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Research Article

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Investigation of a Novel Ultrasonically Aided Electrochemical Magnetic Abrasive Machining Process for SS 316L

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Abstract
Many present day applications require machining and finishing of complex shaped and tough to machine materials with precision and accuracy by conventional or non-conventional machining and polishing processes. Ultrasonically aided electrochemical magnetic abrasive machining (UAEMAM) process is a novel non-conventional machining technique which can machine and finish the product for better surface quality. In present research work, the development and performance evaluation of UAEMAM process for machining of SS 316L is reported. The UAEMAM process is optimised using response surface methodology (RSM) based on central composite design (CCD) and grey relational analysis. The main machining variables such as work piece rotational speed, working gap, concentration of NaNO₃, percentage of abrasives by weight and pulse on time were chosen to determine percentage improvement in surface finish improvement (PISF) and material removal rate (MRR) in the UAEMAM process. The significant machining factors and the best combination levels of machining parameters associated with PISF and MRR were determined. The benefits of ultrasonic aided electrochemical magnetic abrasive machining were also confirmed from the micrograph observations of the surface. Experimental results show that UAEMAM process is effective for machining and polishing components for better surface finish.

Keywords: Ultrasonic Aided Electrochemical Magnetic Abrasive Machining (UAEMAM), Magnetic Abrasive Finishing, Ultrasonic Frequency, Electrochemical Machining, Material Removal Rate, Percentage Surface Finish Improvement.

1 Introduction
In current industrial applications, conventional machining and polishing techniques fail to process hard and complex shaped materials with minimum surface defects and precision. Finishing of materials with stringent properties by conventional machining may lead to various defects such as surface deformation, hair line cracks and geometrical errors of machined components. Conventional machining processes are also not able to accomplish the current needs of better quality and efficiency. These processes can be used in few cases but they demand more intensive skilled labour. The accuracy and required finish level of the component can be accomplished by hybrid processes. UAEMAM is a new hybrid non-conventional machining technique for machining and polishing of components for various applications.

The performance of machining enhanced by using latest trends in manufacturing integrates several processes to meet the latest trends are known as hybrid machining [1]. According to Kozak and Rajurkar [2], constituent processes produce various negative outcomes when applied individually. The effectiveness of a hybrid machining technique is valuable and more significant. Kim and Cho conducted experiments on Cr-coated roller using polishing system of magneto electrolytic abrasive. They reported an improvement of roughness value 1.0 µm to 0.15 µm and roundness from 1.95 µm to 0.81 µm [3]. Venkatesan and Ramanujam carried out machining of Inconel 718 alloy using hybrid of LAHM. They reported speed (60 meter per min.), power (1.3 kilowatt) and feed (0.06 mm/rev) at optimal conditions [4]. Sun and Zou developed a set up for electrochemical magnetic abrasive finishing of SUS 304. They found machining efficiency increased by 50% by using electrochemical magnetic abrasive finishing (EMAF) as compared to magnetic abrasive finishing (MAF) process [5]. Kant and Dhami conducted experiments on EN31 using an abrasive water jet machining method. They reported time of machining (36 sec), hardness (41.7 HRC) and roughness of surface (1.59 µm) at optimal conditions [6]. Lin et al. carried out machining of SKD 61 steel using hybrid of
ultrasonic vibration and electric discharge machining in gas. They reported the machining response increases with increase in peak current [7]. Sihag et al. conducted experiments on the copper alloy with chemo-ultrasonic aided MAF technique. They reported 82.86% improvement in surface quality over the original component [8].

The aluminium/aluminium oxide composite work pieces were processed by hybridization of two processes - electrochemical turning and MAF resulting in surface quality improvement of 33% as compared to traditional process [9]. Elhami et al. conducted experiments on AISI 4140 using hybrid milling and found that flank wear decreased by 16% with thermally enhanced and ultrasonic assisted machining when compared with other processes [10]. Brar et al. carried out machining of brass using hybrid of abrasive flow and electrochemical machining (ECM). They reported 46.83% improvement in surface quality over the original component [11]. Judal and Yadava carried out machining of stainless steel tubes (AISI 304) employing electrolytic finishing with magnetic abrasives and found that machining efficiency increased by 50% with EMAF when compared to the MAF process [12].

Ebeid and El-Taweel conducted experiments to increase surface quality by hybrid process of electrolytic cutting and roller burnishing. The burnishing force concentration and applied voltage were discovered to be the main factors for better improvement of surface [13].

Many researchers proposed different hybrid machining methods based on numerous operating mechanisms. Further, to produce smooth surface for metals, roller burnishing was combined with electrochemical turning. For excellent finishing properties, the traditional MAF technique has undoubtedly been utilised, mostly on complicated components. Jain et al. conducted an experimentation with abrasive flow machining. They reported the evaluation of forces and stresses generated during process with FEM. Experimental and theoretical results found to close well [14]. Mori et al. conducted an experimental study on SS304 using MAF process. They reported the calculated and measured values of normal force on abrasive particle during MAF process [15]. Singh et al. performed an experimental work on MAF process. The high level of working gap, voltage, rpm and grind grit size were found for better improvement in ∆Ra [16]. Singh et al. conducted an experimental study on aluminium tubes using magneto abrasive flow machining. They reported surface finish improvement 72.7% at optimal conditions [17]. Yadav et al. conducted an experimental study on EN 24 steel using magnetorheological gear profile finishing. Surface reduction from 220 nm to 20 nm in 40 minutes was reported at optimum levels [18]. However, MAF has the drawback of a lower efficiency, when used to materials with stringent properties [19]. Farwaha et al. used an ultrasonic assisted electrochemical magnetic abrasive finishing technique on SS 316L. The influence of process variables (frequency time, job rpm, and abrasive percentage by weight) on percentage surface finish improvement was evaluated using a L9 orthogonal array. They found that rotating speed influences max. (82.2%), followed by pulse duration (13.39%) and percentage abrasive weight (4.34%). At optimum levels, 82 percent enhancement in surface texture was noticed [20]. Farwaha et al. investigated as pilot experimentation with ultrasonic assisted electrochemical magnetic abrasive machining process on SS 316L. Experiments were conducted to identify the process variables for improvement in surface quality. The machining time, frequency time, work piece rpm, working gap and voltage were used as input variables during the study. From TOPSIS, the best combinations for PISF, MRR, and PCMH were machining time (5 minutes), frequency time (4 sec), rotational speed (600 rpm), working gap (3mm), and voltage (3V). From optimization plot of Taguchi, machining time (15 minutes), frequency time (6 sec), rotational speed (600 rpm), working gap (3mm), and voltage (4.5V) [21]. Farwaha et al. designed and investigated as pilot experimentation with ultrasonic assisted magnetic abrasive finishing combined with electrolytic process for the finishing of SS 316L. They concluded that effective efficiency was attained at high electrolyte contents and ultrasonic vibration period. From a starting roughness of 1.872 μm, the roughness was turned down to 0.332 μm after 15 minutes [22].

AISI 316L stainless steel is used in many applications including chemical industry and medical devices because of its high corrosion resistance and mechanical properties. Treatment and replacement of human body bones and joints, many medical applications like bone screws, artificial joints, rods and other devices require a number of different machining operations and also necessitate mirror like surface and accuracy. One such component is a femoral head used in hip replacement surgery in which bar stock must be turned, milled, ground and super finished to produce these prosthetics. UAEMAM is novel technique to deliver finished components like these.

The literature shows that many researchers used hybrid processes for machining and finishing components for special applications. There have been studies on hybridization of ultrasonic and MAF, electrochemical and MAF. There is no effort undertaken till date for combining ultrasonic vibrations, magnetic abrasive finishing and electrochemical machining all together. So, in this new work an effort is to investigate percentage surface finish improvement
and rate of material removal for AISI 316L stainless steel by UAEMAM process.

2 Methodology

2.1 Principle of UAEMAM

The schematic of the UAEMAM process is shown in Fig. 1. The UAEMAM process is mainly used for machining and finishing of materials with stringent properties. Just like ECM, the transfer of charge between electrode and work piece takes place through the electrolyte solution. A jet of electrolyte is supplied via copper electrode that creates passive film on work surface due to electrolysis process. The diamond abrasive particles are used to remove the oxide film. Ultrasonic vibrations helps to change the magnetic abrasive particles orientation. In UAEMAM process, the oxide film formed on work piece by ECM, material removal layer by layer with the use of MAF and particles reorientation simultaneously.

2.2 Details of experimental set up

The machining and finishing set up used for cylindrical work piece using UAEMAM process comprises four main units, namely

- Electrochemical machining unit
- Magnetic abrasive finishing unit
- Ultrasonic generator unit
- Electromagnet holding fixture

The experimentation was done on UAEMAM set up as shown in Fig. 2. The touch panel display is provided for setting of voltage, output current, electrolyte pump flow and feed rate as shown in Fig. 3. The whole machining setup operates with three phase 440 volts A.C. (Alternating Current) supply. The power supply is perfect integration of high electrical current, power electronics and precision programmable micro controller based technologies. The all machining parameters can be varied through the touch panel as per requirement. Copper electrode used in electrochemical unit along with DC power source and electrolyte (NaNO₃). MAF unit works along with electromagnets and MAPs. Ultrasonic vibrations for electromagnets excitation is generated with the help of ultrasonic generator. With the help of a DC motor, the chuck is rotated at a variable speed. The rotation of motor per minute observed and recorded from the variac’s screen. The job rotation is done by holding in an insulated jaw. The Teflon bush is used for insulation of work piece clamping chuck. The copper electrode is placed at the work piece top surface with gap of 2 mm. After reaction, the used electrolyte is drained to the reservoir for reuse and again pumped as depicted in Fig. 1. Reactivity of various oxidising chemicals with 316L stainless steel was tested by pilot experiments. For present study NaNO₃ will take place electrolytic reactions are shown below:

\[
\text{NaNO}_3 \rightarrow \text{Na}^+ + \text{NO}_3^- \quad (1)
\]

\[
\text{H}_2\text{O} \rightarrow \text{H}^+ + \text{OH}^- \quad (2)
\]

NO₃⁻ and OH⁻ moves toward anode and Na⁺ and H⁺ moves toward cathode. The ionization tendency of H is less than Na, eq. (3) represents the reaction which occurs at cathode. The OH⁻ discharges easily as compared to NO₃⁻ discharge, eq. (4) represents the reaction occurring at anode.

\[
\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2 \uparrow \quad (3)
\]

\[
2\text{OH}^- \rightarrow \text{H}_2\text{O} + \frac{1}{2}\text{O}_2 \uparrow + 2\text{e}^- \quad (4)
\]

From eqs. (3) and (4), it was observed that O₂ is generated at anode and H₂ generated at the cathode. The major composition of 316L stainless steel is Cr (16%) and Ni (14%). Under action of oxygen, most of anode metal is oxidized. Lot of metal ions such as Fe³⁺, Cr⁶⁺, Fe²⁺, Cr³⁺, Ni²⁺ and other elements on the surface of metal are eluted by oxidation reaction.

MAF is the second unit of setup. The oxide film is generated on the work piece surface due to electrolytic reaction. Flexible abrasive brush helps to eliminate the oxide layer formed during electrolytic process. In MAF, the space between magnetic poles and work piece have been packed with abrasive particles and rotational movement with dc motor is given to the work piece. Flexible abrasive brush is formed with the help of magnetic field created by electromagnet.

Third unit of set up is ultrasonic generator. While experiment investigations, the electromagnets installed in a fixture which is fabricated for experimentation. The fixture was energised with vibrational frequency which is generated by horn of ultrasonic generator. The apparatus also permits little longitudinal movement of electromagnet.

3 Experimental details

3.1 Selection of process parameters

316L stainless steel was used as a work piece for performance evaluation of UAEMAM process. The range of input parameters were selected by performing pilot study. Based on preliminary research,
Fig. 1 Schematic of UAEMAM Process

Fig. 2 Experimental setup of UAEMAM

Fig. 3 Control Panel
the machining and finishing duration was kept constant as 15 minutes for the whole of the experimental runs. From pilot experimentation and literature review, five prominent parameters were identified which affect performance of UAEMAM. Five process variables were chosen in the present work.

- Rotational speed of work piece
- Gap between work piece and magnet
- Concentration of NaNO₃
- Percentage weight of abrasives
- Pulse on time for vibration

Improvement in surface finish as a percentage and rate of material removal was selected as output response. Table 1 lists the constant parameters in detail.

### 3.2 Experimental Procedure

In present work to solve machining and finishing problem, central composite DOE was used. The initial work pieces were finished using grinding machine by conventional method. Emery paper attached on grinding machine for finishing of work piece. So, surface roughness ($R_a$) of initial and finished work piece was noted down at three points for each work piece before and after UAEMAM. The average of three values was determined. Based on inputs, runs came out to be 32. For completion of whole experimentation 32 tests were conducted and surface roughness values were recorded to calculate PISF.

$$\text{PISF} = \frac{\text{Initial roughness} - \text{Final roughness}}{\text{Initial roughness}} \times 100 \quad (5)$$

The work specimens obtained after conventional grinding were thoroughly cleaned with acetone solution. All specimens were weighed three times. The average reading of each specimen was noted. The same procedure was adopted for weight measurement after the specimens were machined by UAEMAM process. The difference between the initial and final measurement for a particular sample calculates the mass of material removed. Material removal rate is calculated as.

$$\text{MRR} = \frac{\text{Initial weight} - \text{Final weight}}{\text{Operation time}} \quad (6)$$

### Table 1 Constant process parameters

| Sr. No. | Parameter                  | Value     |
|---------|----------------------------|-----------|
| 1       | Density of Magnetic flux   | 8000 Gauss|
| 2       | Mesh number of diamond powder | 140      |
| 3       | Pulse off time, $t_{off}$  | 10 sec    |
| 4       | Power supply of ultrasonic | 720 W     |
| 5       | Experiment time            | 15 minutes|
| 6       | Work piece material        | 316L stainless steel |

### Table 2 Process factors and levels

| Sr. No. | Level | -2 | -1 | 0   | 1   | 2   |
|---------|-------|----|----|-----|-----|-----|
| Rotational speed (RPM) |       | 50 | 100| 150 | 200 | 250 |
| Working gap (mm)        |       | 1  | 2  | 3   | 4   | 5   |
| Conc. of NaNO₃ (wt. %)  |       | 2  | 4  | 6   | 8   | 10  |
| % Weight of abrasive    |       | 10 | 15 | 20  | 25  | 30  |
| Pulse on time $t_{on}$ (s) |     | 2  | 4  | 6   | 8   | 10  |

### 4 Grey relational analysis

A grey methodology represents a method having a portion of data known and remaining portion of data unknown [23]. Normally in these type of cases there is always an existence of uncertainty. So grey analysis will fetch a diversity of solutions. Therefore grey relational analysis can be utilized for finding the solutions of real life problems having complex nature and interconnected relation of parameters defining the problem or performance parameters. For evaluation, the technique of grey relational analysis is employed and grade of grey relation represents the multiple performance parameters. Calculation of grey relational grade is done through the procedure discussed below.
4.1 Pre-processing of data

For grey relational analysis pre processing of original pattern of data is required to be converted into comparable data pattern. For this purpose various techniques for data processing are available and suitable technique can be applied. Normalization of given data is done and its values (higher the better) is calculated as:

\[ X_{ij} = \frac{y_{ij} - \min (y_{ij})}{\max (y_{ij}) - \min (y_{ij})} \]  

(7)

As shown in Table 3, the values of PISF and MRR are normalized. \( X_{ij} \) which is \( j \)-th response corresponding to \( i \)-th experiment is processed by suitable pre processing technique. The value of \( x_{ij} \) which is equal to or closer to 1 as compared to other experiments, is counted as best value for \( j \)-th response. \( X_0 \) is the reference series which is expressed as \( (x_{01}, x_{02}, ..., x_{0j}, ..., x_{0n}) = (1, 1, ..., 1, ..., 1) \), here \( x_0 \) denotes reference value corresponding to \( j \)-th response, which is performed in order to fetch the experiment which has comparability sequence nearest to that of reference sequence. Deviation sequences are shown in Table 3.

The grey relational factor is applied finding the closeness of \( x_{ij} \) and \( x_{0j} \). The significance of grey relational coefficient is directly proportional to closeness of \( x_{ij} \) and \( x_{0j} \). Following equation is used for finding the grey relational coefficient:

\[ \gamma (x_{0j}, x_{ij}) = \frac{\Delta_{min} + \xi \Delta_{max}}{\max (y_{ij}) - \min (y_{ij})} \]

\[ \text{for } i = 1, 2, ..., m \text{ and } j = 1, 2, ..., n \]  

(8)

Where \( \gamma (x_{0j}, x_{ij}) \) is the grey relational coefficient between \( x_{ij} \) and \( x_{0j} \).

\[ \Delta_{ij} = |x_{0j} - x_{ij}| \]  

(9)

\[ \Delta_{min} = \min \{\Delta_{ij} \text{, } i = 1, 2, ..., m \text{; } j = 1, 2, ..., n \} \]  

(10)

\[ \Delta_{max} = \max \{\Delta_{ij} \text{, } i = 1, 2, ..., m \text{; } j = 1, 2, ..., n \} \]  

(11)

\( \xi \) is distinguishing coefficient, \( \xi \in (0,1] \). Grey relational grade is used to quantify the grey relational data. The following equation is used to determine grade of grey relation:

\[ \Gamma (X_0, X_i) = \sum_{j=1}^{n} w_j \gamma (x_{0j}, x_{ij}) \]  

(12)

\( \Gamma (X_0, X_i) \) is the grade of grey relational between reference sequence \( X_0 \) and comparability sequence \( X_i \). The level of closeness between the comparability series and standard series indicates with grey relational grade.

5 Result and Discussion

The present work shows complete elimination of oxide layer from work piece surface, subsequently increasing the PISF value to 84.73%, approximate 2% higher than 82% value achieved by previous studies employed [9, 20, 21, 22]. The previous works on similar workpieces have shown PISF values ranging from 44% to 73% [17, 18]. The ability of UAEMAM is to provide both improved material removal rates and a superior work piece surface quality. In this process, the combined action of ultrasonic, electric and magnetic field is applied on the ferromagnetic abrasive particles so as to suitably change the path of motion of the anions towards the anode. Through selective breakdown of the peaks with reference to the valleys of surface imperfections this alteration in the direction of the ionic particles results in better process capacities. Even the most difficult, hard and high-strength work piece materials can be processed with minimal effort. It is about 1.8 to 1.9 times quicker than the MAF technique. Moreover, the process is capable of achieving surface finishing up to 0.02 µm within 15 to 20 minutes of machining time. Figure 4 shows comparison of the surface finish attainable from some of the conventional and advanced machining processes [24].

Fig. 4 Range of surface roughness obtained in various machining processes
### Table 3 Output of grey relational analysis

| Exp. No. | PISF (%) | MRR (mg/min.) | Normalized values | Deviation sequences | Grade | Grey order |
|----------|----------|---------------|-------------------|---------------------|-------|------------|
| 1        | 65.48    | 82.14         | 0.36              | 0.88                | 0.64  | 0.12       | 0.63 | 7      |
| 2        | 76.50    | 64.83         | 0.73              | 0.19                | 0.27  | 0.81       | 0.51 | 15     |
| 3        | 78.20    | 77.87         | 0.78              | 0.71                | 0.22  | 0.29       | 0.67 | 5      |
| 4        | 67.07    | 82.10         | 0.42              | 0.88                | 0.58  | 0.12       | 0.64 | 6      |
| 5        | 66.27    | 68.38         | 0.39              | 0.33                | 0.61  | 0.67       | 0.44 | 28     |
| 6        | 70.94    | 68.94         | 0.54              | 0.35                | 0.46  | 0.65       | 0.48 | 21     |
| 7        | 54.43    | 68.59         | 0.00              | 0.34                | 1.00  | 0.66       | 0.38 | 32     |
| 8        | 73.68    | 63.20         | 0.64              | 0.12                | 0.36  | 0.88       | 0.47 | 25     |
| 9        | 82.73    | 60.23         | 0.93              | 0.00                | 0.07  | 1.00       | 0.61 | 8      |
| 10       | 70.61    | 70.67         | 0.53              | 0.42                | 0.47  | 0.58       | 0.49 | 18     |
| 11       | 69.41    | 70.19         | 0.49              | 0.40                | 0.51  | 0.60       | 0.48 | 23     |
| 12       | 71.00    | 68.94         | 0.55              | 0.35                | 0.45  | 0.65       | 0.48 | 20     |
| 13       | 68.85    | 85.00         | 0.48              | 1.00                | 0.52  | 0.00       | 0.74 | 1      |
| 14       | 69.68    | 72.18         | 0.50              | 0.48                | 0.50  | 0.52       | 0.50 | 17     |
| 15       | 78.40    | 65.25         | 0.79              | 0.20                | 0.21  | 0.80       | 0.55 | 12     |
| 16       | 79.30    | 76.72         | 0.82              | 0.67                | 0.18  | 0.33       | 0.67 | 4      |
| 17       | 67.18    | 61.50         | 0.42              | 0.05                | 0.58  | 0.95       | 0.40 | 31     |
| 18       | 73.96    | 63.63         | 0.64              | 0.14                | 0.36  | 0.86       | 0.48 | 24     |
| 19       | 70.36    | 69.94         | 0.53              | 0.39                | 0.47  | 0.61       | 0.48 | 19     |
| 20       | 71.30    | 78.96         | 0.56              | 0.76                | 0.44  | 0.24       | 0.60 | 9      |
| 21       | 80.38    | 79.81         | 0.86              | 0.79                | 0.14  | 0.21       | 0.74 | 2      |
| 22       | 72.30    | 70.17         | 0.59              | 0.40                | 0.41  | 0.60       | 0.50 | 16     |
| 23       | 69.00    | 68.94         | 0.48              | 0.35                | 0.52  | 0.65       | 0.46 | 27     |
| 24       | 74.32    | 61.47         | 0.66              | 0.05                | 0.34  | 0.95       | 0.47 | 26     |
| 25       | 70.60    | 68.94         | 0.53              | 0.35                | 0.47  | 0.65       | 0.48 | 22     |
| 26       | 84.73    | 66.23         | 1.00              | 0.24                | 0.00  | 0.76       | 0.70 | 3      |
| 27       | 76.88    | 66.94         | 0.74              | 0.27                | 0.26  | 0.73       | 0.53 | 14     |
| 28       | 78.11    | 68.34         | 0.78              | 0.33                | 0.22  | 0.67       | 0.56 | 10     |
| 29       | 71.39    | 75.09         | 0.56              | 0.60                | 0.44  | 0.40       | 0.54 | 13     |
| 30       | 78.88    | 64.96         | 0.81              | 0.19                | 0.19  | 0.81       | 0.55 | 11     |
| 31       | 67.19    | 64.43         | 0.42              | 0.17                | 0.58  | 0.83       | 0.42 | 29     |
| 32       | 64.76    | 66.55         | 0.34              | 0.26                | 0.66  | 0.74       | 0.42 | 30     |

### Table 4 ANOVA table for PISF

| Source                | DF | Adj SS | Adj MS | F-  | P-  | Remarks |
|-----------------------|----|--------|--------|-----|-----|---------|
| Model                 | 20 | 111.22 | 55.561 | 11.23 | 0.000 | Significant |
| Linear                | 5  | 491.63 | 98.326 | 19.88 | 0.000 | Significant |
| RPM                   | 1  | 63.34  | 63.343 | 12.81 | 0.004 | Significant |
| Working Gap           | 1  | 99.59  | 99.593 | 20.13 | 0.001 | Significant |
| Conc. of NaNO₃        | 1  | 47.74  | 47.743 | 9.65  | 0.010 | Significant |
| % Wt. of abrasive     | 1  | 83.44  | 83.440 | 16.87 | 0.002 | Significant |
| Pulse on time t₀ (sec)| 1  | 197.51 | 197.513| 39.93 | 0.000 | Significant |

R² = 0.9533  Adjusted R²= 0.8685
Table 5 Anova table for MRR

| Source                     | DF | Adj SS   | Adj MS   | F-Value | P-Value | Remarks  |
|----------------------------|----|----------|----------|---------|---------|----------|
| Model                      | 20 | 1264.19  | 63.210   | 13.99   | 0.000   | Significant |
| Linear                     | 5  | 918.24   | 183.649  | 40.66   | 0.000   | Significant |
| RPM                        | 1  | 178.11   | 178.106  | 39.43   | 0.000   | Significant |
| Working Gap                | 1  | 400.00   | 400.003  | 88.55   | 0.000   | Significant |
| Conc. of NaNO₃             | 1  | 70.86    | 70.864   | 15.69   | 0.002   | Significant |
| % Wt. of abrasive          | 1  | 104.00   | 104.000  | 23.02   | 0.001   | Significant |
| Pulse on time t_on (sec)   | 1  | 165.27   | 165.270  | 36.59   | 0.000   | Significant |

R² = 0.9622        Adjusted R²= 0.8934

Table 6 Experimental results for various levels of process on response (PISF) and confirmation analysis

| Exp. No. | Rotational speed (RPM) | Working gap (mm) | Conc. of NaNO₃ (% wt.) | % Wt. of abrasives | Pulse on time (s) | PISF | MRR  |
|-----------|------------------------|------------------|------------------------|--------------------|-------------------|------|------|
| 1         | 200                    | 2                | 8                      | 15                 | 8                 | 65.48 | 82.14|
| 2         | 100                    | 2                | 8                      | 15                 | 4                 | 76.50 | 64.83|
| 3         | 200                    | 4                | 8                      | 25                 | 8                 | 78.20 | 77.87|
| 4         | 100                    | 2                | 8                      | 25                 | 8                 | 67.07 | 82.10|
| 5         | 100                    | 4                | 8                      | 15                 | 8                 | 66.27 | 68.38|
| 6         | 150                    | 3                | 6                      | 20                 | 6                 | 70.94 | 68.94|
| 7         | 100                    | 2                | 4                      | 15                 | 8                 | 54.43 | 68.59|
| 8         | 200                    | 4                | 4                      | 15                 | 8                 | 73.68 | 63.20|
| 9         | 100                    | 4                | 4                      | 15                 | 4                 | 82.73 | 60.23|
| 10        | 50                     | 3                | 6                      | 20                 | 6                 | 70.61 | 70.67|
| 11        | 150                    | 3                | 6                      | 20                 | 6                 | 69.41 | 70.19|
| 12        | 150                    | 3                | 6                      | 20                 | 6                 | 71.00 | 68.94|
| 13        | 150                    | 1                | 6                      | 20                 | 6                 | 68.85 | 85.00|
| 14        | 150                    | 3                | 6                      | 20                 | 10                | 69.68 | 72.18|
| 15        | 100                    | 4                | 4                      | 25                 | 8                 | 78.40 | 65.25|
| 16        | 200                    | 2                | 8                      | 25                 | 4                 | 79.30 | 76.72|
| 17        | 150                    | 3                | 6                      | 10                 | 6                 | 67.18 | 61.50|
| 18        | 150                    | 3                | 2                      | 20                 | 6                 | 73.96 | 63.63|
| 19        | 150                    | 3                | 6                      | 20                 | 6                 | 70.36 | 69.94|
| 20        | 200                    | 2                | 4                      | 25                 | 8                 | 71.30 | 78.96|
| 21        | 250                    | 3                | 6                      | 20                 | 6                 | 80.38 | 79.81|
| 22        | 150                    | 3                | 6                      | 30                 | 6                 | 72.30 | 70.17|
| 23        | 150                    | 3                | 6                      | 20                 | 6                 | 69.00 | 68.94|
| 24        | 150                    | 3                | 6                      | 20                 | 2                 | 74.32 | 61.47|
| 25        | 150                    | 3                | 6                      | 20                 | 6                 | 70.60 | 68.94|
| 26        | 100                    | 2                | 4                      | 25                 | 4                 | 84.73 | 66.23|
| 27        | 200                    | 4                | 8                      | 15                 | 4                 | 76.88 | 66.94|
| 28        | 200                    | 4                | 4                      | 25                 | 4                 | 78.11 | 68.34|
| 29        | 200                    | 2                | 4                      | 15                 | 4                 | 71.39 | 75.09|
| 30        | 150                    | 5                | 6                      | 20                 | 6                 | 78.88 | 64.96|
| 31        | 150                    | 3                | 10                     | 20                 | 6                 | 67.19 | 64.43|
| 32        | 100                    | 4                | 8                      | 25                 | 4                 | 64.76 | 66.55|
5.1 Statistical model to predict PISF

The statistical model for PISF was obtained as shown in equation (13). ANOVA was use to analysed the results. Table 4 represents the ANOVA values. The obtained model for calculation of PISF is given below.

\[
PISF = 70.180 - 1.625 \text{ RPM} + \\
2.037 \text{ working gap} - 1.410 \text{ Conc. of NaNO}_3 + \\
1.865 \% \text{ Wt. of abrasive} - 2.869 \text{ pulse on time} + \\
1.358 (\text{RPM})^2 + 0.950 (\text{Working gap})^2 + \\
0.128 (\text{Conc. of NaNO}_3)^2 - 0.081 (\% \text{ Wt. of abrasive})^2 + \\
0.484 (\text{Pulse on time})^2 + 0.623 \text{ RPM} \times \\
\text{Working gap} + 1.942 \text{ RPM} \times \text{Conc. of NaNO}_3 + \\
0.278 \text{ RPM} \times \% \text{ Wt. of abrasive} + 1.596 \text{ RPM} \times \\
\text{Pulse on time} - 2.082 \text{ Working gap} \times \\
\text{Conc. of NaNO}_3 - 2.168 \text{ Working gap} \times \\
\% \text{ Wt. of abrasive} + 2.982 \text{ Working gap} \times \\
\text{Pulse on time} - 1.632 \text{ Conc. of NaNO}_3 \times \\
\% \text{ Wt. of abrasive} + 1.171 \text{ Conc. of NaNO}_3 \times \\
\text{Pulse on time} + 2.232 \% \text{ Wt. of abrasive} \times \\
\text{Pulse on time} \tag{13}
\]

5.2 Statistical model to predict MRR

The statistical model for MRR was obtained as shown in equation (14). ANOVA was use to analysed the results. Table 5 represents the ANOVA values. The obtained model for calculation of MRR is given below.

\[
\text{MRR} = 69.076 - 2.724 \text{ RPM} - \\
4.082 \text{ working gap} + 1.718 \text{ Conc. of NaNO}_3 + \\
2.082 \% \text{ Wt. of abrasive} + 2.624 \text{ pulse on time} + \\
1.720 (\text{RPM})^2 + 1.655 (\text{Working gap})^2 - \\
1.082 (\text{Conc. of NaNO}_3)^2 - 0.631 (\% \text{ Wt. of abrasive})^2 - \\
0.383 (\text{Pulse on time})^2 + 0.951 \text{ RPM} \times \\
\text{Working gap} - 0.217 \text{ RPM} \times \text{Conc. of NaNO}_3 - \\
0.224 \text{ RPM} \times \% \text{ Wt. of abrasive} - 0.713 \text{ RPM} \times \\
\text{Pulse on time} + 0.362 \text{ Working gap} \times \\
\text{Conc. of NaNO}_3 + 0.369 \text{ Working gap} \times \\
\% \text{ Wt. of abrasive} - 1.017 \text{ Working gap} \times \\
\text{Pulse on time} + 0.580 \text{ Conc. of NaNO}_3 \times \\
\% \text{ Wt. of abrasive} + 1.834 \text{ Conc. of NaNO}_3 \times \\
\text{Pulse on time} + 0.695 \% \text{ Wt. of abrasive} \times \\
\text{Pulse on time} \tag{14}
\]

5.3 Effect of process parameters on PISF

Table 6 shows the output response data for each run. The influence of input factors on PISF is shown by Figure 5. The variation of centrifugal force occurs with rotational speed. The centrifugal force has a significant impact on the PISF. Centrifugal force acting on abrasive particle is very low at low RPM, so improper brush formation due to accumulation of particles at centre of flexible brush. Increased centrifugal force pushed the abrasives outward as the rpm of the specimen increased, resulting in the formation of a perfect flexible abrasive brush. At low working gap, improper brush formation due to accumulation of particles at centre of flexible brush. The formation of a perfect flexible abrasive brush with increase in gap between work piece and magnet which results an increase in PISF value. PISF reduces with rise in electrolyte concentration. Due to rise in the amount of ions in the machining zone which raises the reaction rate, resulting in significant increase in PISF due to increase in MRR. A rise in percentage of abrasives by weight from 10 to 30% results in significant increase in PISF due to increase in the quantity of diamond abrasives in iron particles. With increase in pulse on duration from 2 to 10 sec, surface finish from the work surface changes from abrasive removal of passive layer to more abrupt ‘pulling out’ of atoms from work surface. This pulling out of the atoms is probably responsible for decrease in PISF value.

5.4 Effect of process parameters on MRR

Main effect plot for MRR as shown in Figure 6. With increasing rotational speed, the centrifugal force varies. The centrifugal force has a significant impact on the MRR. Centrifugal force acting on abrasive particle is very low at low RPM, so improper brush formation due to accumulation of particles at centre of flexible brush. Enhanced centrifugal force pushed the abrasives outward as the rpm of the specimen increased, resulting in the formation of a perfect flexible abrasive brush. When the working space increased from 1 to 5 mm, the MRR decreases. With increase in working gap, magnetic density in the machining zone would decreases which in turn will result in changed magnitude and direction of Lorentz’s force. The impingement of abrasive particles on work surface therefore decreases, which in turn results in lower MRR at higher value of working gap. An increase in concentration of electrolyte (NaNO_3) from 2 to 6% by weight increases the number of ions in the machining area which in turn increases the reaction rate and results an increase in MRR. Further rise in electrolyte concentration (NaNO_3) from 6 to 10% by weight probably hinders ionic mobility because of overcrowding of ions and results in decrease in MRR. MRR rises with rise in percentage of abrasives by weight from 10 to 30 due to increase the quantity of
diamond abrasives in iron particles. MRR increases as pulse on time increases from 2 to 10 seconds. Due to high intensity impacts of abrasives impacting work piece surface along longitudinal and circumferential directions simultaneously under the influence of ultrasonic vibrations.

5.5 Response of Grey relational grade

Optimised pattern of performance variables: RPM (level 2), working gap (level -2), conc. NaNO₃ (level 1), % wt. of abrasive (level 1), pulse on time ton (level -1). Table 7 shows the response table for grey relational grade.

5.6 Improvement in GRG

The best parameter combination of UAEMAM process found by means of GRA is 2 -2 1 1 -1. Improvement in GRG presents in Table 8. Improvement in GRG by 0.1363.

![Main Effects Plot for PISF](image1.png)

Fig. 5 Main effects plot for PISF

![Main Effects Plot for MRR](image2.png)

Fig. 6 Main effects plot for MRR

| Parameter                  | Level | Level | Level | Level | Level | GRG   | Rank |
|----------------------------|-------|-------|-------|-------|-------|-------|------|
| Rotational speed (RPM)     | 0.49  | 0.53  | 0.49  | 0.58  | 0.74  | 0.250 | 2    |
| Working gap (mm)           | 0.74  | 0.58  | 0.49  | 0.53  | 0.55  | 0.254 | 1    |
| Conc. of NaNO₃ (wt. %)     | 0.48  | 0.55  | 0.52  | 0.56  | 0.42  | 0.143 | 4    |
| % Weight of abrasive       | 0.40  | 0.51  | 0.52  | 0.60  | 0.50  | 0.195 | 3    |
| Pulse on time $t_{on}$ (s) | 0.47  | 0.57  | 0.51  | 0.55  | 0.50  | 0.099 | 5    |

Table 7 Response table for grey relational grade
### Table 8 Improvement in GRG

| Setting level | RPM   | Working gap (mm) | Conc. of NaNO₃ (% wt.) | % Wt. of abrasives | Ton (s) | GRG   | Improvement in GRG |
|---------------|-------|------------------|------------------------|-------------------|--------|-------|-------------------|
| Optimal control parameters | 2 -2 1 1 -1 | 250  | 1  | 8  | 25  | 4   | 0.6429             |
| Initial control parameters | 0 0 0 0 0 | 150  | 3  | 6  | 20  | 6   | 0.5066 0.1363      |

### 6 Surface tester results

The Ra of initial and finished sample was measured with instrument (Mitutoyo SJ-410) with a 0.001 µm least count and cut-off length 0.8 mm. The surface generated by traditional grinding having hair line scratches. Work piece before UAEMAM and after UAEMAM process as shown in Figure 7(a) and 7(b).

### 7 SEM analysis

The scanning electron microscope (SEM) of initial sample and UAEMAM sample were analyzed the surface produced before and after UAEMAM as shown in Figure 8(a) and 8(b). The deep tool scratches produced on specimen during conventional machining have been minimized. As a result, smooth surface produced after UAEMAM. Thus such finished 316L stainless steel should be more effective in applications like surgical tools and bio-medical applications.

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**Fig. 7(a)** Work piece before UAEMAM

**Fig. 7(b)** Work piece after UAEMAM

**Fig. 8(a)** SEM before UAEMAM

**Fig. 8(b)** SEM after UAEMAM
The surface contour of initial sample and after UAEMAM process as shown in Figure 9(a) and 9(b). Peaks and valleys in roughness profile were more before UAEMAM process and reduced after UAEMAM process as shown in Figure 10(a) and 10(b).

8 EDS Analysis

EDX (Energy Dispersive X-Ray Analysis), commonly known as EDS or EDAX, is an x-ray technique for determining the elemental composition of materials.

Fig. 11 EDX of initial work piece before UAEMAM process
**Fig. 12** EDX sample at best parameter combination of UAEMAM process obtained from GRA

**Fig. 13** EDX of sample number 9 with high passivation after UAEMAM process

**Table 9** Quantitative results of EDX analysis

| Analyzed sample                                      | Element | Mass % |
|-------------------------------------------------------|---------|--------|
| Initial work piece (before UAEMAM)                   | Fe      | 72.17  |
|                                                       | Cr      | 18.89  |
|                                                       | Ni      | 8.95   |
| EDX sample at best parameter combination of UAEMAM process obtained from GRA | Fe      | 72.63  |
|                                                       | Cr      | 17.85  |
|                                                       | Ni      | 9.52   |
| Sample number 9 with high passivation after UAEMAM process | O       | 12.68  |
|                                                       | Fe      | 65.13  |
|                                                       | Cr      | 22.20  |
The EDX analysis shows presence of similar composition of Cr, Fe and Ni for initial work piece before UAEMAM process and sample at best parameter combination of UAEMAM process obtained from GRA as shown in Figs. 11 and 12. The composition of sample number 9 with high passivation shows that composition is different from original surface as shown in Fig. 13. The passive films are completely removed by UAEMAM process. For present study NaNO$_3$ is used for electrolytic reaction, NO$_3^-$ and OH$^-$ moves toward anode and Na$^+$ and H$^+$ moves toward cathode. The ionization tendency of H is less than Na. The OH$^-$ discharges easily as compared to NO$_3^-$. O$_2$ and H$_2$ is generated at anode and cathode respectively. Under the action of oxygen, most of anode metal is oxidized. Lot of metal ions such as Fe$^{3+}$, Fe$^{2+}$, Ni$^{2+}$ and other elements on the surface of metal are eluted by oxidation reaction. This is the main reason that composition of Fe and Ni elements are decreased during more passivation as compare to composition of original surface. The quantitative results of EDX analysis are presented in Table 9.

9 Conclusions

The workpieces of 316L stainless steel has been machined and finished by novel technique i.e. ultrasonically aided electrochemical magnetic abrasive machining. The performance of this novel technique has been analysed with experimentation by applying central composite design of experiments for machining SS 316L. Experiments were conducted to study the effect of rotational speed, working gap, concentration of NaNO$_3$, percentage weight of abrasives and pulse on time on material removal and surface roughness. The following key conclusions can be drawn from the experimental results:

1. A novel technique to hybrid three processes brought improvement of machining and finishing of SS 316L with new designed set up successfully.

2. It was concluded from ANOVA that pulse on time contributes maximum (36.17%) followed by working gap (18.23%), % wt. of abrasives (15.28%), rotational speed (11.60%) and concentration of NaNO$_3$ (8.74%) for PISF. Working gap contributes maximum (41.33%) followed by rotational speed (18.40%), pulse on time (17.07%), % wt. of abrasives (10.74%) and concentration of NaNO$_3$ (7.32%) for MRR.

3. From grey relational grade, the optimal levels for UAEMAM process variables yield - Rotational speed = 250 rpm, Working gap = 1 mm, Concentration of NaNO$_3$ = 8, % wt. of abrasive = 25 and pulse on time ($t_{on}$) = 4 seconds.

4. The EDS analysis revealed the absence of oxide layer further improving surface finish. Also, SEM micrographs and surface roughness profile confirmed the surface finish improvement by UAEMAM process.

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