JMEPEG (2009) 18:399–405
DOI: 10.1007/s11665-008-9308-3

1059-9495/$19.00

Magnetic-Assistance Finishing Processes in Freeform Surfaces

P.S. Pa

(Submitted October 22, 2007; in revised form August 22, 2008)

A new finishing process that uses magnetic force with high efficiency to assist discharging dregs from the electrode gap during electrochemical finishing on freeform surfaces is investigated in the current study. The factors affecting electrochemical finishing and the effects of magnetic assistance are primarily discussed. The main experimental parameters are magnetic strength, distance between the two magnets, diameter of the electrode, current density, the on/off period of pulsed current, and rotational speed of the wire electrode. Providing a large magnetic field intensity or using a smaller distance between the two magnets produces a larger magnetic force and discharge efficiency, and results in a better finish. A higher current density with magnetic assistance reduces the finishing time and avoids difficulties in dreg removal. A high rotational speed of the wire electrode produces a better finish. Pulsed direct current can slightly promote the effect of electrochemical finishing, but the current density needs to be higher. Magnetic assistance during the electrochemical finishing process makes a greater contribution in a shorter time making the surface of the workpiece smooth and bright.

Keywords electrochemical finishing, finishing processes, magnetic assistance, magnetic force, surface finish, wire electrode

1. Introduction

When a coil or solenoid is placed near a metallic conductor and pulsed via stored energy from a capacitor bank, a magnetic field is generated between the coil and the workpiece. If done quickly enough, the magnetic field is excluded from penetrating the work piece for a short period of time. During this time, pressure is generated on the workpiece that is proportional to the magnetic flux density squared. This "magnetic" pressure is what provides the formation energy. The energy is usually supplied to the workpiece in the form of kinetic energy. The magnetic pressure pulse accelerates the work piece up to a certain velocity (such as 200-300 m/s). This kinetic energy drives the material into the die, causing formation on impact (Ref 1). Electromagnetic metal formation (EMF) is an example of a high-speed process that is determined by the dynamics of a coupled electromagnetic-mechanical system. EMF technology has been in existence for over 30 years, but has not seen widespread acceptance among manufacturing engineers. EMF is the direct conversion of electrical energy into useful electromagnetic forces used to form metal. More applications include embossing, blanking, formation, and drawing. EMF works by the magnetic induction effect. Another reason for choosing EMF is to form sheet materials in a different way than conventional processes to improve surface quality. EMF can eliminate sheet surface problems present in conventional metal formation methods such as stretching stringers or marring from punches (Ref 2, 3). Surface roughness plays an important role in product quality, particularly in situations such as precision fits and high-strength applications. Magnetic abrasive finishing (MAF) is a precise polishing method that the cutting tool is a group of magnetic abrasives, where the abrasion pressure is controlled by a magnetic field. A limited amount of material will be removed by conducting a relative motion between the work surface and the abrasives, so as to obtain a mirror-like finished surface. Owing to the magnetic field, the magnetic abrasives will gather to form a flexible magnetic brush. Thus, the magnetic abrasives can move and polish along the profile of a complex surface, so the surface with complex shapes can be finished. Furthermore, the disturbances from the structure due to vibration or chatter will not affect the quality of the finished surface (Ref 4, 5). MAF is relatively a new finishing process among the advanced finishing processes in which the workpiece is kept in the magnetic field created by two poles of an electromagnet. The working gap between the workpiece and the magnet is filled with magnetic abrasive particles. A flexible magnetic abrasive brush is formed, acting as a multipoint cutting tool, due to the effect of magnetic field in the working gap. This process is capable of producing the surface finish of nanometer range. Most of the researchers have been using the electromagnet having a slot in it to improve the performance of the process but hardly any information is available about its effect on the process performance (Ref 6). The stability of EDM gap condition significantly affects the machining characteristics. The machining performance improves when the debris is expelled from the machining gap fast and easily. Therefore, when assistant magnetic poles were attached to EDM machine, the machining zone generates a magnetic force to drive the suspending debris expelling from the machining gap. The debris stacked on the machining zone can be reduced, so the machining condition becomes more stable to improve the

P.S. Pa, Graduate School of Toy and Game Design, National Taipei University of Education, No. 134, Sec. 2, Heping E. Rd., Taipei City 106, Taiwan, ROC. Contact e-mail: myhow@seed.net.tw.

machining performance. In this investigation, the magnetic poles were attached on EDM to explore the effects of assistant magnetic force on EDM machining characteristics (Ref 7, 8).

Electrochemical machining (ECM) is one of the well-established, nontraditional manufacturing processes. It is an effective method for the machining of complex shapes (Ref 9). ECM uses a sufficient current density for the removal of an electrically conductive metal by anodic dissolution when the anode and cathode are separated by a narrow gap containing a high-pressure flowing electrolyte (Ref 10). ECM is suitable for high-strength and high-melting point alloys. More industrial applications have been realized throughout the decades, such as electrochemical drilling, electrochemical grinding, electrochemical deburring, and electro-polishing (Ref 11). The experimental results have shown that the quality of the machined surface will be influenced by the current density, flow rate of electrolyte, and the gap width (Ref 12). Electropolishing is an electrochemical process that actually removes surface material by removing the high points on the microscopic surface; the electropolishing process will improve the surface, leaving it smoother and more reflective. Shen (Ref 13) used $NaNO_3$ as the electrolyte to carry out electropolishing of a die surface. The results showed that the surface roughness of the workpieces decreased with an increase of current density, flow rate, and concentration of electrolyte. Moreover, polishing with pulsed direct current is found to be better than the continuous direct current. The term 'dregs' refers to the electrolytic product that develops in the machining gap during the process of electrochemical machining (Ref 14). The gap width between the electrode and the workpiece directly influences the electrical current condition and the dreg discharge. The pulsed electrochemical finishing (PEF) with an interelectrode gap, made as small as possible, could smooth the anode surface quickly. With a constant gap size, the current density and the machining time are the two key parameters influencing the smoothing effect. An online monitoring system was proposed (Ref 15). The machining resolution is limited to a few micrometers by applying ultrashort pulses of nanoseconds duration, which allows microstructures to be machined by ECM (Ref 16). Electropolishing is a very effective technique for achieving mirror-like surfaces on many metals. For many applications, a smooth and bright surface is essential and electropolishing is the best technique for this. Additionally, it is recognized that highly polished surfaces are easier to maintain in a high state of cleanliness (Ref 17). The electrochemical machining process is still underutilized because of a lack of understanding of the metal removal mechanism and the inefficient tool design and methodology being used. Even for simple cases, it is impossible to predict work profiles accurately (Ref 18). Good surface quality of the workpiece was obtained through the arrangement of the experimental conditions. A disc-form electrode and a borer-shaped type of electrode were also developed for electropolishing (Ref 19, 20).

A better design process is useful for effective flushing, as the dregs are easily discharged from the gap, and a better material removal effect is produced (Ref 14, 19). The potential for the design of magnetic assistance during the surface finish is yet to be explored. Thus, the application of using a magnetic force to discharge dregs from the electrode gap during electrochemical finishing is crucial to the surface finishing process. The current study discusses the design features of the performance assessment on discharging dregs using magnetic force. The freeform surface uses a magnetic system and an effective wire-form electrode supplied with continuous and pulsed direct current during electrochemical finishing. An effective evaluation of the magnetic-assistance finishing processes is expected to result in more use for the freeform surface finishing in the future.

2. Equipment for Magnetic Assistance and the Experimental Setup

The relationship of the expected requirements and the design target of an effective design for magnetic assistance in electrochemical finishing are illustrated in Fig. 1 (Ref 14, 19, 21). It is referenced on a scientific design process method with an analysis that includes design considerations, design development, design details, and experimental analysis to implement the final design (Ref 22-24). The experimental setup of a finishing process using magnetic assistance in electrochemical finishing is illustrated in Fig. 2, and includes a magnetic

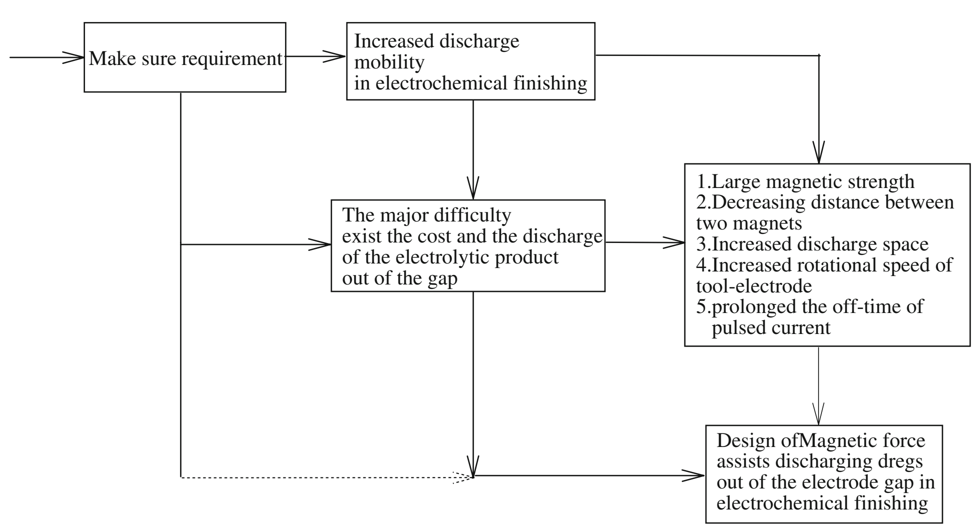

Fig. 1 Relationship of requirement expectation and design target (Ref 14, 19, 21)

system, DC power supply, pulse generator, pump, flow meter, electrolytic tank, and filter. The schematics and configuration of the magnetic assistance system, electrodes, and workpiece are shown in Fig. 3.

The material used for the experimental workpiece is high-speed steel (HSS), the code number is SKH 57 (JIS) or S-6-5-2-5 (DIN). The chemical composition is shown in Table 1 (Ref 25). The initial average end-surface roughness of the workpiece after precise machining is 3.5-4.5 μm (Ref 26). The magnetic-assistance electrochemical finishing (MEF) process is used as a finish operation instead of the conventional hand or machine polishing used in the experiment. The amount of reduction of the workpiece surface after electrochemical finishing is 20 μm, which is designed in the processes for the dimensional control of parts. The different features for the finishing process include electrochemical finishing (EF), PEF, MEF, and magnetic-assistance pulsed electrochemical finishing (MPEF). The settings of the experimental parameters are shown in Table 2. After different finishing processes, all workpieces are measured using the surface roughness measurement (Hommel T500, the accuracy is within ±5% after standard correction). The surface roughness is characterized by Ra, where the length of cutoff is 0.8 mm, and the measuring direction is perpendicular to the tooth mark. The measuring data is chosen from at least two different locations.

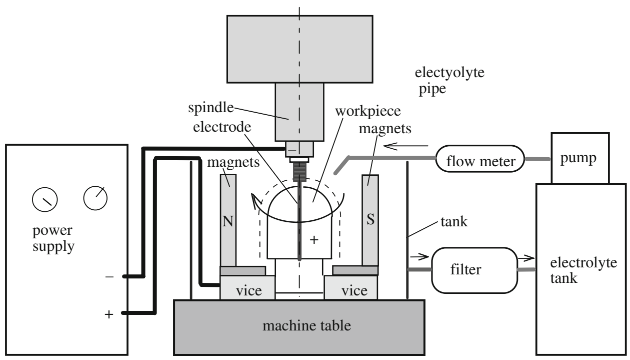

Fig. 2 Experimental setup

Table 2 Experimental parameters

Magnetic field intensity, Gausses	1500, 2000, 2500, 3000
Distance between the two magnets, mm	80, 90, 100, 110, 120
Gap width between electrodes, mm	0.3, 0.4, 0.5, 0.6
Current density, A/cm^2	15, 30, 45, 60
Flow rate of electrolyte, L/min	5, 10, 15, 20, 25
Diameter of wire electrode, mm	2, 4, 6, 8, 10, 12
Pulsed period (on/off time), ms/ms	100/100, 100/200, 100/300, 100/400, 100/500
Rotational speed of electrode, rpm	200, 400, 600, 800, 2000, 1200
Different finish process	EF, PEF, MEF, MPEF

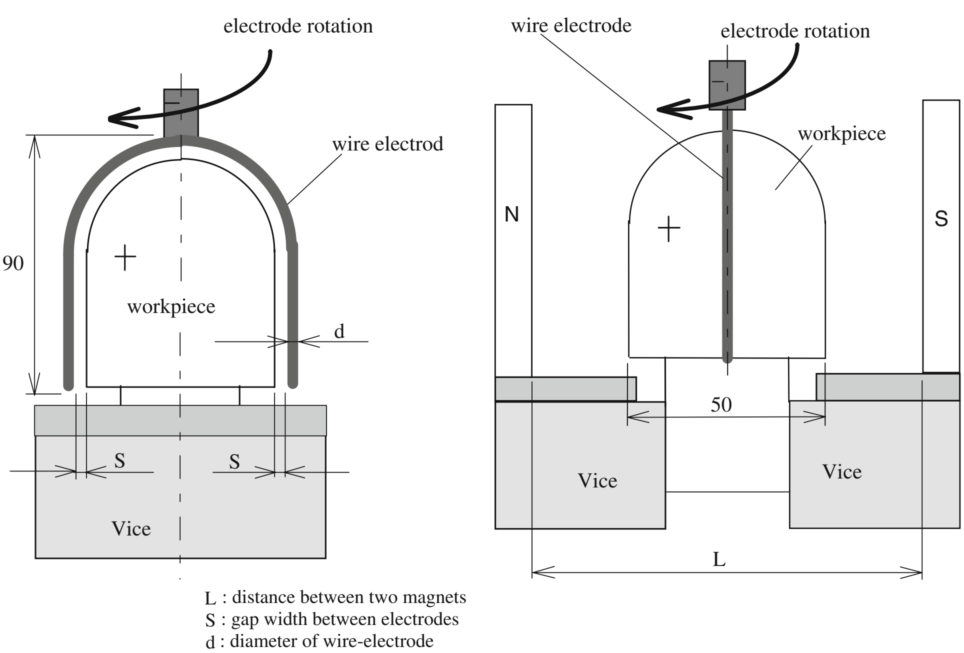

Fig. 3 Configuration of magnetic assistance system

Table 1 Chemical composition of the workpiece

Wt.%	Fe	C	Si	Mn	P	S	Cr	W	Mo	V	Co	Ni
SKH 57 (S-6-5-2-5)	REM.	1.25	0.25	0.35	0.023	0.01	4.15	10.00	3.5	3.45	10.00	/

3. Results and Discussion

Figure 4 shows that the optimal finish time and current density are correlated. The higher the current density (30 A/cm^2), the shorter the time (32 s) needed for a better finish to be achieved by MEF. Figure 4 also illustrates that magnetic force indeed helps electrochemical finishing, since magnetic force is very effective in dreg removal (Ref 14). The use of a lower current density can thus be replaced by a higher current density aided by magnetic assistance to promote finishing efficiency. Figure 5 shows that a small distance between the two magnets provides a larger magnetic force and dreg discharge rate and a better finish. Figure 6 illustrates the effects of the wire-form electrode's diameter. A small diameter provides more open space for dreg discharge and produces a better finish effect in the current study (Ref 14, 19). Figure 7 illustrates that a large magnetic strength (magnetic field intensity) produces a better finish. The reason being that the magnetic force allows the electrolyte to remove the dregs from the tight machining gap more rapidly. These effects streamline the electrochemical reaction and improve the finish quality. Figure 8 shows that an adequate gap width between the electrode and the workpiece produces a better finish. The proper gap width can not only facilitate the removal of electrolytic products, but also provide adequate and prompt smooth flow of the electromagnetic forces, which further assists in the removal of electrolytic products. It is apparent that the finishing effect is better when the gap width is between 0.3 and 0.4 mm. A smaller gap width makes the discharge of electrolytic depositions from the gap difficult, and the finishing effect is reduced. A large gap width

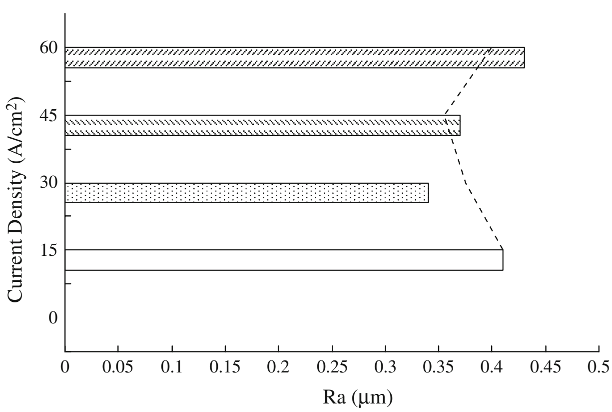

Fig. 4 Effects of current density of MEF (SKH 57, $NaNO_3$ 20 wt.%, 15 L/min, 2500 Gauss, 32 s, continuous DC)

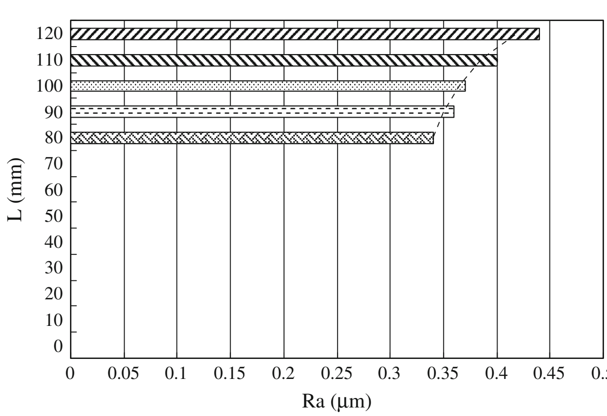

Fig. 5 Magnetic-assistance electrochemical finishing using different distance between two magnets (SKH 57, $NaNO_3$ 20 wt.%, 15 L/min, 2500 Gauss, 30 A/cm^2, 32 s, continuous DC)

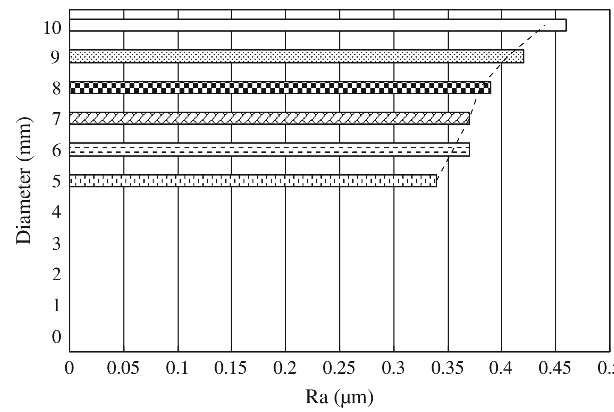

Fig. 6 Magnetic-assistance electrochemical finishing at different electrode diameter (SKH 57, $NaNO_3$ 20 wt.%, 15 L/min, 2500 Gauss, 30 A/cm^2, 32 s, continuous DC)

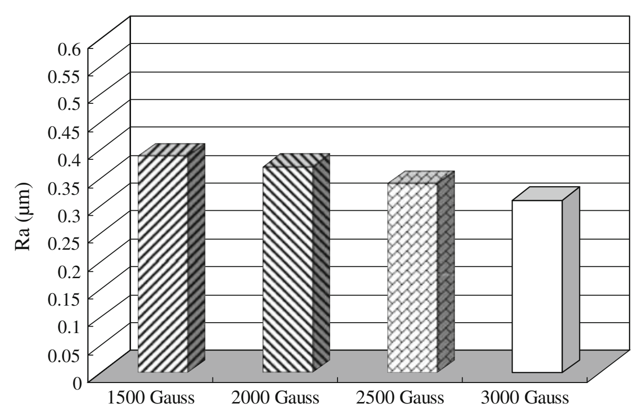

Fig. 7 Effects of magnetic field intensity in MEF (SKH 57, $NaNO_3$ 20 wt.%, 15 L/min, 30 A/cm^2, 32 s, continuous DC)

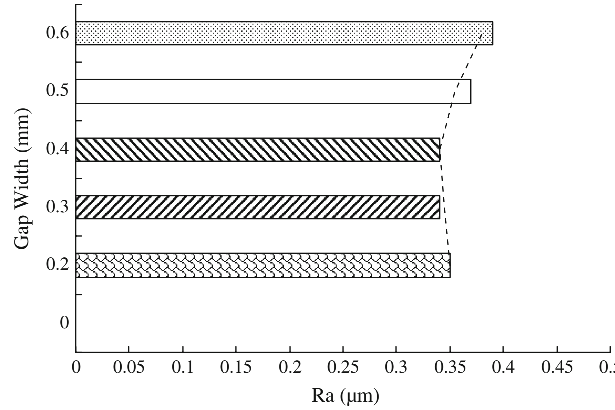

Fig. 8 Magnetic-assistance electrochemical finishing at different gap width between electrode and workpiece (SKH 57, $NaNO_3$ 20 wt.%, 15 L/min, 2500 Gauss, 30 A/cm^2, 32 s, continuous DC)

limits the effect of electrochemical finishing (Ref 14, 19). Thus, a gap width of 0.4 mm is more effective in the current experiment.

Figure 9 illustrates the use of electrode rotation. A higher rotational speed of the electrode produces a better finish. A high rotational speed supplies kinetic energy to the electrolyte for dreg discharge and produces a better effect for the electrochemical finishing process. The electrolytic products can be quickly removed as a result of the combination of the effects of the electromagnetic forces and the higher rotational speed of the electrode. Figure 10 shows the effects of pulsed direct current. A longer off-time is slightly more advantageous because the removal of electrochemical finishing dregs and cuttings during the off-time is more complete. The effects of the electromagnetic forces facilitate a prompt removal of the electrolytic products during the off-time.

However, the machining time of the pulsed direct current is longer and the cost is higher. Figure 11 shows the evaluation of the finish effect of four process features. Both the magnetic assistance and the pulsed current can further improve electrochemical finishing. The former not only performs better, but also has a significant economic advantage. The finish time when using magnetic assistance will not be as long as with the pulsed current. In fact, the off-period is often several times as long as the on-period. Owing to the effective discharge of electrolytic dregs and lower cost, magnetic assistance is the recommended process feature rather than the PEF. Figure 12 demonstrates the photograph of the workpiece (SKH 57) after executing the MEF process. The average contribution of MPEF to surface finish is 61%, and that of pulsed current is 39% (Fig. 13). In summary, the design using magnetic assistance produces the most influential parameters in this study. According to the formula of theoretical removal rate on alloy from Faraday's Law (Ref 10):

$$R = \frac{\eta I}{F A \rho \left(\frac{n_A}{M_A} a_A + \frac{n_B}{M_B} a_B + \cdots \right)} \qquad \text{(Eq 1)}$$

where η is the efficiency of current, I is the current, t is time, F is the Faraday constant, n_i is the atomic number, a_i is the proportion of chemical composition, and M_i is the atomic mass, A is the electrochemical machining area, ρ is the density of workpiece, and R is the removal rate in the longitudinal direction.

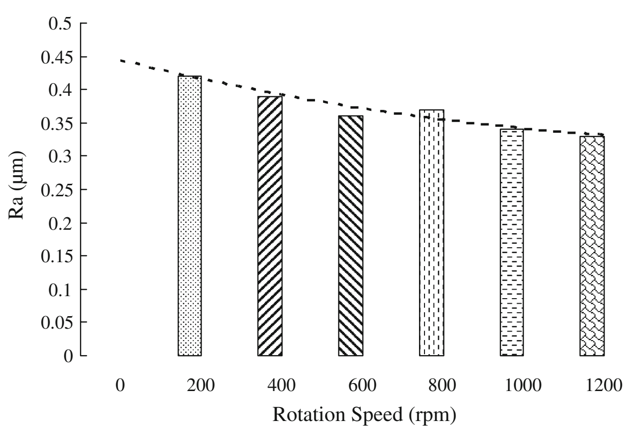

Fig. 9 Effects of rotational speed of electrode in MEF (SKH 57, $NaNO_3$ 20 wt.%, 15 L/min, 2500 Gauss, 30 A/cm^2, 32 s, continuous DC)

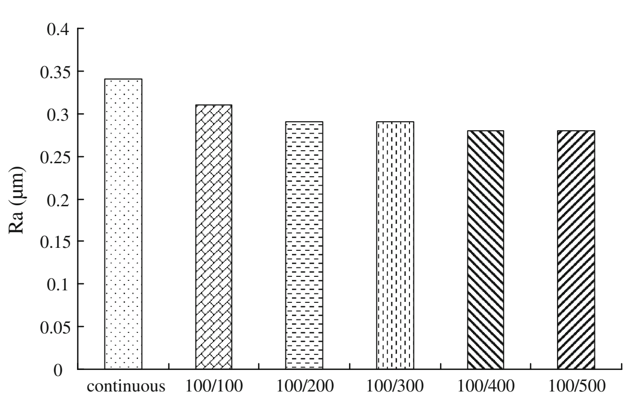

Fig. 10 Magnetic-assistance electrochemical finishing through continuous and pulsed direct current (SKH 57, $NaNO_3$ 20 wt.%, 15 L/min, 2500 Gauss, 30 A/cm^2, continuous DC)

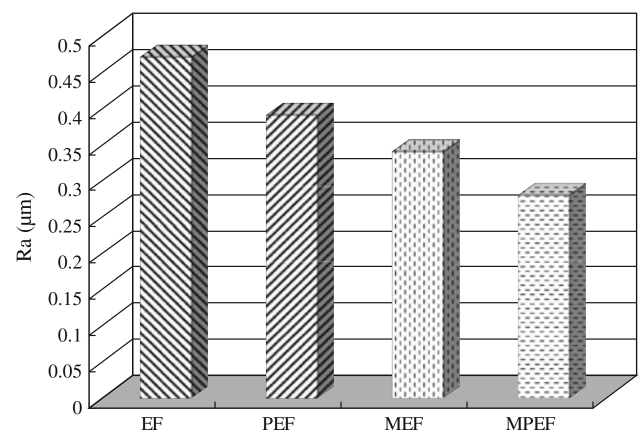

Fig. 11 Effects of evaluation of the finishing effect of four process (SKH 57, $NaNO_3$ 20 wt.%, 15 L/min, 2000 Gauss, 20 A/cm^2, 100/500 ms)

Fig. 12 Outward appearance of workpiece (SKH 57) after MEF

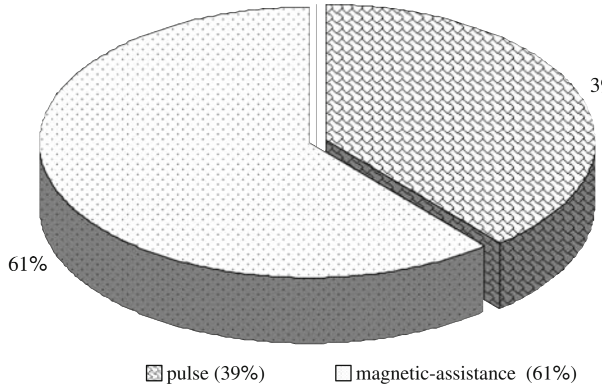

Fig. 13 The contribution pie of surface finish improvement of design magnetic assistance (SKH 57, $NaNO_3$ 20 wt.%, 15 L/min, 2500 Gauss, 30 A/cm^2, 100/500 ms

$$\text{Let } w = W/At \quad \text{(Eq 2)}$$

$$w = \frac{\eta I}{FA\left(\frac{n_A}{M_A}a_A + \frac{n_B}{M_B}a_B + \cdots\right)} \quad \text{(Eq 3)}$$

$$\text{and } f_v = w/\rho \quad \text{(Eq 4)}$$

$$I_A = I/A \quad \text{(Eq 5)}$$

$$f_v = \frac{\eta I_A}{F\rho\left(\frac{n_A}{M_A}a_A + \frac{n_B}{M_B}a_B + \cdots\right)} \quad \text{(Eq 6)}$$

$$= \frac{\eta V\sigma}{F\rho\left(\frac{n_A}{M_A}a_A + \frac{n_B}{M_B}a_B + \cdots\right)} \quad \text{(Eq 7)}$$

where A is the electrochemical machining area, ρ is the density of the workpiece, f_v is the etching rate in the longitudinal direction, I_A is the current density, V is the voltage of the gap width, and σ is the reciprocal resistance.

From the above equations, the theoretical feed rate of workpiece during the same material etching rate can be calculated. Where η, I, F, and A are regarded as constant for the material. Compared with the experiment results, the removal is directly proportional to the current density (I_A) and agrees well with the theoretical prediction. Controlling the reciprocal resistance (σ) can stabilize the finishing effect, and as a result, increased discharge mobility (providing a small distance between the two magnets, a small diameter of wire-form electrode, a large magnetic strength, a longer off-time of pulsed direct current, or a higher rotational speed of the electrode assists the removal of dregs from the electrode), guiding discharge transport, and providing a flushing passage will provide reciprocal resistance (σ) the stability, and produce a better finish.

4. Conclusions

Magnetic-assistance electrochemical finishing can be used for freeform surfaces to assist the removal of dregs from the electrode gap during electrochemical finishing. With magnetic assistance, the electrolytic products can effectively prevent unwanted attachment to the electrodes and rapidly discharge dregs from the gap. For the experimental processes, a small distance between the two magnets or large magnetic field intensity provides a larger magnetic force, better discharge ability, and a better finish. A higher current density with magnetic assistance can avoid the difficulties related to dreg discharge, and thus reduce the finishing time. A pulsed current, instead of continuous current, provides an off-period for better dreg discharge. The use of MEF saves the need for precise machining, making the total process time less than that of the traditional polishing, which is more evident in improving the finish effect. In addition, the cycle time is no longer than that of the PEF. One should use the most effective magnetic assistance in electrochemical finishing, and take advantage of the low cost of equipment as well.

Acknowledgment

The current study is supported by National Science Council, contract 96-2622-E-152-001-CC3 and 96-2411-H-152-003.

References

1. B.H. Amstead, P.F. Ostwald, and M.L. Begeman, *Manufacturing Processes*, John Wiley and Sons, Inc., New York, 1977, p 614
2. J. Unger, M. Stiemer, B. Svendsen, and H. Blum, Multifield Modeling of Electromagnetic Metal Forming Processes, *J. Mater. Process. Technol.*, 2006, **177**(1–3), p 270–273
3. M. Badelt, C. Beerwald, A. Brosius, and M. Kleiner, Processes Analysis of Electromagnetic Sheet Metal Forming by On Line-Measurement and Finite Element Simulation, *Proceedings of the 6th International ESAFORM Conference on Materials Forming* (Salermo, Italy), 2003, p 123–126
4. V.K. Jain, S.C. Jayswal, and P.M. Dixit, Modeling and Simulation of Surface Roughness in Magnetic Abrasive Finishing Using Non-Uniform Surface Profiles, *Mater. Manuf. Process.*, 2007, **22**, p 256–270
5. G.W. Chang, "Study on Finishing Characteristics of Magnetic Abrasive Finishing and Electrolytic Magnetic Abrasive Finishing," Doctoral Dissertation, National Central University, Taiwan, 2003
6. S.C. Jayswal, V.K. Jain, and P.M. Dixit, Analysis of Magnetic Abrasive Finishing with Slotted Magnetic Pole, *Mater. Process. Des.*, 2004, **712**, p 1435–1440
7. H.S. Lee, "Machining Characteristics and Optimization of Machining Parameters with Assistant Magnetic Force in EDM," M.Sc. Thesis, National ChungChou Institute of Technology, Taiwan, 2005
8. S. Hao, P.M. Kirkham, T.M. Myers, G.H. Cassell, and G.U. Lee, The Application of Magnetic Force Differentiation for the Measurement of the Affinity of Peptide Libraries, *J. Magn. Magn. Mater.*, 2005, **293**(1), p 382–388
9. P. Domanowski and J. Kozak, Inverse Problem of Shaping by Electrochemical Generating Machining, *J. Mater. Process. Technol.*, 2001, **109**, p 347–353
10. J.A. McGeough, *Principles of Electrochemical Machining*, Chapman & Hall, London, 1974, p 1–10
11. J. Wilson, *Practice and Theory of Electrochemical Machining*, Wiley-Interscience, New York, 1971, p 79–161
12. A.R. Mileham, S.J. Harrey, and K.J. Stout, The Characterization of Electrochemically Machined Surfaces, *Wear*, 1986, **109**, p 207–214
13. W.M. Shen, "The Study of Polishing of Electric Discharge-Machined Mold With ECM," M.Sc. Thesis, National Yunlin Institute of Technology, Taiwan, 1995
14. M. Datta and D. Landolt, Electrochemical Machining Under Pulsed Current Conditions, *Electrochim. Acta*, 1981, **26**, p 899–907
15. J. Zhou, G. Pang, H. Wang, and W. Xu, Research on Pulse Electrochemical Finishing Using a Moving Cathode, *Int. J. Manuf. Technol. Manage.*, 2005, **7**(2–4), p 352–365

16. L. Cagnon, V. Kirchner, M. Kock, R. Schuster, G. Ertl, W.T. Gmelin, and H. Kuck, Electrochemical Miromachining of Stainless Steel by Ultra Short Voltage Pulses, *Z. Phys. Chem.*, 2003, **217**, p 299–313
17. T. Jones, Electropolishing of Precious Metals, *Metal Finish.*, 2004, **102**(7–8), p 45–49
18. V.K. Jain, P.G. Yogindra, and S. Murugan, Prediction of Anode Profile in ECBD and ECD Operations, *Int. J. Mach. Tools Manuf.*, 1987, **27**(1), p 113–134
19. H. Hocheng and P.S. Pa, Electropolishing of Cylindrical Workpiece of Tool Materials Using Disc-Form Electrodes, *J. Mater. Process. Technol.*, 2003, **142**(1), p 203–212
20. P.S. Pa and H. Hocheng, Using Borer-Shape Electrode in Electrochemical Smoothing of Holes, *Mater. Sci. Forum*, 2006, **505–507**, p 793–798
21. T.P. Griego and J.W. Eichman, Electrodeposition Apparatus and Method using Magnetic Assistance and Rotary Cathode for Ferrous and Magnetic Particles, United States Patent 6890412, 2003, p 1–9
22. L.B. Archer, Systematic Method for Designer, *Developments in Design Methodology*, N. Cross, Ed., John Wiley, 1984, p 57–82
23. S.S. Rao, *Engineering Optimization*, John Wiley and Sons, New York, 1996
24. G. Pahl and W. Beitz, *Engineering Design*: *A Systematic Approach*, K. Wallace, Ed., Springer, Berlin, 1996, p 79–81
25. Yung Dah Special Steel Co., Ltd., Hitachi, YSS, Cold Work Tool-Steel, Taiwan, 2000, p 2–3
26. Institute of Advanced Manufacturing Sciences, Inc., *Machining Data Handbook*, 3rd ed., Vol. 2, Sec. 18, 1980, p 11