Process Parameter Optimization of Ultrasonic Assisted Electrochemical Magnetic Abrasive Finishing of 316L Stainless Steel

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Abstract. There is requirement of advancements in the machining processes able to achieve better surface finish in tight tolerances. It is not always easy to produce work piece characteristics in order to fulfill the listed requirements by only using the traditional finishing processes. Ultrasonic assisted electrochemical magnetic abrasive finishing (UEMAF) is a hybrid micro machining process and finish surfaces of hard and brittle materials up to nanometer scale. UEMAF integrates the use of electrochemical machining, ultrasonic vibrations and magnetic abrasive finishing. Taguchi technique is used to find optimal process parameters of Ultrasonic assisted electrochemical magnetic abrasive finishing (UEMAF). A L9 Orthogonal array, applied to analyze the effect of ultrasonic assisted electrochemical magnetic abrasive finishing process parameters (rpm of work piece, % wt. of abrasive and ultrasonic frequency time) on percentage improvement in surface finish (PISF).

Keywords: Ultrasonic Frequency, Magnetic Abrasive Finishing, Electrochemical Machining, Hybrid micro machining processes, Surface roughness.

1. Introduction
In industrial applications, uses of some materials are hard to machine and finish with minimal surface defects and high accuracy using traditional machining and polishing methods. Use of conventional machining methods for finishing of hard materials may also lead to different defects like surface distortions, micro cracks and errors in geometry of the work piece. It is not always easy to produce work piece characteristics in order to fulfill the listed requirements by only using the traditional finishing processes. Even in some cases, if these processes can be used, they demand large and extremely skilled labor. The required degree of accuracy and surface finish is attained by newly developed hybrid processes.
However, the traditional machining which involves a single process only cannot cope with the existing need for both high efficiency and high quality. Thus, the current and latest trend in the manufacturing field is represented by a process known as hybrid machining that integrates various processes to acquire the current demand. The constituent machining processes produce some adverse effects when they are separately applied. Therefore, a hybrid machining process not only reduces these adverse effects but also make use of the mutually or combined enhanced benefits. The efficiency of a hybrid machining process may be valuable and considerable (Kozak, 2000; Kozak, 2001; Dabrowski, 2006; Hocheng, 2002).

Numerous researchers have suggested various hybrid machining processes based on different working mechanisms (Kozak, 2001; Dabrowski, 2006; Hocheng, 2002; Ilhan, 1992). In electrochemical grinding (ECG) process, the method of material removal includes two different actions viz. mechanical and electrochemical (Ilhan, 1992; Tehrani, 2000). Further, to produce high level of surface finish for metals, roller burnishing and electrochemical turning have been combined together.

2. Principle of ultrasonic assisted electrochemical magnetic abrasive finishing

Ultrasonic assisted electrochemical magnetic abrasive finishing can primarily be used for machining and finishing of hard materials. In electrochemical machining, the current supply between work piece and electrode. The oxidation film formed on work piece surface due to chemical reaction. The oxide film is removed with the use of particles of magnetic abrasives and orientation of magnetic abrasive particles change with the help of ultrasonic vibrations. The formation of oxide film by ECM, removal of film with MAF and change the orientation of magnetic abrasive particles is on-going at the same time in UEMAF process.

3. Experimental Set up

The experiments were conducted on UEMAF set up as shown in figure 3. The electrochemical unit having copper electrode, electrolyte (NaNO₃) and DC power supply is installed for ECM unit. The electromagnets and MAPs are used for MAF unit. Ultrasonic generator is used to produce ultrasonic vibrations for excitation of electromagnets.

DC motor is used for rotation of chuck with variable rpm. The rpm of motor sensed by sensor and monitored on the display of variac. The work piece is hold in an insulated chuck and gives the rotational speed. The work piece holding chuck is insulated with the use of Teflon bush. The copper electrode with jet system is placed at the upper surface of the work piece at a gap of 5mm. Electrolyte is injected through copper electrode on the upper surface of cylindrical work piece. The used electrolyte is collected back to the sump and re-circulated again as shown in figure 1.
The passive films are generated by electrolytic process. Magnetic abrasive brush was used to remove the passive films formed by electrolytic process. In MAF, particles of magnetic abrasives are placed between work piece and magnetic poles, rotational movement is given to the work piece. For finishing of cylindrical work piece, magnetic field produced by electromagnet is used for formation of flexible abrasive brush. While conducting experiments, the electromagnets were held in a designed fixture which was excited with ultrasonic generator through horn. Electromagnet holding fixture was designed to hold the electromagnets and the electromagnetic fixture is directly connected to horn. The fixture also allow small longitudinal movement of electromagnet.

4. Experimental Procedure
In present work, Taguchi technique was used for solving machining and finishing problem. Nine experiments were conducted in random order. Input variables and their corresponding levels are shown in Table 2.

### Table 1. Constant process parameters.

| Sr. No. | Parameter                      | Value  |
|---------|--------------------------------|--------|
| 1       | Magnetic flux density          | 8000 Gauss |
| 2       | Pulse off time, T<sub>off</sub> | 10 sec     |
| 3       | Working gap                    | 5 mm    |
| 4       | Time for each experiment       | 15 minutes |
| 5       | Ultrasonic power supply        | 720 W    |

Initially, surface roughness (R<sub>a</sub>) of 316L stainless steel cylindrical work piece was measured at five different points and average of five values was calculated. After finishing of work piece with UEMAF process, R<sub>a</sub> values were measured again at five different points and average of R<sub>a</sub> was calculated.
Table 2. Selected variable levels for UEMAF.

| Variable                  | Level 1 | Level 2 | Level 3 |
|---------------------------|---------|---------|---------|
| Rotational Speed (RPM)    | 200     | 400     | 600     |
| % Wt. of abrasives        | 15      | 20      | 25      |
| Ultrasonic Frequency time (s) | 2      | 4       | 6       |

Table 3. Response Table.

| Experiment No. | Rotational speed (rpm) | % wt. of abrasives | Ultrasonic frequency time (sec) | PISF   |
|----------------|------------------------|--------------------|---------------------------------|--------|
| 1              | 200                    | 15                 | 2                               | 68.29  |
| 2              | 200                    | 20                 | 4                               | 68.09  |
| 3              | 200                    | 25                 | 6                               | 72.12  |
| 4              | 400                    | 15                 | 4                               | 76.27  |
| 5              | 400                    | 20                 | 6                               | 81.63  |
| 6              | 400                    | 25                 | 2                               | 79.23  |
| 7              | 600                    | 15                 | 6                               | 73.09  |
| 8              | 600                    | 20                 | 2                               | 68.56  |
| 9              | 600                    | 25                 | 4                               | 72.30  |

In present work, the S/N ratio (Signal to Noise ratio) is selected as per criterion, the ‘larger-the-better’ in order to improvement in surface finish maximize. The signal strength to background noise is measured by plotted S/N ratio as shown in Figure 4.

Table 4. S/N Ratio for PISF.

| Level | Rotational speed (rpm) | % Wt. of abrasives | Ultrasonic frequency time(sec) |
|-------|------------------------|--------------------|--------------------------------|
| 1     | 36.84                  | 37.20              | 37.13                          |
| 2     | 37.95                  | 37.21              | 37.16                          |
| 3     | 37.06                  | 37.44              | 37.56                          |
| Delta | 1.12                   | 0.24               | 0.43                           |
| Rank  | 1                      | 3                  | 2                              |

For each parameter of process, the highest S/N ratio is the optimal level. From figure 4, it is observed that the PISF is highest for rotational speed of work piece at the level 2, % wt. of abrasives and ultrasonic frequency time at level 3. The analysis of variances shows that rotational speed of work piece (82.2%) is the most influencing factor for PISF followed by ultrasonic frequency time (13.39%) and % wt. of abrasive (4.34%) as shown in Table 5.
The effect of rotational speed, % wt. of abrasives and ultrasonic frequency time when machining and surface finish of 316L stainless steel using ultrasonic assisted electrochemical magnetic abrasive finishing as shown in figure 4. The variation of centrifugal force depends upon rpm. At low value of rpm, the centrifugal force acting on work piece is also less. It was observed that PISF increases from 200 to 400 rpm and value of PISF goes on decreasing with further increase in rpm. After 400 rpm, improper contact of flexible abrasive brush with work piece. The PISF increases with increase in % wt. of abrasives 15 to 25 gm. It is so because with increase in % wt. of abrasives, quantity of diamond powder increases as compare to iron powder which lead to increase the finishing ability. The PISF increases with increase in ultrasonic frequency time 2 to 6 sec. The cutting force increases by number of active particles come in contact with work piece increases.

The optimal value of PISF can be determined by using Eq. (1)
\[
\eta_{opt} = m + (m_{rpm2} - m) + (m_{% wt. of abrasive3 - m}) + (m_{ultrasonic freq.3 - m})
\]

\[
\text{where } m_{rpm3} \text{ is S/N data mean value for RPM at highest level,}
\]
\[
m_{% wt. of abrasive3} \text{ is S/N data mean value for % wt. of abrasive at highest level.}
\]

From Eq. (1), \( \eta_{opt} = 38.39 \), which calculate the optimum value of PISF to be 83.08.

| Source                  | DF | Seq SS     | % Contribution |
|-------------------------|----|------------|----------------|
| Rotational Speed        | 2  | 2.09683    | 82.2           |
| % Wt. of abrasive       | 2  | 0.11076    | 4.34           |
| Ultrasonic frequency time | 2  | 0.34152    | 13.39          |
| Error                   | 2  | 0.05770    | 2.21           |
| Total                   | 8  | 2.60681    |                 |
At the optimum process parameters, confirmatory experiments were carried out to validate the optimum results evaluated by the statistical analysis. At optimum levels, the comparison of experimental results with predicted PISF is shown in Table 6.

**Table 6. Results of confirmation test.**

| RPM | % wt. of abrasive | Ultrasonic frequency time | PISF | Error (%) |
|-----|-------------------|---------------------------|------|-----------|
| 400 | 25                | 6                         | 83.08| 82.12     | 1.15      |

5. **Surface tester**
Surface roughness tester (Mitutoyo SJ-410) having a least count of 0.001 µm was used. The surface having scratches generated by conventional grinding. The result of the surface produced by conventional grinding is shown in figure 5 and surface produced after UEMAF is shown in figure 6. This profiles indicates that the valleys and peaks are minimize to greater extent to achieve superior surface finish.

![Figure 5. Surface roughness result before UEMAF.](image1)
![Figure 6. Surface roughness result after UEMAF.](image2)

6. **Conclusions**
In present work, 316L stainless steel cylindrical work pieces were successfully machined and finished by UEMAF process. From ANOVA, it was concluded that rotational speed contributes maximum (82.2%), as followed by ultrasonic frequency time (13.39%) and % wt. of abrasives (4.34%). For maximization of PISF, the optimum process parameters are rotational speed of 400 rpm, % wt. of abrasives of 25 and ultrasonic frequency time of 6 seconds. With UEMAF process, 82 % improvement in surface finish was observed at optimum levels.

**ACKNOWLEDGEMENTS**
Authors would like to express special thanks to Mechanical Engineering Department, Punjabi University, Patiala (Punjab) for providing the opportunity to carry out this research work.
References

[1] Choi, J.P., Jeon, B.H. and Kim, B.H. (2007) “Chemical-assisted ultrasonic machining of glass.” J Mater Process Technol 191:153–162.

[2] Dabrowski, L., Marciniak, M. and Szewczyk, T. (2006) “Analysis of abrasive flow machining with an electrochemical process aid.” Proc Inst Mech Eng B Eng Manuf 220:397–403.

[3] De’Silva, A.K.M., Pajak, P.T., Harrison, D.K. and Mcgeough, J.A. (2004) “Modelling and experimental investigation of laser assisted jet electrochemical machining.” CIRP Ann Manuf Technol 53(1):179–182.

[4] De’Silva, A.K.M., Pajak, P.T., Mcgeough J.A. and Harrison D.K. (2011) “Thermal effects in laser assisted jet electrochemical machining.” CIRP Ann Manuf Technol 60(1):243–246.

[5] Ding, H., Shen, N. and Shin, Y.C. (2012) “Thermal and mechanical modeling analysis of laser assisted micro-milling of difficult-to-machine alloys.” J Mater Process Technol 212(1):01–13.

[6] Ebeid, S.J. and El-Taweel, T.A. (2005) “Surface improvement through hybridization of electrochemical turning and roller burnishing based on the Taguchi technique.” Proc Inst Mech Eng B Eng Manuf 219:423–430.

[7] Ebeid, S.J., Hewidy, M.S., El-Taweel, T.A. and Youssef, A.H. (2004) “Towards higher accuracy for ECM hybridized with low frequency vibrations using the response surface methodology technique.” J Mater Process Technol 149(1):3428–3434.

[8] Egashira, K., Mizutani, K. and Nagao, T. (2002) “Ultrasonic vibration drilling of micro holes in glass.” CIRP Ann Manuf Technol 51(1):339–342.

[9] Enache, S. and Opran, C. (1989) “The mathematical model of the ECM with magnetic field.” Ann CIRP 83(1):207–210. Fang JC, Jin ZJ, Xu WJ, Shi YY (2002) Magnetic electrochemical finishing machining. J Mater Process Technol 129(1–3):283–287.

[10] Gangopadhyay, S., Sarkar, B.R. and Bhattacharyya, B. (2005) “Analysis of surface integrity of EDMed jobs through RSM based models”, in the Proceedings of 4th National Conference on Precession Engineering (COPEN), Kolkata, 269–275.

[11] Ghoshal, B. and Bhattacharyya, B. (2013) “Influence of vibration on micro-tool fabrication by electrochemical machining.” Int Mach Tools Manuf 64:49–59.

[12] Farwaha, H.S., Singh, S. and Singh, G. (2016) “Design and performance of magnetic abrasive finishing set up for finishing of extended surfaces” Asian Review of Mechanical Engineering 5(1):1–4.

[13] Hewidy, M.S., El-Taweel, T.A. and El-Safty, M.F. (2005) “Modelling the machining parameters of wire electrical discharge machining of Inconel 601 using RSM,” J Mater Process Technol 169: 328–336.

[14] Hoang, K.T. and Yang, S.H. (2013) “A study on the effect of different vibration-assisted methods in micro-WEDM.” J Mater Process Technol 213:616–622.

[15] Hocheng, H. and Pa, P.S. (2002) “The application of turning tool as the electrode in electro polishing.” J Mater Process Technol 120:6–12.

[16] Ilhan, R.E., Sathyanarayanan, G., Storer, R.H. and Phillips, R.E. (1992) “A study of wheel wear in electrochemical surface grinding.” ASME J Eng Ind 114:82–93.

[17] Jain, V.K., Kumar, P., Behra, P.K. and Jayswal, S.C. (2001), “Effect of working gap and circumferential speed on the performance of magnetic abrasive finishing process”, Wear 250: 384-390.

[18] Judal, K. and Yadava, V. (2013) “Electrochemical Magnetic Abrasive Machining of AISI304 Stainless steel tubes.” International journal of precision engineering and manufacturing 14(1): 37-43

[19] Mulik, R.S. and Pandey, P.M. (2010), “Ultrasonic assisted magnetic abrasive finishing of hardened AISI 52100 steel using unbounded SiC abrasives,” Int. Journal of Refractory Metals and Hard Materials 29: 68-77.
[20] Mukesh, M., Singh, S. and Farwaha, H.S. (2018) “Optimization and prediction of sintering process parameter of magnetic abrasives preparation using response surface methodology” International Journal of Data and Network Science 3(2):103-108.

[21] Sihag, N., Kala, P. and Pandey, P. M. (2014), “chemo-ultrasonic assisted magnetic abrasive finishing: experimental investigations” 5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014) December 12th–14th, 2014, IIT Guwahati, Assam, India.

[22] Yasuo Kimoto (1994) “Ultra-precision machining by electrolytic complex method”. Tokyo: aipishi : 111-116.

[23] Zhu, D., Zeng, Y.B., Xu, Z.Y. and Zhang, X.Y. (2011) “Precision machining of small holes by the hybrid process of electrochemical removal and grinding.” CIRP Ann Manuf Technol 60:247–250.