FABRICATION OF CuW ELECTRODE FOR PRODUCING MICRO-HOLE ON WC-Co USING EDM PROCESS

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This thesis dedicated to…

My mother and father, who taught me that the best kind of knowledge to have is that, which is learned for its own sake

My beloved brother and sister

My love to you will always remain and thank you so much for being

So patient and being there for me.

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ABSTRACT

Micro-machining is one of the fundamental technologies for manufacturing miniaturized parts and products with size of between 1 to 999 µm. A micro-mold cavity is required for the mass production of micro component using injection molding machine. Moreover, micro-holes are also required in a micro-die. Nowadays, WC and its composite (WC-Co) are the widely used material in the making of cutting tools, dies and other special tools and components. Therefore, machining of WC is an important activity in manufacturing. Micro-EDM is one of the most effective methods for machining WC. Unfortunately there is limited information available about fabricating micro-hole electrode made from CuW for electrical discharge machining. This includes information on suitable electrode material for electrical discharge machining of CuW, the processing method and suitable parameter for micro-EDM of CuW and WC-Co. In this research, PGM WHITE 3 is used as the dielectric fluid, Cu-W as the micro-electrode, WC-Co as the workpiece material and Sodik AG40L as the die-sinking machine selected for the project. Process parameters investigated are polarity and voltage while the effects investigated are time of machining, end wear and diameter of hole. An electrode with a diameter of 372.76 µm has been successfully fabricated using selected process. Results of the experiment show that Micro-electrode with negative polarity has lower end wear of tool than positive polarity. Negative polarity of micro-electrode is used for micro-EDM of hole and positive polarity of micro-electrode is used for facing of micro-electrode. Lowest end wear of electrode has been achieved at P of CuW (-), I_P (0.4 A), t_{on} (1 µs), D_f (0.5), S_r (20 rpm), E_g (50). Lowest hole diameter has been achieved at P of CuW (+), I_P (0.4 A), t_{on} (1 µs), D_f (0.5), S_r (20 rpm), E_g (70). The shortest time of machining is achieved at P of CuW (-), I_P (0.4 A), t_{on} (1 µs), D_f (0.5), S_r (20 rpm) E_g (70) when investigating 50, 70 and 90V.

ABSTRAK

Mikro-pemesinan adalah salah satu teknologi asas untuk pembuatan bahagian-bahagian dan produk bersaiz kecil dengan saiz antara 1-999 µm. Sebuah rongga mikro acuan diperlukan untuk pengeluaran besar-besaran komponen mikro menggunakan mesin suntikan acuan. Selain itu, mikro-lubang juga diperlukan dalam mikro-die. Kini, karbida tungstan dan komposit (WC-Co) adalah bahan yang digunakan secara meluas dalam pembuatan alat pemotong, die dan alat-alat dan komponen khas yang lain. Oleh itu, pemesinan WC adalah aktiviti yang penting dalam pembuatan. Mikro-EDM adalah salah satu kaedah yang paling berkesan untuk pemesinan WC. Malangnya maklumat mengenai pembuatan elektrod mikro-lubang yang diperbuat daripada CuW yang diperlukan untuk pemesinan nyahcas elektrik. adalah amat terhad. Ini termasuk maklumat mengenai bahan elektrod yang sesuai untuk pemesinan nyahcas elektrik CuW, kaedah pemprosesan dan parameter yang sesuai untuk mikro-EDM CuW dan WC-Co. Dalam kajian ini, PGM WHITE 3 digunakan sebagai bendalir dielektrik, CuW adalah seperti mikro elektrod, WC-Co sebagai bahan benda kerja dan mesin Sodick AG40L EDM *Die Sinking* dipilih untuk projek. Parameter proses yang disiasat adalah kekutuban dan voltan manakala kesan yang disiasat adalah masa pemesinan, Kehausan hujung dan garispusat lubang. Elektrod dengan garispusat 372.76 µm telah berjaya dihasilkan menggunakan proses yang dipilih. Keputusan ujikaji menunjukkan bahawa mikro-elektrod dengan kekutuban negatif mempunyai kehausan hujung yang lebih rendah daripada menggunakan mikro-electrod dengan kekutuban positif. Kekutuban negatif mikro elektrod digunakan untuk mikro EDM lubang manakala kekutuban positif mikro elektrod digunakan untuk *facing* mikro-elektrod. Kehausan hujung elektrod terendah telah dicapai dengan P CuW (-), I_P (0.4 A), t_{on} (1 µs), D_f (0.5), S_r (20 rpm), E_g (50). Lubang diameter terendah telah dicapai dengan P CuW (+), I_P (0.4 A), t_{on} (1 µs), D_f (0.5), S_r (20 rpm), E_g(70). Masa yang singkat pemesinan telah dicapai dengan P CuW (-), I_P (0.4 A), t_{on} (1 µs), D_f (0.5), S_r (20 rpm), E_g (70) apabila menkaji 50, 70 dan 90V.

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LIST OF SYMBOLS

A	-	Sum of thickness of gage block and diameter of micro-electrode
AgW	-	Silver tungsten
BEDG	-	Stationary sacrificial block electro discharge grinding
Cu	-	Copper
CuW	-	Copper tungsten
D	-	Diameter of micro-electrode
D_f	-	Duty factor, unit: %
ECM	-	Electrical chemical machining
EDG	-	Electrical discharge grinding
EDM	-	Electrical discharge machining
E_g	-	Gap-load voltage, unit: V
EWR	-	Electrode wear ration
I_P	-	Peak current, unit: A
L	-	Length of gage block
MBEDG	-	Moving block electro discharge grinding
Micro-EDM	-	Micro electrical discharge machining
MRR	-	Material removal rate
P	-	Polarity
R_C power supply	-	Resistor-capacitor power supply
R_a	-	Average surface roughness
R_{max}	-	Peak-to-valley surface roughness
S_r	-	Electrode rotational speed, unit: rpm
SR	-	Surface roughness
t	-	Machining time in minutes
t_m	-	Machining times (min)

t_{on}	-	Pulse duration, unit: µs
W	-	Tungsten
W_a	-	Weight of workpiece material and electrode after machining (g)
W_b	-	Weight of workpiece material and electrode before machining (g)
WC	-	Tungsten carbide
WC-Co	-	Tungsten carbide with Cobalt
WEDG	-	Wire electrical discharge grinding
WEDM	-	Wire electrical discharge machining
W_f	-	Final weight of workpiece in machining (g)
W_i	-	Initial weight of workpiece before machining in (g)
X_1	-	First position of micro-electrode touches the gage block
X_2	-	Second position of micro -electrode touches the gage block
ρ_s	-	Density g/mm

CHAPTER 1

INTRODUCTION

1.1 Overview

Micro-machining is one of the fundamental technologies to miniaturize parts and products. Based on CRIP committee of Physical and chemical processes, manufacture products are between 1 to 999 µm (Masuzawa & Tönshoff, 1997). Recently, the miniaturization of products is an important paradigm in every aspects of the society such as information technology, biotechnology, environmental and medical industries. In the process of product miniaturization and industrial realization of nanotechnology, micromachining is an important supporting technology which can overcome the challenges associated with the requirement of the process (M. Rahman *et al.*, 2010). A micro-mold cavity is required for mass production of micro component, that can be produced by injection molding (Lim *et al.*, 2003). Moreover, micro-holes are used in the micro-die (Mark *et al.*, 2009). Hard-to-machined materials are used for micro-injection that should be machined very accurately and complex shape in three-dimensional forms in the micron range (Lim *et al.*, 2003).

Among the difficult-to-cut materials tungsten carbide (WC) is an extremely hard material used extensively in manufacturing because of its superior wear and corrosion resistance. Nowadays, WC and its composite (WC-Co) have a great influence in the production of cutting tools, dies and other special tools and components due to their high hardness, strength and wear resistance over a wide range of temperature (Mahdavinejad & Mahdavinejad, 2005); thus, recently machining of WC plays significant roles in manufacturing (Jangra *et al.*, 2012).

On the other hand, among the non-conventional methods, electro-discharge machining (EDM) and electro-chemical machining (ECM) are the only methods capable of machining WC–Co composites (Mahdavinejad & Mahdavinejad, 2005). However, it was demonstrated by Watson and Freer (1980) that ECM process generates a resistant oxide layer on the tungsten carbide surface promoting very slow material removal rate; which is further decreased when high cobalt percentage is used in the alloy. Although the material removal rate by ECM can be increased compared to EDM for other conductive materials, the EDM process is more suitable for machining carbides and other refractory materials as mentioned by Singh (2007). However, the cost of production will be higher as ECM process itself is less cost-effective compared to EDM (Singh, 2007). Due to lower material removal rate and ability to provide shiny surface, so far electro-chemical machining has been reported to be used for finishing purpose only for the machining of tungsten carbide (Masuzawa & Kimura, 1991).

Electrical Discharge Machining (EDM) is one of the important and cost-effective non-conventional methods for machining of extremely hard and brittle materials (Guitrau, 1997). EDM or spark machining removes electrically conductive material by means of rapid, repetitive spark discharges from electric pulse generators with the dielectric fluid supplying between the tool and workpiece. No mechanical cutting forces exist between the workpiece and tool. The non-contact machining process has been endlessly evolving from a mere tools and dies making process to a micro-scale application machining. Micro-EDM is the application of EDM in micro-field. The low energy range is becoming important when the EDM process is used in micro-field. Micro-EDM has similar characteristics as EDM except that the size of tool, discharge energy and axis movement resolutions are in micron level (Masuzawa, 2000). At the present time, micro-EDM is a widespread technique used in industry for high-precision machining of all types of conductive materials such as: metals, metallic alloys, graphite, or even some ceramic materials, of whatsoever hardness (Puertas *et al.*, 2004). Micro-EDM has been used extensively in the field of micro-mold making, production of dies, cavities and even complex 3D structures (Alting *et al.*, 2003). The major advantage of EDM or micro-EDM over the conventional machining process is that it is an electro-thermal process of removing metal regardless of hardness where the force between the workpiece and tool is negligible. Thus, the error caused by the tool deformation due to force is almost zero (Tsai & Masuzawa, 2004). Furthermore, there are no chatters, mechanical stress and vibration problem during the machining as there is no direct contact between the electrode and the workpiece (K. Ho & Newman, 2003). Consequently, micro-EDM can be used as one of the most effective methods of machining WC (Jahan *et al.*, 2009).

According to Jahan *et al.* (2009), between AgW, CuW and W electrodes for machining of WC, AgW electrode produces smoother and defect-free nanosurface with the lowest R_a and R_{max} among the three electrodes. Besides, a minimum amount of material migrates from the AgW electrode to the WC workpiece during the finishing micro-EDM. On the other hand, a CuW electrode achieves the highest MRR followed by AgW and W. In the case of electrode wear, the W electrode has the lowest wear followed by CuW and AgW. Also, Jameson (2001) stated that copper tungsten is often used for machining of tungsten carbide. Due to its high cost and limited availability of Silver Tungsten, it has a very limited range of applications (Kern, 2008). As result, CuW is chosen as micro-EDM electrode.

Consequently, micro-holes are used in the WC micro-die (Mark *et al.*, 2009) and CuW is used as micro-hole electrode to fabricate the micro-holes in WC micro-dies. There is less information about fabricating CuW micro-hole electrode that is used for electrical discharges machining WC. This includes information about which electrode material is suitable for EDM machining of CuW, the process setting and suitable parameter for micro-EDM. This research carries out to fabricate to CuW micro-hole electrode for electrical discharge machining of WC.

1.2 Research Questions

- What is the suitable material of electrode, process and methodology for fabricating a CuW electrode with a diameter of less than 400 µm for producing micro-holes using the EDM process?
- How to fabricate the electrode of micro-EDM?
- What are the effects of various Electrical Discharge Machining process parameters when EDMing WC?

1.3 Problem Statement

Limited information is available about fabricating micro-hole electrode made from CuW for electrical discharge machining. This includes information on suitable electrode material for electrical discharge machining of CuW, the processing method and suitable parameter for micro-EDM of CuW and WC-Co.

1.4 Objective of Study

- To identify suitable material of electrode, process and methodology for fabricating a CuW electrode with a diameter of less than 400 µm for producing micro-holes using the EDM process.
- To fabricate the above electrode using the EDM process.
- To evaluate the effects of various Electrical Discharge Machining process parameters when micro-EDMing WC.

1.5 Scope of Study

The scopes of the project are:

1. AG40L Sodik die-sinking machine is used for experiment.
2. PGM WHITE 3 is used as dielectric fluid.
3. Cu-W is used as micro-hole electrode material.
4. WC-Co is used as workpiece material.
5. Process parameters investigated are polarity and voltage while the effects investigated are time of machining, end wear and diameter of hole.

1.6 Organization of Report

This project report is organized as below:

Chapter1 (Introduction): this chapter introduces the research area and describes the problem.

Chapter 2 (Literature Review): this chapter reviews the previous literature related to type of material removal rate, EDM, micro-EDM, fabrication process of micro-electrode and material of block electrode, micro-electrode and workpice.

Chapter 3 (Research Methodology): this chapter describes the methodology and equipment are used in this research.

Chapter 4 (Result): this chapter describes the detail of fabrication process of micro-electrode and all of the results.

Chapter 5 (Discussion): this chapter illustrates the steps of developing Cu block electrode and evaluating the effect of polarity and voltage during micro-EDMing of micro-hole on WC-Co for time of machining, end wear and diameter of hole.

Chapter 6 (Conclusion and Recommendation): this chapter describes conclusion of results and recommendation for future work.

REFERENCES

Allen, D. M., & Lecheheb, A. (1996). Micro electro-discharge machining of ink jet nozzles: optimum selection of material and machining parameters. *Journal of Materials Processing Technology, 58*(1), 53-66. doi: http://dx.doi.org/10.1016/0924-0136(95)02107-8

Alting, L., Kimura, F., Hansen, H. N., & Bissacco, G. (2003). Micro engineering. *CIRP Annals-Manufacturing Technology, 52*(2), 635-657.

Asad, A., Masaki, T., Rahman, M., Lim, H., & Wong, Y. (2007). Tool-based micro-machining. *Journal of Materials Processing Technology, 192*, 204-211.

Bleys, P., Kruth, J. P., & Lauwers, B. (2004). Sensing and compensation of tool wear in milling EDM. *Journal of Materials Processing Technology, 149*(1), 139-146.

Caydas, U., & Hasçalik, A. (2008). Modeling and analysis of electrode wear and white layer thickness in die-sinking EDM process through response surface methodology. *The International Journal of Advanced Manufacturing Technology, 38*(11), 1148-1156.

Che Haron, C., Deros, B. M., Ginting, A., & Fauziah, M. (2001). Investigation on the influence of machining parameters when machining tool steel using EDM. *Journal of Materials Processing Technology, 116*(1), 84-87.

Chen, S., Yan, B., & Huang, F. (1999). Influence of kerosene and distilled water as dielectrics on the electric discharge machining characteristics of Ti–6A1–4V. *Journal of Materials Processing Technology, 87*(1), 107-111.

Das, J., Chakraborty, A., Bagchi, T., & Sarma, B. (2008). Improvement of machinability of tungsten by copper infiltration technique. *International Journal of Refractory Metals and Hard Materials, 26*(6), 530-539.

El-Hofy, H. (2005). *Advanced Machining Processes: Nontraditional and Hybrid Machining Processes*: The McGraw- Hill Companies.

Guitrau, E. B. (1997). *The EDM Handbook*. Cincinnati: Hanser Gardner Publications.

Ho, K., & Newman, S. (2003). State of the art electrical discharge machining (EDM). *International Journal of Machine Tools and Manufacture, 43*(13), 1287-1300.

Ho, P., Li, Q., & Fuh, J. (2008). Evaluation of W–Cu metal matrix composites produced by powder injection molding and liquid infiltration. *Materials Science and Engineering: A, 485*(1), 657-663.

Ibrahim, A., Abdallah, M., Mostafa, S., & Hegazy, A. A. (2009). An experimental investigation on the W–Cu composites. *Materials & Design, 30*(4), 1398-1403.

Jahan, M. P., Wong, Y. S., & Rahman, M. (2009). A study on the fine-finish die-sinking micro-EDM of tungsten carbide using different electrode materials. *Journal of Materials Processing Technology, 209*(8), 3956-3967. doi: http://dx.doi.org/10.1016/j.jmatprotec.2008.09.015

Jameson, E. C. (2001). *Electrical Discharge Machining*. Dearbern, Michigan: Society of Manufacturing Engineers.

Jangra, K., Grover, S., & Aggarwal, A. (2012). Optimization of multi machining characteristics in WEDM of WC-5.3% Co composite using integrated approach of Taguchi, GRA and entropy method. *Frontiers of Mechanical Engineering*, 1-12.

Kern, R. (2008). Sinker electro material selection. *EDM Today.*

Kumar, S., Singh, R., Singh, T., & Sethi, B. (2009). Surface modification by electrical discharge machining: A review. *Journal of Materials Processing Technology, 209*(8), 3675-3687.

Kunieda, M., Lauwers, B., Rajurkar, K., & Schumacher, B. (2005). Advancing EDM through fundamental insight into the process. *CIRP Annals-Manufacturing Technology, 54*(2), 64-87.

Lee, S. H., & Li, X. P. (2001). Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide. *Journal of Materials Processing Technology, 115*(3), 344-358. doi: http://dx.doi.org/10.1016/S0924-0136(01)00992-X

Li, T., & Gianchandani, Y. B. (2006). A micromachining process for die-scale pattern transfer in ceramics and its application to bulk piezoelectric actuators. *Microelectromechanical Systems, Journal of, 15*(3), 605-612.

Lim, H., Wong, Y., Rahman, M., & Edwin Lee, M. (2003). A study on the machining of high-aspect ratio micro-structures using micro-EDM. *Journal of Materials Processing Technology, 140*(1), 318-325.

Llanes, L., Idanez, E., Martínez, E., Casas, B., & Esteve, J. (2001). Influence of electrical discharge machining on the sliding contact response of cemented carbides. *International Journal of Refractory Metals and Hard Materials, 19*(1), 35-40.

Lu, Z., & Yoneyama, T. (1999). Micro cutting in the micro lathe turning system. *International Journal of Machine Tools and Manufacture, 39*(7), 1171-1183.

Luis, C. J., Puertas, I., & Villa, G. (2005). Material removal rate and electrode wear study on the EDM of silicon carbide. *Journal of Materials Processing Technology, 164–165*(0), 889-896. doi: http://dx.doi.org/10.1016/j.jmatprotec.2005.02.045

Machado, A., & Wallbank, J. (1990). Machining of titanium and its alloys—a review. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 204*(1), 53-60.

Mahdavinejad, R., & Mahdavinejad, A. (2005). ED machining of WC–Co. *Journal of Materials Processing Technology, 162*, 637-643.

Mandal, D., Pal, S. K., & Saha, P. (2007). Modeling of electrical discharge machining process using back propagation neural network and multi-objective optimization using non-dominating sorting genetic algorithm-II. *Journal of Materials Processing Technology, 186*(1), 154-162.

Mark, B., Toshihiko, M., Teruaki, M., & Kazushi, T. (2009). Micro-Hole Punching Using Multi-Point Punch and Die Made by EDM. *Journal of Advanced Manufacturing Technology, 3*(1), 73-86.

Maskiell, E. C., & Galbraith, W. (1985). *Machine Shop Technology*: McGraw-Hill Book Company.

Masuzawa, T. (2000). State of the art of micromachining. *CIRP Annals-Manufacturing Technology, 49*(2), 473-488.

Masuzawa, T., & Kimura, M. (1991). Electrochemical surface finishing of tungsten carbide alloy. *CIRP Annals-Manufacturing Technology, 40*(1), 199-202.

Masuzawa, T., & Tönshoff, H. (1997). Three-dimensional micromachining by machine tools. *CIRP Annals-Manufacturing Technology, 46*(2), 621-628.

Matsui, S., Kaito, T., Fujita, J., Komuro, M., Kanda, K., & Haruyama, Y. (2000). Three-dimensional nanostructure fabrication by focused-ion-beam chemical vapor deposition. *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures, 18*(6), 3181-3184.

MFM. (2008). Zinc Alloy Classification and Uses Retrieved 23th May 2013, from http://www.markusfarkus.com/reference/zinc.htm

Okuyama, H., & Takada, H. (1998). Micromachining with SR and FEL. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 144*(1), 58-65.

Pham, D. T., Dimov, S. S., Bigot, S., Ivanov, A., & Popov, K. (2004). Micro-EDM—recent developments and research issues. *Journal of Materials Processing Technology, 149*(1), 50-57.

Puertas, I., Luis, C., & Alvarez, L. (2004). Analysis of the influence of EDM parameters on surface quality, MRR and EW of WC–Co. *Journal of Materials Processing Technology, 153*, 1026-1032.

Raghu, T., Sundaresan, R., Ramakrishnan, P., & Rama Mohan, T. (2001). Synthesis of nanocrystalline copper–tungsten alloys by mechanical alloying. *Materials Science and Engineering: A, 304*, 438-441.

Rahman, M., Asad, A., Masaki, T., Saleh, T., Wong, Y., & Senthil Kumar, A. (2010). A multiprocess machine tool for compound micromachining. *International Journal of Machine Tools and Manufacture, 50*(4), 344-356.

Rahman, M., Senthil Kumar, A., & Prakash, J. (2001). Micro milling of pure copper. *Journal of Materials Processing Technology, 116*(1), 39-43.

Rahman, M. A., Rahman, M., Kumar, A. S., Lim, H., & Asad, A. (2006). Development of micropin fabrication process using tool based micromachining. *The International Journal of Advanced Manufacturing Technology, 27*(9), 939-944.

Schoth, A., Förster, R., & Menz, W. (2005). Micro wire EDM for high aspect ratio 3D microstructuring of ceramics and metals. *Microsystem technologies, 11*(4), 250-253.

Schumacher, B. M. (2004). After 60 years of EDM the discharge process remains still disputed. *Journal of Materials Processing Technology, 149*(1), 376-381.

Shaw, M. C. (1996). *Principles of Abrasive Processing*: OXFORD University Press.

Singh, M. K. (2007). Introduction of Unconventional Manufacturing Process *Unconventional Manufacturing Process* (1 th ed., pp. 6–7). New Delh: New Age International.

Smid, I., Akiba, M., Vieider, G., & Plöchl, L. (1998). Development of tungsten armor and bonding to copper for plasma-interactive components. *Journal of nuclear materials, 258*, 160-172.

Snoeys, R., Staelens, F., & Dekeyser, W. (1986). Current trends in non-conventional material removal processes. *CIRP Annals-Manufacturing Technology, 35*(2), 467-480.

Sodick. ,Sodick Wire-cut EDM PGM WHITE3 AG SERIES *instruction manual* (version 2 ed., Vol. 2): Sodick.

Sommer, C. (2000). *Non-traditional machining handbook*. Houston: Advance Publishing.

Soni, J., & Chakraverti, G. (1996). Experimental investigation on migration of material during EDM of die steel (T215 Cr12). *Journal of Materials Processing Technology, 56*(1), 439-451.

Tsai, Y. Y., & Masuzawa, T. (2004). An index to evaluate the wear resistance of the electrode in micro-EDM. *Journal of Materials Processing Technology, 149*(1), 304-309.

Tungsten Copper. (2011) Retrieved 1, November, 2012, from http://www.tungstenchina.com/product/Tungsten-Copper.html

Uhlmann, E., Piltz, S., & Doll, U. (2005). Machining of micro/miniature dies and moulds by electrical discharge machining—Recent development. *Journal of Materials Processing Technology, 167*(2), 488-493.

Walsh, R. A. (2001). *Handbook of Machining and Metalworking Calculations*: McGraw-Hill.

Wang, C. C., & Lin, Y. C. (2009). Feasibility study of electrical discharge machining for W/Cu composite. *International Journal of Refractory Metals and Hard Materials, 27*(5), 872-882.

Watson, S., & Freer, H. (1980). *A comparative study of electro-chemical and electro discharge machining of a tungsten carbide 25% Cobalt alloy*. Paper presented at the Proceedings of 6 th Symposium for Electro-Machining, ISEM VI.

Weller, E. J. (1984). *Nontraditional machining process*. Dearborn, Michigan: Society of Manufacturing Engineers.

Wong, Y., Lim, L., & Lee, L. (1995). Effects of flushing on electro-discharge machined surfaces. *Journal of Materials Processing Technology, 48*(1), 299-305.

Yan, B. H., Wang, C. C., Chow, H. M., & Lin, Y. C. (2000). Feasibility study of rotary electrical discharge machining with ball burnishing for Al2O3/6061Al composite. *International Journal of Machine Tools and Manufacture, 40*(10), 1403-1421. doi: http://dx.doi.org/10.1016/S0890-6955(00)00005-5

Yu, Z., Masuzawa, T., & Fujino, M. (1998). Micro-EDM for three-dimensional cavities-development of uniform wear method. *CIRP Annals-Manufacturing Technology, 47*(1), 169-172.

Zhao, W., Yang, Y., Wang, Z., & Zhang, Y. (2004). A CAD/CAM system for micro-ED-milling of small 3D freeform cavity. *Journal of Materials Processing Technology, 149*(1), 573-578.

Zhengui, Y., Stiglich, J., & Sudarshan, T. (1998). Nano-grained Tungsten Carbide Cobalt (WC/Co). *Materials Modification, Inc, 2929*.