An investigation into magnetic electrolytic abrasive turning

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Abstract. The magnetic electrolytic abrasive turning (MEAT) process as a non-traditional machining is used to obtain surface finishing like mirror. MEAT provides one of the best alternatives for producing complex shapes with good finish in advanced materials used in aircraft and aerospace industries. The improvement of machining accuracy of MEAT continues to be a major challenge for modern industry. MEAT is a hybrid machining which combines two or more processes to remove material. The present research focuses on the development of precision electrochemical turning (ECT) under the effects of magnetic field and abrasives. The effect of magnetic flux density, electrochemical conditions and abrasive parameters on finishing efficiency and surface roughness are investigated. An empirical relationship is deduced.

1. Introduction

The electrolytic magnetic abrasive turning (EMAT) process is used for metal removal without burrs from complex shapes and gives supper finishing surface for hard and difficult to machine workpieces. Many previous studies have reported that EMAT is a very efficient finishing method for inner and outer finishing of tubes, the edge finishing and the finishing of flat surface [1, 2]. Many researchers have reported their experimental results and confirmed the high efficiency of the magnetic finishing methods for various materials and shapes of workpiece [3, 4]. The magnetic field can accelerate the mobility of the charged particles, accelerate the electrochemical reaction and reduce the surface roughness of the workpiece more quickly, which improves the lapping efficiency [3]. Electrolytic magnetic abrasive finishing is a compound process, involving magnetic field, abrasives and an electrolyte for finishing workpieces. The electrolytic process and abrasive pad is the much easier removal of the produce passive film (or oxide film layer on the original metal surface during electrolytic processing). Moreover, in the presence of both electric and magnetic field, the negatively charged ions move toward the anode surface along a cycloid curve by the action of the Lorentz force. Under appropriate operating conditions, this phenomenon build electrolytic effects, which produces increase in finishing efficiency, yielding a superior surface and excellent finishing, better than those obtained by magnetic abrasive finishing only [5].

During abrasive electrolytic process, electrochemical first produces a passive film on the work surface, the passive film was then immediately removed using an abrasive pad, which was made of a nonwoven cloth that contained abrasives. But magnetic electrolytic abrasive process can produce a fine surface finish due to the effect of magnetic field [6, 7]. However, many operating conditions with
wide ranges are applicable to magnetic electrolytic abrasive process within the range, short circuits will not occur in electrolysis. The finishing efficiency of magnetic electrolytic abrasive finishing is much higher than that of magnetic abrasive finishing only because of the contributions of both the electrolytic process and the effects of the magnetic field. Hence, the magnetic electrolytic abrasive finishing is a process that matches the current demand closely and can be used to accelerate the removal of material and simultaneously obtain a superior finishing surface.

Finally magnetic electrolyte abrasive finishing has better finishing characteristics than magnetic abrasive finishing, especially at a high electrolytic current. The parameters of electrode gap, magnetic flux density and electrolytic current must be appropriately fitted to produce passive film quickly. The softening of the passive film makes it easier to remove from the original metal surface [8]. The rate of workpiece revolution must also be matched to remove the passive film rapidly and thereby efficiently obtain a superior surface finish. A NaNO₃ electrolyte with concentration of 20% with pad of Al₂O₃ (mesh 8000) are used to produce a good surface quality [5]. A theoretical study of electrochemical, abrasive process and magnetic is presented [9]. The aim of the present paper are the construction of a prototype of the electrolytic magnetic abrasive turning (EMAT) process and the investigation of the effect of the main parameters on the EMAT process. Magnetic fields with electrolytic machining: Magnetic field affects the move path of electrolytic ions, from a linear path to a curved (cycloid) path, and also accelerates the ions. This results in the improvement of finishing efficiency [2, 9]. Therefore in the magnetic abrasive polishing process, surface roughness and metal removal improve at the same time compared with the traditional electrolytic process.

2. Experimental set-up
To carry out the experimental investigation, an electrochemical turning (ECT) system is developed, having the provisions of controlled electrolyte flow and automatic tool electrode feed as well as electrical circuit. The electrical circuitry of the ECT set-up includes a DC power supply with electrical elements for short-circuit prevention, spark detection and operation of the ECT system. Variation of the tool feed rate is obtained with the help of DC motor driving system. Figure 1 shows the parts of the abrasive pad device. The abrasive pad causes the removal of metal layers (oxide film) due to electrochemical operation. The removal of the oxide film causes the renewal of the electrochemical process and tacking sludge from workpiece resulting in good surface finishing. Figure 2 shows a photo of the abrasive device with mechanical vibration.

![Figure 1. Parts of abrasive pad device](image1.png)

![Figure 2. Photo of the abrasive device with mechanical vibration](image2.png)
The specifications of MEAT prototype are: $I_{\text{max}} = 60 \text{ A}$, $v_{\text{steps}} = (15, 18, 21, 24, 27, 30 \text{volt})$, tank capacity for electrolyte $Q = 60 \text{ L}$, pump motor power = 1.5 HP, swing over bed = 80 mm, distance between center = 300 mm and magnetic field ($H = 0.06 \text{ Tesla}$). Figure 3 shows a photo for magneto-electrolytic-abrasive turning (MEAT) process on lathe. While Figure 4 shows the schematic diagram of the MEAT process. During electrolyte supply with magnetic field the magnetic lines causes change of pass of ions movement, which add forces. The viscoelastic abrasive pad is set on the lathe and pressurized to produce the finishing pressure. This pressure removes the passive layer easily and allows the electrolytic process to arise continuously.

This was investigated to establish the processes conditions of MEAT for finishing to reduce the surface roughness value to reach high quality product for important industry parts. The MEAT process involved are required to be more precise and efficient to obtain a product whilst maintaining high productivity. A recent trend for quality by the MAET machining is alternate manufacturing process for traditional machining, which improves the surface finishing at low cost and reducing the surface roughness value. The MAET is a high polishing machine with compounded more of processes in simultaneous machining. These hybrid effect are run on simple lathe model, with additional variables: speed power unit, electrolyte system, mechanical device abrasive and magnetic field.

A calibration curve is obtained for the abrasive pad device which can be used to know the value of the exerted force on the abrasive pad and then the required pressure can be calculated. Surface roughness measurements are taken on the specimen ring workpiece of $\varnothing 50 \times 15 \text{ mm}$. The roughness values recorded are average of seven readings measured along the width of the specimen. The surface roughness value for the machined surface is measured using the average roughness ($R_a$) in μm and peak to valley height ($R_z$) in μm.
3. Electrolytic-magnetic -abrasive turning (MEAT)

To investigate the effect of variables of MEAT process on the obtained roughness during the variation of machining time, rotational speed, pad pressure and material of workpiece. Tests were carried out according to the variable levels given in table 1.

| MEAT Variables       | Variable Levels | Units |
|----------------------|-----------------|-------|
| Machining time $t_m$ | 4 8 12 16 20 24 28 | min   |
| Rotational speed $n$ | 25 100 225 400 600 | rpm   |
| Pad pressure         | 0.5 1 2         | N     |
| Abrasive mesh        | 36 100 280      | # mesh|
| Magnetic field       | 0.06            | Tesla |

4. Results and discussion

4.1. Comparison between MEAT and EAT processes

It is required to study the further effect of magnetic field (for magnetic gap $G_m = 3$ mm) on the obtained surface roughness as another effect in case of EAT process. The EAT process parameters are carried out using SiC as abrasive of mesh 280 concentration 15% of NaNO$_3$ as electrolyte with 0.3 mm initial gap between the workpiece and stainless steel electrode while the flow rate 8 L/min as well as a voltage difference of 21 volt. The effect of EAT process only on the obtained surface roughness ($R_a$, $R_z$) is shown in Figure 5. It was noticed that the average roughness is decrease from $R_a = 0.13 \mu m$ to $R_a = 0.07 \mu m$ only, Which means that the intial $R_{ai}$ is decreased by 45% under the effect of EAT while under the effect of magnetic field as MEAT process a further decrease on surface roughness is occurred. The magnetic field is normal to the electrolyte gap.

The surface roughness value is decrease in the presence of a magnetic flux density compared with the case without the magnetic field. The relationships ($t_m - R_a$) and ($t_m - R_z$) during two processes MEAT and EAT is shown in Figure 5. A comparison between EAT and MEAT processes using NaNO$_3$ electrolyte on the obtained surface roughness ($R_a$, $R_z$) is shown in Figure 6. Under the effect of magnetic field average roughness is decreased from $R_a = 0.13 \mu m$ to 0.033 $\mu m$, which means that the initial $R_{ai}$ is decreased by 74% which means that the magnetic field shear in decrease of initial $R_{ai}$ by 29% over EAT process. It is important to introduce relative improvement scales in the present investigation as the reduction % of the initial roughness. The reduction percent of the initial roughness during MEAT process is the percent ratio between improvement in initial roughness after MEAT process and initial roughness before MEAT process. Therefore the reduction % in initial roughness can be mathematically evaluated as:

$$U_a = \frac{\Delta R_a}{R_{ai}} = \frac{R_{ai} - R_a}{R_{ai}} = \text{redu.} \% \text{ in } R_{ai}$$

$$U_z = \frac{\Delta R_z}{R_{zi}} = \frac{R_{zi} - R_z}{R_{zi}} = \text{redu.} \% \text{ in } R_{zi}$$

The effect of the type of processes as ECT or MEAT on both relationships ($u_a - t_m$) and ($u_z - t_m$) is shown in Figure 7 and Figure 8. It can be found out that the effect of magnetic field causes the decrease of the initial surface roughness ($R_{ai}$, $R_{zi}$) or ($U_a$, $U_z$) by (74%, 65%) respectively.
4.2. MEAT process for different workpiece materials

The effect of MEAT process for different workpiece materials in case of rotating workpiece on relationships (R_a - t_m) and (R_z - t_m) is shown in Figure 9. A magnetic field created by a magnet is applied on the region of the electrolyte in a normal direction. The magnetic flux is 0.06 Tesla (T), this effect is used for further improvements of surface roughness. A magnetic gap of (G_m = 3 mm) is used between the magnetic pole and the workpiece. Through ECT process with addition of both abrasive pad and magnetic field the increase of (t_m) causes the decrease of peak to valley height (R_z) and average roughness (R_a) of the machined workpiece with NaNO_3 electrolyte are shown in Figures 9 and 10 for different workpiece material. It was found out that R_a decrease by the increase of (t_m) for different workpiece materials of St 70, Stainless Steel and Cr-coated steel.

The decrease of roughness is due to the both effects of abrasive pad and magnetic flux density of 0.06 Tesla (T). Where the easier removal of the produced oxide film on the cycloid pass causes more removal rate in peak roughness as shown in Figure 9. During MEAT process using SiC particles of mesh 280 as a pad and a magnetic field of 0.06 T, the surface roughness was decrease sharply in the first 16 min but from 16 to 24 min there was no big different between surface roughness. the workpiece surface by abrasive pad results in the continuity of ECT process. While magnetic field causes addition force on ions and change its moving pass to cycloid pass.

Figure 6. A comparison between EAT process and MEAT process using NaNO_3 electrolyte on the obtained surface roughness (R_a, R_z).
Workpiece mat.: Cr-coated steel, Flux density = 0.06 T, Abrasive type: SiC, n = 100 rpm, grain size = 280, C = 15 % NaNO_3, v = 21 volt, Q = 8 L/min, G_i = 0.3 mm and G_m = 3 mm, t_m = 28 min, R_{ai} = 0.13 μm, R_{zi} = 1.1 μm

Figure 5. A comparison between EAT process and MEAT process using NaNO_3 electrolyte on relationships: (a) (t_m-R_a) (b) (t_m-R_z).
Workpiece mat.: Cr-coated steel, Flux density = 0.06 T, abrasive type: SiC, n = 100 rpm, grain size = 280, C = 15% NaNO_3, v = 21 volt, Q = 8 L/min, G_i = 0.3 mm and G_m = 3 mm, t_m = 4 min
Figure 8. Effect of type of process (ECT or MEAT) on the reduction percent of initial surface roughness ($U_a$, $U_z$) using NaNO$_3$ electrolyte. Workpiece mat.: Cr-coated steel, Flux density = 0.06 T, abrasive type: SiC, n = 100 rpm, grain size = 280, C = 15 % NaNO$_3$, v = 21 volt, Q = 8 L/min, $G_i$ = 0.3 mm and $G_m$ = 3 mm, $t_m$ = 28 min, $R_{ai}$ = 0.13 $\mu$m, $R_{zi}$ = 1.1 $\mu$m

By MEAT process the final surface roughness of $R_a = 0.058 \mu$m and $R_z = 0.54 \mu$m was obtained for a workpiece material of Cr-Coated steel while for stainless steel workpiece $R_a = 0.064 \mu$m and $R_z = 0.6 \mu$m was obtained. For Steel 70 workpiece $R_a = 0.072 \mu$m and $R_z = 0.67 \mu$m was obtained for the conditions given in Figure 10.

Figure 7. Effect of type of process using NaNO$_3$ electrolyte on relationships: (a)($U_{ai}$-$t_m$) (b) ($U_{zi}$-$t_m$). Workpiece mat.: Cr-coated steel, Flux density = 0.06 T, abrasive type: SiC, n = 100 rpm, grain size = 280, C = 15 % NaNO$_3$, v = 21 volt, Q = 8 L/min, $G_i$ = 0.3 mm and $G_m$ = 3 mm, $t_m$ = 4min, $R_{ai}$ = 0.13 $\mu$m, $R_{zi}$ = 1.1 $\mu$m

Figure 9. Effect of magnetic electrolytic abrasive turning (MEAT) process for different work piece materials for NaNO$_3$ electrolyte on the relation:  (a) ($R_a$ - $t_m$)  (b) ($R_z$ - $t_m$) Tool material: stainless steel, abrasive type: SiC, mesh = 280, n = 100 rpm, v = 21 volt, C = 15% NaNO$_3$, Q = 8 Lit/min, $G_i$ = 0.3 mm, $G_m$ = 3 mm, flux density = 0.06 T
Figure 10. Effect of different workpiece material in case of (MEAT) process using NaNO₃ electrolyte on surface roughness ($R_a$, $R_z$).

Tool material: stainless steel, Abrasive type: SiC, Grain size: 280, $n = 100$ rpm, $v = 21$ volt, $C = 15\%$ NaNO₃, $Q = 8$ L/min, $G_i = 0.3$ mm, $G_m = 3$ mm, flux density = 0.06 T, $t_m = 28$ min

Figure 11. Effect of different workpiece material in case of (MEAT) process in case of rotating workpiece for NaNO₃ electrolyte on relationships:

(a) $(t_m - U_a)$
(b) $(t_m - U_z)$

Tool material: stainless steel, Abrasive type: SiC, Grain size: 280, $n = 100$ rpm, $C = 15\%$ NaNO₃, $Q = 8$ L/min, $G_i = 0.3$ mm, $G_m = 3$ mm, flux density = 0.06 T, $t_m = 28$ min, $v = 21$ volt, ($R_{ai} = 0.16$ µm, $R_{zi} = 1.34$ µm for St 70), ($R_{ai} = 0.15$ µm, $R_{zi} = 1.24$ µm for Stainless steel) and ($R_{ai} = 0.143$ µm, $R_{zi} = 1.1$ µm for Cr-Coated steel)

Figure 12. Effect workpiece material on $U_a$ and $U_z$ during MEAT after $t_m = 28$ min.

Tool material: stainless steel, Abrasive type: SiC, Grain size: 280, $n = 100$ rpm, $C = 15\%$ NaNO₃, $Q = 8$ L/min, $G_i = 0.3$ mm, $G_m = 3$ mm, flux density = 0.06 T, $v = 21$ volt

The reduction percent in $R_{ai}$ and $R_{zi}$ or $U_a$ and $U_z$ is shown in Figure 11 and Figure 12 for the used materials. It can be noticed that the increase of the machining time causes the increase of $U_a$ and $U_z$ or the increase in the improvements of surface quality. The higher improvements occurred for Cr-coated steel due to its fine grains.

4.3. Effect of magnetic gap ($G_m$)

The effect of magnetic gap ($G_m$) on the relationships of ($R_a - t_m$) and ($R_z - t_m$) is shown in Figure 13 using NaNO₃ (15 %) electrolyte.
Figure 13. Effect of magnetic gap ($G_m$) in case of MEAT process using NaNO$_3$ electrolyte on relationship: (a) ($R_a - t_m$) (b) ($R_z - t_m$)

Workpiece mat.: Cr-coated steel, flux density = 0.06 T, Abrasive type: SiC, Grain size = 280, $n = 100$ rpm, $C = 15\%$ NaNO$_3$, $v = 21$ volt, $Q = 8$ L/min, $G_i = 0.3$ mm, $t_m = 28$ min, $R_{ai} = 0.15 \mu$m, and $R_{zi} = 1.45 \mu$m

Figure 14. Effect of magnetic gap ($G_m$) in case of MEAT process using NaNO$_3$ electrolyte on surface roughness ($R_a$, $R_z$).

Workpiece mat.: Cr-coated steel, flux density = 0.06 T, Abrasive type: SiC, Grain size = 280, $n = 100$ rpm, $C = 15\%$ NaNO$_3$, $v = 21$ volt, $Q = 8$ L/min, $G_i = 0.3$ mm, $t_m = 28$ min, $R_{ai} = 0.15 \mu$m, and $R_{zi} = 1.45 \mu$m

Figure 15. Effect of magnetic gap ($G_m$) in case of MEAT process using NaNO$_3$ electrolyte on relationship: (a) ($U_a - t_m$) (b) ($U_z - t_m$)

Workpiece mat.: Cr-coated steel, flux density = 0.06 T, Abrasive type: SiC, Grain size = 280, $n = 100$ rpm, $C = 15\%$ NaNO$_3$, $v = 21$ volt, $Q = 8$ L/min, $G_i = 0.3$ mm, $t_m = 28$ min, $R_{ai} = 0.15 \mu$m, and $R_{zi} = 1.45 \mu$m

Figure 16. Effect of magnetic gap ($G_m$) in case of MEAT process using NaNO$_3$ electrolyte on the reduction of initial roughness ($U_a$, $U_z$).

Workpiece mat.: Cr-coated steel, flux density = 0.06 T, Abrasive type: SiC, Grain size = 280, $n = 100$ rpm, $C = 15\%$ NaNO$_3$, $v = 21$ volt, $Q = 8$ L/min, $G_i = 0.3$ mm, $t_m = 28$ min, $R_{ai} = 0.15 \mu$m, and $R_{zi} = 1.45 \mu$m
It can be found out that the decrease of the magnetic gap ($G_m$) caused the decrease of the surface roughness ($R_a$, $R_z$). The decrease of surface roughness is due to the increase of the effect of changing path of moving electrolytic ions by the decrease of ($G_m$). As shown in Figure 14 the decrease of magnetic gap from $G_m = 4$ mm to $G_m = 2$ mm causes the decrease of the final $R_a$ from 0.07 µm to 0.047 µm, which means that $R_a$ decreased by 33 %. It can be shown in Figure 15 and Figure 16 that the decrease of $G_m$ causes the increase of both $U_a$ and $U_z$ the decrease of $G_m$ from 4 to 2 mm causes the increase of $U_a$ from 53 % to 68 % and the increase of $U_z$ from 49 % to 64%.

4.4. Effect of rotational speed of the workpiece ($n$)

The effect of the rotational speed ($n$) on the relationships of both ($R_a - t_m$) and ($R_z - t_m$) is shown in Figure 17. It can be deduced that the increase of ($n$) causes the decrease of the surface roughness. The increase of ($n$) causes the increase of the both effects of electrochemical metal removal and the mechanical abrasion by abrasives from the peaks of roughness. As shown in Figure 18 the increase of ($n$) from 100 to 300 rpm cause the decrease of roughness ($R_a$, $R_z$) from (0.06, 0.65 µm) to (0.035, 0.34 µm) respectively. Which means that the increase of rotational speed from 100 to 300 rpm causes the decrease of roughness ($R_a$, $R_z$) by (42 %, 52 %) respectively. The effect of ($n$) on both relationships ($U_a - t_m$) and ($U_z - t_m$) is shown in Figure 19.

It was found that the increase of ($t_m$) or ($n$) causes the increase of the reduction percent of initial roughness ($U_a$, $U_z$) as a relative measure of roughness. As shown in Figure 20 the increase of the rotational speed from 100 to 300 rpm and after MEAT process of a machining time of $t_m = 28$ min causes the increase of ($U_a$, $U_z$) from (50 %, 35 %) to (70 %, 73%) respectively. The magnetic field causes the improvement in surface roughness as explained before [22]. Figure 21 shows photo of mirror-like finishing workpiece, its surface roughness was improved to $R_a = 0.03$ µm and $R_z = 0.38$ µm for both stainless steel and Cr coated workpieces.

4.5. Governing equation for the results

The reduction percent in initial average roughness value ($U_a$) and main working parameters ($t_m$, $n$ and $G_m$) can be represented by the following empirical formula:

$$U_a = 0.0798 * n^{0.1923} * t_m^{0.31} / (G_m^{-0.0275})$$

The above empirical formula is used to deduce the reduction percent in initial average roughness in the following ranges. The magnetic field 0.06 T in the magnetic gap ($G_m$) from 2 to 4 mm. The rotational speed ($n$) from 100 to 300 rpm. The machining time ($t_m$) from 4 to 28 min. the MEAT conditions are $C = 15$ % NaNO$_3$, volt $v = 21$ volts, $Q = 8$ L/min, $G_i = 0.3$ mm, abrasive type SiC and grain mesh = 280. The deduced equation can be used for finishing Cr Coated steel while a correction factor may be used for other workpiece material.

4.6. Correlation between experimental and calculated ($U_a$):

Figure 22 shows the experimental results of reduction percent in initial average roughness ($U_a$) using MEAT parameters. ($U_a$) is estimated from the experimental data as ($U_a$) experimental while it can also calculated using the above empirical formulas as ($U_a$) calculated. Using least square method it was found a good correlation exists between ($U_a$) Experimental and ($U_a$) calculated.

5. Conclusions

1- The use of amagnetic field normal to the working gap in case of electrochemical abrasive turning process causes a further improvements in surface roughness (mirror-like) due to the effect of cycloid pass of ions.
2- The decrease of the magnetic gap ($G_m$) while the increase of the rotational speed ($n$) causes improvements in the surface roughness during MEAT.
3- Hard workpiece like Cr-coated can be easily polishing by MEAT process ($R_a = 0.03$µm).
Figure 18. Effect of rotational speed (n) in case of MEAT process using NaNO₃ electrolyte on surface roughness (Rₐ, Rₜ).
Workpiece mat.: Cr-coated steel, flux density = 0.06 T, Abrasive type: SiC, Grain size = 280, C = 15% NaNO₃, v = 21 volt, Q = 8 L/min, Gᵢ = 0.3 mm, Gₘ = 3 mm, tₘ = 28 min, Rₐᵢ = 0.125 µm, and Rₜᵢ = 1.1 mm

Figure 19. Effect of rotational speed (n) in case of MEAT process using NaNO₃ electrolyte on relationships: (a) (Uₐ – tₘ) (b) (Uₜ – tₘ)
Workpiece mat.: Cr-coated steel, Flux density = 0.06 T, abrasive type: SiC, Grain size = 280, C = 15% NaNO₃, v = 21 volt, Q = 8 L/min, Gᵢ = 0.3 mm, tₘ = 28 min, Rₐᵢ = 0.125 µm, and Rₜᵢ = 1.1 µm

Figure 20. Effect of rotational speed (n) in case of MEAT process using NaNO₃ electrolyte on the reduction percent of the initial surface roughness (Uₐ, Uₜ).
Workpiece mat.; Cr-coated, Flux density = 0.06 T, abrasive type: SiC, grain size = 280, C = 15% NaNO₃, v = 21 volt, Q = 8 L/min, Gᵢ = 0.3 mm, Gₘ = 3 mm, tₘ = 28 min, Rₐᵢ = 0.125 µm, and Rₜᵢ = 1.1 mm
Figure 21. Photo showing mirror-like finishing two sampling workpiece, its surface roughness was improve to $R_a = 0.03 \, \mu m$ and $R_z = 0.38 \, \mu m$

![Figure 21](image1.png)  (a) Stainless steel

![Figure 21](image2.png)  (b) Cr- coated steel

Figure 22. A good correlation between $(U_a)$ experimental and $(U_a)$ calculated

4- An imperical equations is deduced to obtain a relationship between the reductin percent in initial roughness $(U_a)$ and the govering parameter machining time $(t_m)$, rotating speed $(n)$ and magnetic gap $(G_m)$ as follow:

$$U_a = 0.0798 \times n^{0.1923} \times t_m^{0.31} / (G_m^{0.0275}) \quad (4)$$

6. Appendices

Table A1. Nomenclature; Symbols, definitions, and units used

| Symbols | Definition                                      | Units            |
|---------|-------------------------------------------------|------------------|
| $A_i$   | current densities                               | A/cm$^2$         |
| $B$     | the magnetic flux density                        | Tesla            |
| $C$     | electrolyte concentration                        | weight / weight  |
| $D$     | workpiece diameter before ECT                   | mm               |
| $d_e$   | workpiece diameter after ECT                    | mm               |
| $G$     | gap between tool electrode and workpiece        | mm               |
| $G_i$   | initial gap between tool electrode and workpiece| mm               |
H: magnetic strength in the location of magnetic abrasive
I: machining current
n: workpiece rotational speed
Q: flow rate of electrolyte
R_a: average roughness
R_z: peak to valley height roughness
t: electrochemical machining time
t_m: turning machining time
v: applied voltage
ECT: electrochemical turning
MEAT: magnetic-electrolytic-abrasive turning

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