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RECENT RESEARCH TRENDS IN TOOL ELECTRODE OF ELECTRICAL DISCHARGE MACHINING: A REVIEW

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Abstract — Electrical Discharge Machining (EDM) is a thermo-electrical based non-contact material removal process for machining of the electrically conductive difficult-to-machine materials. The machinability of the EDM process is not affected by mechanical and physical properties of the workpiece materials. Even though, its performances are highly affected by the tool materials and their designs. Most of the research papers refer to enhance the productivity of the EDM process without considering the effect of the parameters related to the tool electrodes. Generally, the tool wear is the well known phenomenon of the EDM process that affects the plasma formation as well as surface quality and productivity. The aim of the present study is to summarize a report on the published works related to the tool electrodes materials, designs and their effect on the performances of the EDM process. Instead of this, the present paper also focuses to future research scope in the same field and discussed in the brief.

Keywords — edm, edg, electrode, material, tool, polarity, plasma

I. INTRODUCTION

Electrical discharge machining (EDM) is more acceptable and industrialized non-traditional machining process for making of the molds and dies. The basic reasons behind this are to machining capability of EDM for difficult-to-machine electrically conductive materials. The machinability of the EDM process is not affected by mechanical and physical properties of the materials [1-3]. Therefore, the materials with high hardness, brittleness and strength like heat treated alloys, super alloys, metal matrix composites, advanced ceramics, glass etc. can be easily machined by it. The materials having conductivity more than 0.01/ohm cm can be machined by this process [4]. Due to applicability in machining, it is widely used in the field of die and mould industries, aerospace, aeronautics, and nuclear industries [3]. Instead of this, the EDM process shows their presence in the several other fields like sports, optical, medical and surgical instruments, dental and jewelry industries including advanced manufacturing, research and development areas [3, 5].

EDM can be defined as a thermo-electrical material removal process in which material is removed by melting and vaporization with application of controlled sparks generated between two electrodes (tool and workpiece), when pulse direct current (DC) applied to EDM machine. In this process, the tool and workpiece are connected to + ve or – ve polarity depending upon nature of machining. Both the electrodes are separated by dielectric fluid during machining. Generally, it works on the principle of erosion of the metals by controlled spark discharges between two-electrodes [6, 7]. Due to sparks, high temperature is generated between electrodes [7-10]. Generally, the each spark produces temperature between 8,000°C and 12,000°C [7] or as high as 20,000°C [11]. During machining, thousand of sparks are generated per second as a result melting and vaporization of the material occurs at the surface of electrodes and produces tiny craters. Due to erosion of workpiece material forms the shape of tool at the workpiece surface resulting machining can be performed [12].

Generally, EDM process involves the complex interaction of the many physical phenomena and many parameters those affected the performances of the EDM process [13]. These parameters can be divided into two categories, i.e. electrical and non-electrical parameters. The electrical parameters are as discharge voltage, pulse current, pulse frequency, pulse duration, pulse interval, duty factor and polarity of electrodes while non-electrical parameters are as flushing of dielectric fluid, electrodes rotation and electrode materials [14, 15]. Although, the performances of the EDM process are not affected by hardness and strength of materials. Even though, it is much slower process as compared to the milling and turning processes [16]. As a result, the enhancement in the productivity with high precision and accuracy becomes a big challenge for researchers.

Most of the research works show that the material removal rate (MRR), tool wear rate (TWR), and average surface roughness (Ra) are the main performance parameters of the EDM process [14, 15]. The analysis of the each process parameters on the performance parameters becomes difficult to explain because the EDM shows the stochastic thermal nature with complicated discharge mechanism for material removal [17]. Instead of this, the tool wears are well known problems of the EDM process [18]. Most of the researchers made their efforts to achieve the faster and more efficient metal removal rate with reduction in the tool wear rate at higher productivity by controlling the process parameters during machining [19-21]. Even though, the performances of the EDM process are highly affected by tool configurations i.e. tool materials and design [22].

Generally, most of the EDM tools are made by conventional methods by rapid prototyping technology. Even though, it is also possible to fabricate the complex electrodes. However, the fabrication methods are rather complicated but saved the time and cost too. [23, 24]. Therefore, considering the popularity of the EDM process and the role of the tool electrode in the machining, the present study has been presented. This paper summarized a report on the recent research and development in the EDM tool electrodes with future scopes of the works in the same area.

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II. EDM TOOL MATERIALS AND PROPERTIES

Tool electrode is an important parameter that responsible for the sparks generation and surface quality. The main characteristics of the tool materials are electrical and thermal conductivity, high melting temperature, low wear rate with high resistance to the deformation during machining. The common electrodes materials such as Graphite, Copper and their alloys, Copper-Tungsten, Brass, Silver, Silver-Tungsten and Steel are mostly used in the EDM process [22, 25, 26]. The Graphite tool material with finer grain gives higher material removal, lower tool wear with better surface quality. Even though, it is high brittleness in nature as which it is undesired for tool material [25]. The other material as Copper is most popular commercial tool material due to its excellent electrical and thermal conductivity [27]. The Copper tool material posses several unique properties such as high thermal conductivity, low tool wear rate and low thermal expansion coefficient etc. The combination of the Copper with Tungsten as Cu-W electrodes becomes popular tool material for machining of the hard and brittle materials such as die steel, glass, heat treated alloys and tungsten carbides [28]. The other tool materials like Silver or Silver alloys are highly expensive and used in only special applications.

III. RESEARCH IN TOOL MATERIALS

The several researchers, who works in field of EDM are made their efforts to get the better electrode materials. Several researchers were focused on the effect of tool materials during EDM process. Singh et al. [29] compared the performances of Copper, Brass and Graphite tool materials during EDMed of the mild steel workpiece. They claimed that the Graphite electrode exhibits superior quality with respect to the machining characteristics except for surface finish. The theoretical analysis related to the cathode erosion rate as a point heat source model (PHSM) for workpiece-tool materials was presented by Dibitonto et al. [30]. They analyzed the role of the electrodes in energy distribution during EDM process. Saha and Kumar [31] experimentally evaluated the cathode erosion rate for different materials (similar and dissimilar) of work/tool such as Steel, Copper, Titanium and Graphite using PHSM model. They show that Copper as anode results in greater fraction of the power going to the cathode.

The role of Copper and Graphite electrodes were analyzed by Lonardo and Bruzzone [32]. They investigated that wear rate of Copper electrode is higher as compared to Graphite electrode during machining the Cr, Mo, V steel. They also investigated that Copper electrode gives better surface finish as compared to the Graphite electrode. Lee and Li [33] investigated that the Cu-W tool electrode gives better performances (higher MRR, better surface quality, higher dimensional accuracy with low tool wear) as compared to the Copper and Graphite electrodes as shown in Fig. 1 (a)-(c). They suggested that Graphite electrode is more suitable for rough machining while Copper electrode is a better option to achieve the better surface quality.

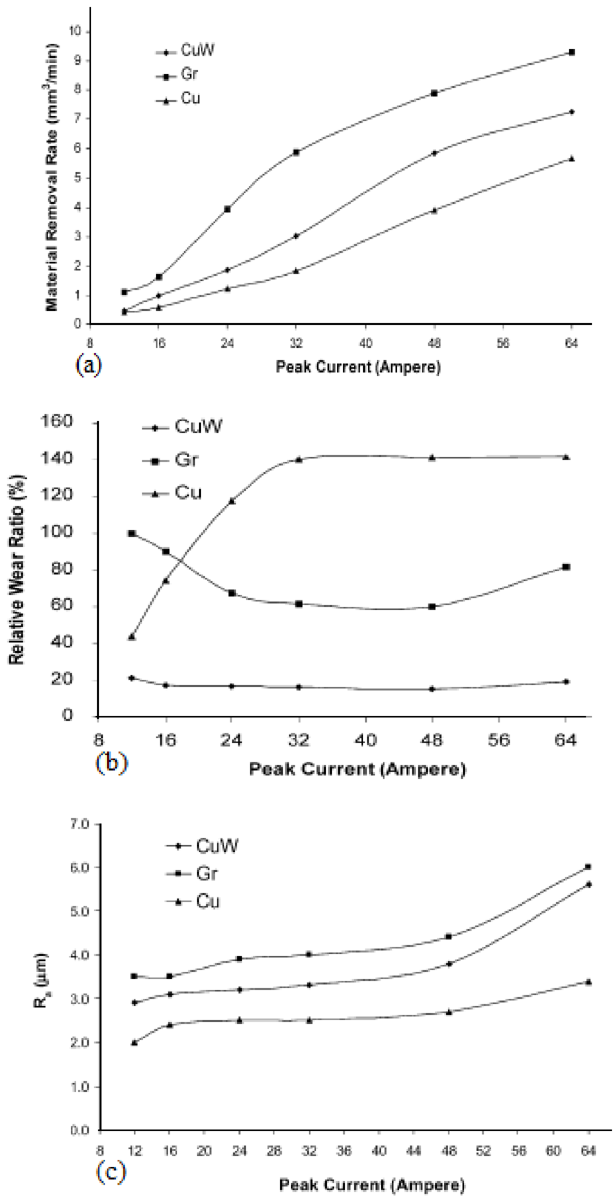

Fig. 1(a)-(c) Comparison of different of tool materials [33]

The performance of Copper, Copper-Tungsten, Brass and Aluminium electrodes on the En-31 tool steel were tested by Singh et al. [34]. They found Copper tool gives higher MRR, better surface finish, lower tool wear and overcut as compared to the other materials. Khan [35] was experimentally proved that the wear rate of the Copper electrode is less than Brass electrodes during EDMed of the aluminium and mild steel workpieces due to higher thermal conductivity and melting point of Copper as compared to Brass tool. Haron et al. [36] suggested that Copper electrode is more suitable for rough machining while graphite is a better option for the finish machining for EDMed of the XW42 tool steel. Singh et al. [37] also tested the performance of Copper tool during drilling-EDMed of the steel.

The effects of multi-electrodes (three-electrodes) in the EDM for pipe cutting were tested by Chena et al. [38]. They found higher MRR and lower tool wear with multi-electrodes as compared to the single electrode. Ming et al. [39] observed that electro-formed Copper electrode of sulfate bath shows better wear resistance than deposited tool electrode. Beri et al. [40] claimed that Cu-W electrode made be powder metallurgy gives better performance as compared to the electrode made by conventional methods.

The different EDM tool materials were also tested for machining of the metal matrix composites (MMCs) and ceramics workpiece materials. Mohan et al. [41, 42] examined that Copper tool gives higher MRR as compared to Brass tool during EDMed of Al/SiCp workpiece. Muttamara et al. [43] compared the performances of Copper, Graphite and Copper-infiltrated-Graphite tools during EDMed of alumina ceramic workpiece. They found that that Graphite is the comparatively better material for machining of the alumina because it gives higher MRR, lower electrode wear with better surface finish. Ahamad et al. [44] studied the effect of tubular Copper tool on EDMed of the hybrid-MMCs and found significant improvement in the performances. Senthilkumar and Omprakash [45] analyzed the effects of process parameters during machining of the Al/TiC composite workpiece.

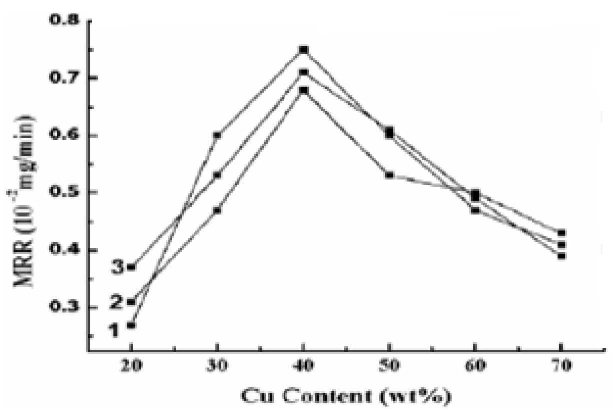

Fig. 2 Effect of percentage of Cu on material removal [49]

A. Research in Composites Tool Materials

To improve the productivity of the EDM process, several researchers were tested the performance of composites tools also. Ming and He [46] observed improvement in corrosion resistance of the die surface with Cu-Cr composite electrode in EDMed machining. They clarified that the Cr elements can be migrated towards die surface as a result improvement in the corrosion resistance of die material. Zaw et al. [22] compared the performances of the Cu, ZrB_2/Cu and TiSi/Cu electrodes in EDM and shows that TiSi/Cu electrode leads in high tool wear rate with damages at the workpiece surface. The performances of the TiC/Cu and TiC/Cu-W electrodes were compared with conventional electrode by Li et al. [23]. They found that the composite electrode with 15% TiC gives lower tool wear, higher material removal with better surface finish as compared to the conventional tool electrode.

The role of sintering pressure of the Cu/Cr composites tool electrodes in EDM were analyzed by Tasai et al. [47]. They claimed that high sintering pressure responsible for the higher material removal while lower pressure leads to easily drop-out of the Cu and Cr particles from the electrode material due to their weak bonding strength. The performance of the ZrB_2/Cu composites as an EDM electrode has been reported by Khanra et al. [48, 49]. They identified that composite tool with 40% of Cooper electrode gives higher material removal and lower tool wear as compared to the Copper electrode with some loss in the surface quality as shown in the Fig. 2. The performances of the hybrid-composite tool of Al/Cu/Si/TiC were tested by Taweel [50]. They experimentally proved that the hybrid-tool electrode shows high sensitive to peak current and pulse on-time than conventional tool electrode.

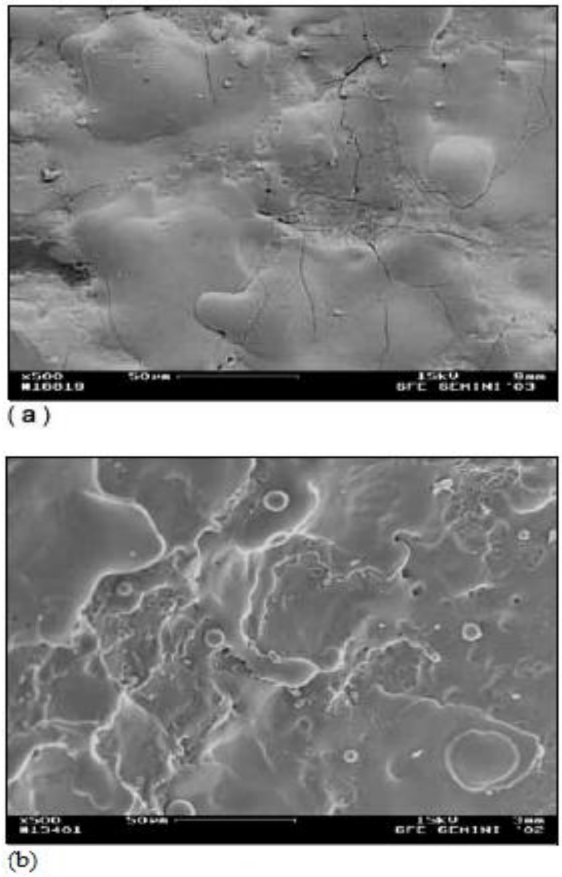

Fig. 3 Effect of tool diameter on EDMed surface [52]
(a) EDMed surface with 4 mm (diameter) tool
(b) EDMed surface with 0.5 mm (diameter) tool

IV. ESEARCH IN TOOL DESIGN

The shape and size of the tool electrodes also affect the performances of the EDM process. Several researchers were focused their research in that directions. The effect of the size and length of the electrode were studied by Lonardo and Bruzzone [32]. They observed that larger frontier area of tool electrode responsible for higher material removal due to erosion takes place in the larger area. On other hand, longer length of the electrode facilitates to thermal conduction as a result lower in the tool wear. Khan [35] investigated that higher tool wear occurs along their cross-section as compared to the wear along the length of tool.

Several researchers were shown that the cross section and diameter of tool electrode were also responsible for responses of the EDM process. Cogun and Akaslan [51] analyzed that higher tool wear occurs at inner radii as compared to the outer radii of the cylindrical hollow tool electrodes. Haron et al. [36] investigated that the tool wear rate decreases and material removal rate increases with the larger diameter of the tool as compared to the smaller diameter of the tool electrode in EDM process. Lee et al. [52] found that larger diameter of electrode leads in formation of micro-cracks on EDMed surface as compared to the smaller diameter of tool electrode. Such phenomenon has been shown in the Fig. 3(a) and (b).

The variations of geometrical tool wear characteristics such as edge and front wears during EDMed of steel with Copper tool were analyzed by Ozgedik and Cogun [53]. They explain the tool wears phenomena of EDM process as shown in the Fig. 4. They clarified the effect of the flushing on the tool wears behaviors and found that injection flushing leads in the larger inner edge wear while suction flushing shows larger outer edge wear. They also observed that the higher front-surface wear and larger edge-wear radius are observed at the dielectric inlet as compared to the dielectric outlet.

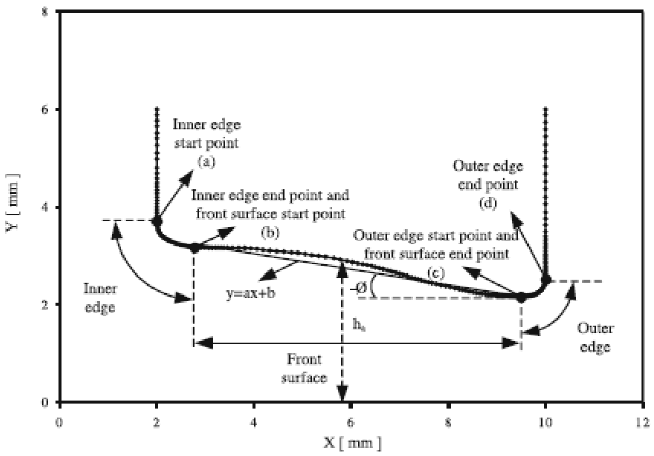

Fig. 4 Tool wear phenomenon in EDM process [53]

Instead of this, Marafona [54] investigated that the migrated carbon from the dielectric fluid during the EDM process are attached to the tool surface and form the black layer, which consist some other elements like iron, chromium, vanadium and molybdenum and known as equivalent carbon as shown in the Fig. 5. Such phenomenon leads to decrease in tool wear rate. Abdulkareem [55] investigated that the tool wear rate reduces approximately 27% with application of the effective cooling during EDMed of the Titanium alloy with Copper electrode in presence of the liquid Nitrogen. They also claimed that liquid nitrogen improves the electrical as well as thermal conductivity of the Copper electrode as a result reduction in the electrode wear rate with improvement in the surface quality of the EDMed surfaces.

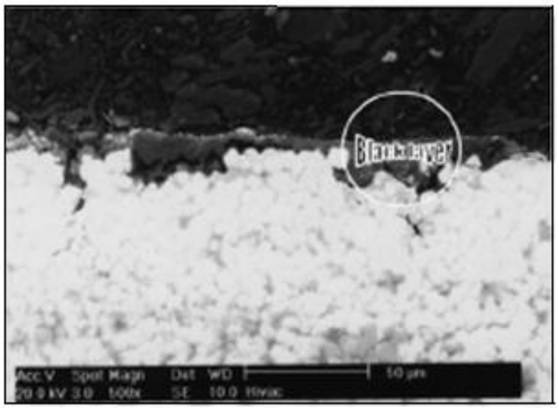

Fig. 4 Black layer formation on tool surface [54]

V. DISCUSSION AND FUTURE SCOPES

After carefully analysis of the published papers on the electrode material for the EDM process, following points become obligatory to discuss here.

- Among various tool materials (Copper, Brass, Graphite, Mild Steel) Copper has been found a good material for tool electrode of EDM process due to their high thermal and electrical conductivity properties. It gives higher material removal with better surface finish.
- Graphite electrodes are capable to give higher material removal but the brittleness property of the Graphite limits their wide applicability as a tool material.
- The electrode made of Copper and Tungsten i.e. Cu-W electrodes are a better option for machining of the difficult-to-machine materials because it gives better performances (higher MRR, better surface quality, higher dimensional accuracy with low tool wear) as compared to the Copper and Graphite electrodes.
- The applications of the composite electrodes as a tool material for the EDM process are limited and few researchers were focuses toward that direction. Even

though, composite tool gives higher material removal with lower tool wears.

- The shape and size of the tool electrodes also responsible for the performances of the EDM. Even though, very little works has been found in the same area. The frontier area of tools responsible for material removal while length of tool facilitates in the thermal cooling of the tool electrodes. Instead of this, the larger diameter of electrodes lead in micro-cracks on the EDMed surface while lower diameter of the tool electrodes gives better surface finish without cracks. Therefore, in this direction more researches are required to get the appropriate dimension of the tool electrodes for the EDM process.
- In circular tool electrodes, inner radius shows higher wear as compared to the outer radius of the tool. Therefore, researches are required in this direction to minimize the tool wears.
- Flushing of dielectric fluid responsible for the plasma formation and ejection of the molten material. Instead of this, it affects the tool wears but few papers were focused their studied in this area. Therefore, more research works are required in same area to know the behaviors of flushing on the tool materials.

VI. CONCLUSIONS

In present paper, a review report has been summarized on the different tool materials used in the EDM process. This paper also presented the role of the tool materials, shape and size of electrodes, cross sectional area of tool electrodes and development of the composite electrodes of the EDM process for machining of difficult-to-machine materials. This review becomes helpful for the researchers and industries to select the appropriate tool material for the EDM process. Instead of this, the paper becomes advantageous for the researchers who work in field of EDM and always make their efforts to achieve low cost machining with better quality.

References

[1] H.C. Tsai, B.H. Yan and F.Y. Huang, “EDM performance of Cr/Cu-based composite electrodes”, Int. J. Machin. Tool. Manuf., vol. 43, pp. 245-252, 2003.

[2] R.N. Yadav and V. Yadava, “Electrical discharge grinding (EDG): a review”, Proc. National Conf. Trends Adv. Mech. Eng., (TAME 2012), YMCA Univ. Sci. Technol., Faridabad, India, pp. 590-597, Oct 19-20, 2013

[3] K.H. Ho and S.T. Newman, “State of the art electrical discharge machining (EDM)”, Int. J. Mach. Tool Manuf., vol. 43, pp. 1287-1300, 2003.

[4] B. Wei and K.P. Rajurkar, “Abrasive eelectro discharge grinding of super alloys and ceramics”, Proc. 1st Int. Machin. Grind. Conf. Dearborn, Michigan, pp. 188-196 1995.

[5] D.R. Stovicek, “The state-of-the-art on EDM”, Sci. Tool. Product., vol. 59, pp. 42-65, 1993.

[6] M.S. Sohani, V.N. Gaitonde, B. Siddeswarappa and A.S. Deshpande, “Investigations into the effect of tool shapes with size factor consideration in sink electrical discharge machining (EDM) process”, Int. J. Adv. Manuf. Technol., vol. 45, pp. 1131-1145, 2009.

[7] G. Boothroyd and A.K. Winston, Fundamentals of Metal Machining and Machine Tools, Second Edition, Marcel Dekker, New York, 1989.

[8] R.N. Yadav and V. Yadava, “A new way of electro-abrasion hybrid machining (EAHM) using slotted-diamond grinding wheel”, Int. J. Manuf. Technol. Managem., vol. 28, pp. 132-145, 2014.

[9] R.N. Yadav and V. Yadava, “Influence of input parameters on machining performances of slotted-electrical discharge abrasive grinding of Al/SiC/Gr metal matrix composite”, Mater. Manuf. Proces., vol. 28, pp. 1361-1369, 2013.

[10] A. Ghosh and A.K. Malik, Manufacturing Science, East-West, Press, New Delhi, India, 1999.

[11] J.A. McGeough, Advanced Methods of Machining, Chapman and Hall, London, 1988.

[12] W. Konig, D.F. Dauw, G. Levy and U. Panten, “EDM-future steps towards the machining of ceramics”, Ann. CIRP, vol. 37, pp. 623-631, 1988.

[13] S. Das, M. Klotz and F. Klocke, “EDM simulation: finite element-based calculation of deformation, microstructure and residual stresses”, J. Mater. Process. Technol., vol. 142, pp. 434-451, 2003.

[14] K. Ojha, R.K. Garg and K.K. Singh, “MRR improvement in sinking electrical discharge machining: a review”, J. Miner. Mater. Character. Eng., vol. 9, pp.709-739, 2010.

[15] R.K. Garg, K.K. Singh, A. Sachdeva,V.S. Sharma, K.. Ojha and S. Singh, “Review of research work in sinking EDM and WEDM on metal matrix composite materials”, Int. J. Adv. Manuf. Technol., vol. 50, pp. 611-624, 2010.

[16] Y. Tzeng and F. Chen, “Multi-objective optimisation of high-speed electrical discharge machining process using a Taguchi Fuzzy-based approach”, Mater. Design,vol. 28, pp. 1159-1168, 2007.

[17] S.M. Pandit and T.M. Mueller, “Verification of on-line computer control of EDM by data dependent systems”, J. Eng. Ind., vol. 109, pp. 109-121, 1987.

[18] N. Mohri, M. Suzuki, M. Furuya and N. Saito, “Electrode wear process in electrical discharge machining”, Ann. CIRP, vol. 44, pp. 165-168, 1995.

[19] S.L. Chen, F.Y. Huang, Y. Suzuki and B.H. Yan, “Improvement of material removal rate of Ti–6Al–4V alloy by electrical discharge machining with multiple ultrasonic vibration”, J. Light Metar., vol. 4, pp. 220-225, 1997.

[20] M. Kunieda, S. Furuoya and N. Taniguchi, “Improvement of EDM efficiency by supplying oxygen gas into gap”, Ann. CIRP, vol. 40, pp. 215-218, 1991.

[21] Y. Imai, A. Satake, A. Taneda and K. Kobayashi, “Improvement of EDM speed by using frequency response actuator”, Int. Elect. Machin., vol. 1, pp.21-26, 1996.

[22] H.M. Zaw, J.Y.H. Fuh, A.Y.C. Nee and L.Lu, “Formation of a new EDM electrode material using sintering techniques”, J. Mater. Process. Technol., vol. 89-90, pp. 182-186, 1999.

[23] L. Li, Y.S. Wong, J.Y.H. Fuh and L. Lu, “EDM performance of TiC/copper-based sintered electrodes”, Mater. Design, vol. 22, pp. 669-678, 2001.

[24] A. Arthur, P.M. Dickens and R.C. Cob, “Using rapid prototyping to produce electrical discharge machining electrode”, Rapid Prototyp. J., vol. 2, pp. 4-12, 1996.

[25] V.K. Jain, Advanced Machining Processes, Allied Publisher, New Delhi, India, 2005

[26] H.E. Hofy, Advanced Machining Processes: Nontraditional and Hybrid Machining Processes, McGraw-Hill Companies, New Delhi, 2005.

[27] J.R. Davis, Metals Handbook, Second Edition, ASM International, USA, 1998.

[28] R.B. Ross, Metallic Materials Specification Handbook, Forth Edition, Ross Materials Technology Ltd., East Kilbride, Glasgow, 1992.

[29] U.P Singh, P. . Miller and W. Urquhart, "The influence of electrical discharge parameters on machining characteristics", Proc. 25th Int. Machin. Tool Design Resear. Conf. pp. 337-345, 1985.

[30] D.D. DiBitonto, P.T. Eubank, M.R. Patel and M.A. Barrufet, "Theoretical models of the electrical discharge machining process-I. A simple cathode erosion model", J. Appl. Phy., vol. 66, pp. 4095-4103, 1989.

[31] R. Saha and R. Kumar, "Influence of electrode materials and polarities on the electrode erosion rates in EDM process", Transactions of NAMRI/SME, vol. 25, pp. 2000.

[32] P.M. Lonardo, A. A. Bruzzone, "Effect of flushing and electrode material on die sinking EDM", Ann. ClRP, vol. 48, pp. 123-126, 1999.

[33] S.H. Lee and X.P. Li, "Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide", J. Mater. Process. Technol., vol. 115, pp. 344-358, 2001.

[34] S. Singh, S. Maheshwari and P.C. Pandey, "Some investigations into the electric discharge machining of hardened tool steel using different electrode materials", J. Mater. Process. Technol., vol. 149, pp. 272-277, 2004.

[35] A.A. Khan, "Electrode wear and material removal rate during EDM of aluminum and mild steel using copper and brass electrodes", Int. J. Adv. Manuf. Technol., vol. 39, pp. 482-487, 2008.

[36] C.H.C. Haron, J.A. Ghani, Y. Burhanuddin, Y.K. Seong and C.Y. Swee, "Copper and graphite electrodes performance in electrical-discharge machining of XW42 tool steel", J. Mater. Process. Technol., vol. 201, pp. 570-573, 2008.

[37] P. Singh, V. Yadava and A. Narayana, "Experimental study of electrical discharge machining on stainless steel workpiece using one parameter at a time approach", Proc. 1st Int. Conf. Adv. Recent Inn. Mech. Product. Indust. Eng. (ARIMPIE-2015), ITS Engineering College Gr. Noida, India, pp. 264-269, 2015.

[38] S.L. Chena, M.H. Lina, S.F. Hsiehb and S.Y. Chiou, "The characteristics of cutting pipe mechanism with multi-electrodes in EDM", J. Mater. Process. Technol., vol. 203, pp. 461-464, 2008.

[39] P.M. Ming, D. Zhu, Y.B. Zeng and Y.Y. Hu, "Wear resistance of copper EDM tool electrode electroformed from copper sulfate baths and pyrophosphate baths", Int. J. Adv. Manuf. Technol., vol. 50, pp. 635-641, 2010.

[40] N. Beri, A.Kumar, S. Maheshwari and C. Sharma, "Optimisation of electrical discharge machining process with Cu-W powder metallurgy electrode using grey relation theory", Int. J. Machin. Machin. Mater., vol. 9, pp. 103-115, 2011.

[41] B. Mohan, A. Rajadurai and K.G. Satyanarayana, "Effect of SiC and rotation of electrode on electric discharge machining of Al-SiC composite", J. Mater. Process. Technol., vol. 124, 297-304, 2002.

[42] B. Mohan, A. Rajadurai and K.G. Satyanarayana, "Electric discharge machining of Al–SiC metal matrix composites using rotary tube electrode", J. Mater. Process. Technol., vol. 153/154, pp. 978-985, 2004.

[43] A. Muttamara, Y. Fukuzawa, N. Mohri and T. Tani, "Effect of electrode material on electrical discharge machining of alumina", J. Mater. Process. Technol., vol. 209, pp. 2545-2552, 2009.

[44] A.R. Ahamed, P. Asokan and S. Aravindan, "EDM of hybrid Al–SiCp–B_4Cp and Al–SiCp–Glassp MMCs", Int. J. Adv. Manuf. Technol., vol. 44, pp. 520-528, 2009.

[45] V. Senthilkumar and B.U. Omprakash, "Effect of titanium carbide particle addition in the aluminium composite on EDM process parameters", J. Manuf. Proces., vol. 13, pp. 60-66, 2011.

[46] Q.Y. Ming and L.Y. He, "Powder-suspension dielectric fluid for EDM", J. Mater. Process. Technol., vol. 52, pp. 44-54, 1995.

[47] H.C. Tsai, B.H. Yan and F.Y. Huang, "EDM performance of Cr/Cu-based composite electrodes", Int. J. Machin. Tool Manuf., vol. 43, pp. 245-252, 2003.

[48] A.K. Khanra, B.R. Sarkar, B. Bhattacharya, L.C. Pathak and M.M. Godkhindi, "Performance of ZrB_2–Cu composite as an EDM electrode", J. Mater. Process. Technol., vol. 183, pp. 122-126, 2007.

[49] A.K. Khanra, L.C. Pathak, M M. Godkhindi, "Application of new tool material for electrical discharge machining (EDM)", Bull. Mater. Sci., vol. 32, pp. 401-405, 2009.

[50] T.A. El-Taweel, "Multi-response optimization of EDM with Al-Cu–Si–TiC P/M composite electrode", Int. J. Adv. Manuf. Technol., vol. 44, pp. 100-113, 2009.

[51] C. Cogun and S. Akaslan, "The effect of machining parameters on tool electrode edge wear and machining performance in electric discharge machining (EDM)", KSME Int. J., vol. 16, pp. 46-59, 2002.

[52] H.T. Lee, W.P. Rehbach, T.Y. Tai and F.C. Hsu, "Relationship between electrode size and surface cracking in the EDM machining process", J. Mater. Sci., vol. 39, pp. 6981-6986, 2004.

[53] A. Ozgedik and C. Cogun, "An experimental investigation of tool wear in electric discharge machining", Int. J. Adv. Manuf. Technol., vol. 27, pp. 488-500, 2006.

[54] J. Marafona, "Black layer characterisation and electrode wear ratio in electrical discharge machining (EDM)", J. Mater. Process. Technol., vol. 184, pp. 27-31, 2007.

[55] S. Abdulkareem, A.A. Khan and M. Konneh, "Reducing electrode wear ratio using cryogenic cooling during electrical discharge machining", Int. J. Adv. Manuf. Technol., vol. 45, pp. 1146-1151, 2009.