter for Aluminum and Inconel sheets are given below.



a. Aluminum sheet b. Inconel sheet

Fig6: Perturbation plots

Hole diameters also follow the same trend as MRR but in case of Inconel sheet Hole diameter does not change much with change in pulse frequency as compared to the change in Hole diameter in Aluminum sheet.

The perturbation plots for overcut for Aluminum and Inconel sheets are given below

a. Aluminum sheet b. Inconel sheet

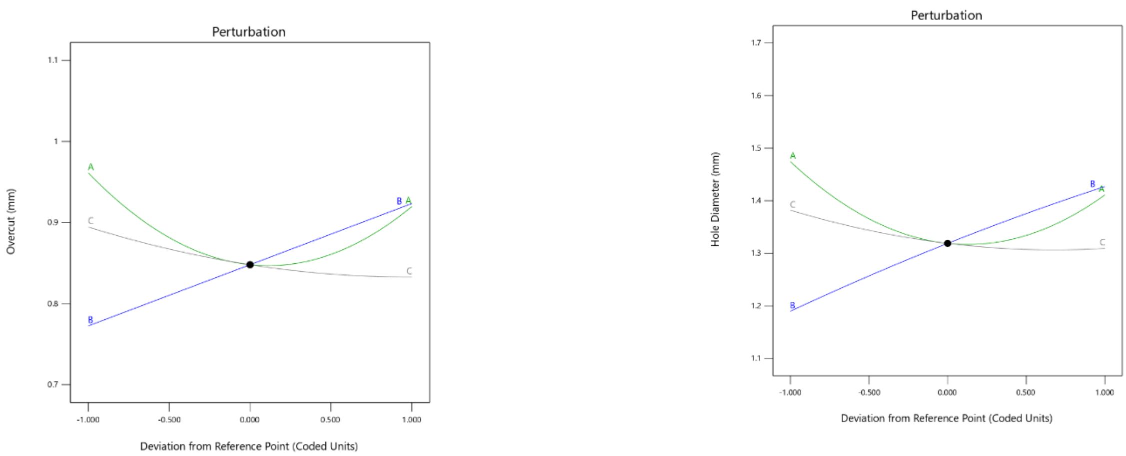


Fig7: Perturbation plots

All the three factors behave similarly for both the materials, and we can also observe that overcut decreases slightly with the increase in Ultrasonic vibration.

Table 3: Optimum process parameters for maximizing MRR and Minimizing Overcut for Aluminum and Inconel sheet.

Material	Pulse Frequency	Duty Cycle	Ultrasonic frequency	MRR	Hole Diameter	Overcut
Aluminum	15	75	31.4	0.2342	1.7379	0.9337
Inconel	25	65	31.1	0.1972	1.419	0.7311

Table 4: Validation runs for drilling on both aluminium and Inconel sheets.

Material	Pulse Frequency	Duty Cycle	Ultrasonic frequency	MRR	Hole Diameter	Overcut
Aluminum	15	75	31.4	0.232	1.7422	0.9341
Inconel	25	65	31.1	0.1945	1.4921	0.7511

5. Conclusion

1) Ultrasonic vibration assisted Electro jet machining on Aluminum sheet and Inconel sheet of 0.5mm thickness, for generation of macro-micro cuts, A mathematical model has also been developed to predict the MRR of the process under various process parameters.
2) The application of Pulse current determined that, a small duty cycle was found to reduce the hole diameter, MRR and Overcut.
3) It is also observed that, a higher pulse frequency results in higher hole diameter and improper cut.
4) The Ultrasonic vibration frequency range was 28 – 34 kHz, the application of Ultrasonic vibration was found to increase the MRR, but at the same time resulting in higher Hole diameter and overcut.
5) Optimization by Response Surface methodology was done on the model.

6. References

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