EFFECTS OF MACHINING VARIABLES ON ELECTRODE WEAR IN ELECTRIC DISCHARGE MACHINING

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ABSTRACT

Electric Discharge machining (EDM) has achieved remarkable success in the manufacturing of conductive materials for the modern industry. EDM is a non-traditional machining method commonly used to produce die-cavities via the erosion effect of electric discharge. The material is removed rapidly and repeatedly by spark discharge across the gap between the tool and the work-piece. In EDM, tool wear problem is very critical since the tool shape degeneration directly affects the final shape of the die cavity. In most of the EDM operation, the contribution of Electrode (tool) cost to the total operation cost is more than 70%. Due to this reason, the wear of Electrode should be carefully taken into consideration in planning and designing EDM operation. In a complete EDM process, machining stages that include rough –cut, middle cut and finish cut are carried out sequentially. The variations of geometrical tool wear characteristics – namely, edge and front wear – and machining performance outputs – namely, work-piece removal rate, tool wear rate, relative wear and work-piece surface roughness – were studied in this paper with varying machining parameters. This research was focused on the electrode wear rate of Electro discharge machining with a focused review on effect of different machining parameters like Discharge current, Pulse duration, Pulse time, Polarity, Dielectric flushing method, flushing pressure, Use of powder suspension in dielectric, Particle size of Powder, Electrode material and Work-piece material, on electrode wear (tool wear) of EDM.

Keywords: Electric discharge machining (EDM), Electrode wear- wear ratio, Material removal rate

1. Introduction

Different non-traditional machining techniques are increasingly employed in manufacturing of complex machine components. Among the non-traditional methods of machining processes, EDM has drawn a great deal of researchers' attention because of its broad industrial applications [41]. In EDM process material is removed by a succession of electrical discharges occurring between an electrode and work-piece that are both submerged in a dielectric bath, such as kerosene or distilled water [36]. EDM is extensively used in machining hard, high strength and temperature-resistant materials like high strength steel, tungsten carbide, hardened steel and alloys which are widely used in aerospace, automotive and die industries. In this process material is removed by controlled erosion through a series of electric spark discharges across the gap between electrode (tool) and the work-piece. In a complete EDM process, machining stages that include rough cut, middle cut and finish cut are carried out sequentially. The thermal energy of the sparks leads to intense heat conditions on the work-piece causing melting and vaporization of work-piece material [38]. Due to high temperature of sparks, not only work-piece material is melted and vaporized, but electrode material is also melted and vaporized, which is known as electrode wear (EW). The EW process is quite similar to the material removal mechanism as electrode in EDM [6], which causes the variation in accuracy due to the dimensional loss of electrode. So it is desirable to obtain maximum material removal rate (MRR) with Minimum EW. Hence the MRR, WR, EW and Job surface finish R_a are the machining performance criteria often applied to evaluate the machining effects in each stage. Many process parameters that can be varied in the different machining stages of EDM process greatly affect the machining performances. Subsequently, it becomes important to select properly the process parameter set for different machining stages in order to promote efficiency [43]. Usually the desired process parameters are determined based on experience or hand-data-book values. However, it is undoubtedly a challenge to ensure that the selected process parameters result in optimal or near optimal machining performance for that particular EDM and environment

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2. Electrical Discharge Machining Process

Electro-discharge machining (EDM) is widely used for machining of hardened tool materials. EDM is a non traditional manufacturing process based on removing material from the work-piece by means of series of repeated electric discharge between the electrode (tool) and the work-piece in the dielectric liquid. By servo controlled feed of tool electrode, the discharge conditions can be stabilized and the complementary shape of the electrode is impressed upon the work-piece. An electrical spark erosion effect takes place in the EDM process to remove the material of work-piece. Metal removal is on a thermal basis and therefore machinability with EDM is governed by thermal rather than mechanical properties. Fig 1 shows a systematic sketch of EDM. Various parameters are kept optimum during the process to obtain optimum results. The process parameters include pulse on time, pulse off time, high-voltage discharge current, low voltage discharge current, gap size, servo –feed, jumping time and working time. The R_a, the EW and MRR are usually the machining effects. R_a (µm) is the central –line average roughness of the machined surface. The MRR represents the volume of work-piece material removed in unit time. The process parameters are always reflected in the machining performances during a normal process.

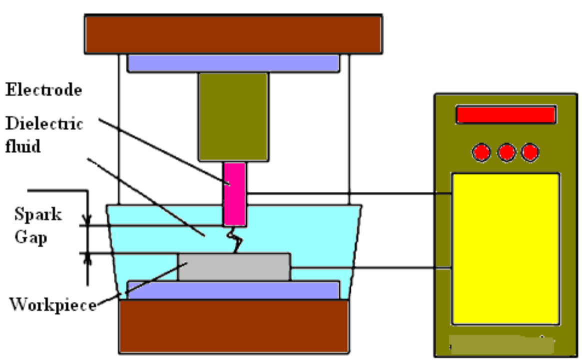


Fig 1 Systematic Sketch of EDM

3. Electrode Material (Tool)

Common electrode materials used in EDM Process (shown in fig 2) are graphite, brass, copper and copper-tungsten alloys [42]. As electrode wear is always there in the process because of high temperature sparks, efforts have been done to minimize EW. A metal matrix composite was also developed adding different amount of copper to get an optimum combination of wear resistance, electrical and thermal conductivity [12]. Copper combination shows more material removal with less EW. Manufacturing of electrodes of special composition of materials has given significant results but they are expensive and not always cost effective. Kunieda suggested that by using a multi-spark electrode discharging system, the MRR can be substantially increased with reduced EW [17]. But again, a special electrode involves additional cost.

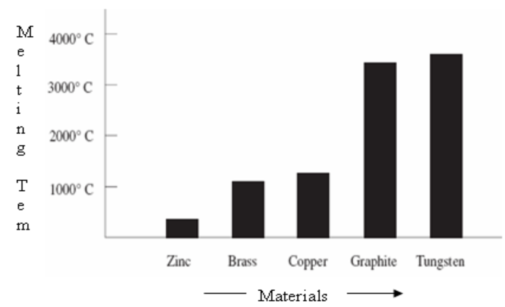


Fig. 2 Melting Temperature of materials

4. Tool Wear

Even after 66 years of EDM, still tool wear is not eliminated completely but it has been reduced to very small level. The tool wear is a very critical problem in EDM because the tool shape degeneration directly affects the final shape of the die cavity. Due to these reasons, The electrode wear should be taken into consideration very carefully in planning and designing of EDM operations because the contribution of the tool cost to the total operation cost is more than 70% in most of the EDM Processes.

A power supply delivers high-frequency electric pulses to the tool and the work-piece in EDM. A stream of dielectric liquid is flushed through the Electrode and work-piece. The insulating property of the dielectric fluid is momentarily broken down as an electric pulse is delivered from the power supply which causes a small spark (discharge) to jump the shortest distances between the tool and work-piece. This results in formation of a small pool of molten metal on the work-piece and the tool at the point of discharge. A gas bubble forms around the discharge and the molten pool. As the electric pulse ceases and the discharge disappears, the gas bubble collapses. The surge of cool dielectric causes the molten metal to be ejected from the work-piece and the tool, leaving small craters. This action is repeated hundreds of thousands of times each second during EDM processing. This removes material from the work-piece in a shape complementary to that of the tool. And it also removes some of the material from the tool electrode that is known as EW. It also affects the accuracy. Electrodes undergo more wear along their cross-section compared to that along length.

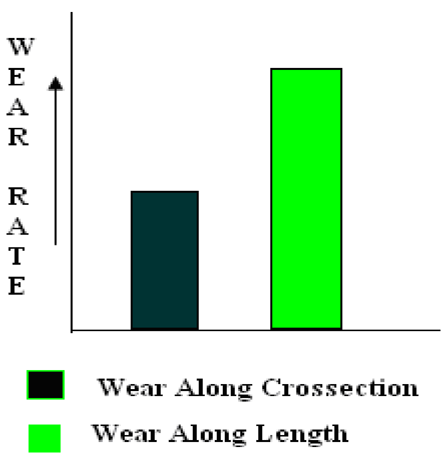


Fig 3. Wear Rate

So a special consideration should be given while designing an electrode (tool) for EDM considering EW. Considering the geometric tool wear characteristics during designing of Electrode (Tool) & EDM process would reduce the error to minimum level, resulting in good quality and cost reduction.

Electrode (tool) wear is generally expressed by means of tool wear rate (TWR) or relative wear and also some times by wear rate.

TWR can be calculated by ratio of volumetric material removal from the tool to machining time and can be expressed as

$$TWR = V_E / t_m \quad (1)$$

where,
V_E is volumetric material removed from tool (mm^3) and t_m is machining time (min**)**.

Work piece removal rate is generally expressed by MRR and can be calculated by ratio of volumetric material removal from the work piece to machining time
It is expressed as

$$MRR = V_W / t_m \quad (2)$$

Where,
V_W is volumetric material removed from the work-piece (mm^3) and t_m is machining time (min**)**.
Wear Ratio is expressed as TWR/MRR

$$WR = TWR/MRR \quad (3)$$

Although there are some other ways for measuring MRR and EW, normally we can calculate them by weight difference of sample and electrode just before and after being subjected to the EDM process. Many investigations have been conducted on EW in EDM process. An experimental analysis is performed to determine EW ratio in EDM with high carbon steel [26] and during the machining process it was observed that a black layer of carbon was formed on the surface of the electrode, which prevented the electrode from being eroded. It indicates that the EW ratio was strongly associated with carbon film. Luis et al. [24] designed and developed models for MRR and EW using the design of experiment (DOE) method and multiple regression analysis considering generator intensity (I), Pulse time, duty cycle, and dielectric parameters as input parameters and the MRR and EW as responses. It was shown that EW is directly proportional to pulse time.

5. Parameters Affecting Tool Wear

5.1 Discharge Current

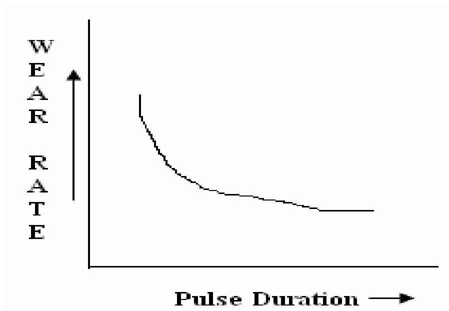
The energy of a pulse (We) is expressed in the following form

$$W_e = u_e \cdot i_e \cdot t_e \quad (4)$$

Where, u_e is the discharge voltage, i_e is the discharge current and t_e is the discharge duration of a pulse. Increase in discharge current results in increase in W_e (Eq. 4) and due to this, melting and evaporation of a large amount of material from the craters formed on both tool and work surfaces occur. Therefore, increasing discharge current results in an increase in the values of EW and MRR. The increase in discharge current results in increasing relative tool wears [3,4, 44]. It is due to the fact that higher current produces a stronger spark resulting in more material to be eroded from the electrode. At low discharge current relative wear increases more due to higher rate of increased EW as compared to MRR. Lee. S H (2001) observed that higher the discharge current, smaller is the machining time [20]. Material Removal Rate and surface roughness of the work piece are directly proportional to the discharge current intensity. Ra values increase with the discharge current since the large craters are formed on the work-piece surface with increasing current. Luis C.J. (2005) reported that current intensity is the most powerful factor affecting EW. As intensity is increased the EW is decreased. [25]

5.2 Pulse duration

WR increases with increase in pulse duration in the interval of short pulse duration [2]. But in longer pulse durations, a slight reduction of WR and a higher MRR are observed due to the increase in pulse duration. This is mainly because of the increase in heat transfer time from the molten crater to the body of the tool. [2,3,23]. Liu C.C (2003) compared performance of different electrode materials like, copper and brass while machining composite material on EDM It was observed that due to increase in pulse current, the EW is also increased[21]. Several authors have reported many qualitative relationships between the EDM process parameters like current and pulse on time in their EDM studies [18, 34,46]. George V (1980) has recommended pulse duration of 70-90 μs for optimum machining rates & Pulse duration greater than 90 μs are desirable with minimum loss in machining rate to reduce degeneration of tool shape and tool wear [45]. It was recently reported in the investigations that the carbon from the decomposition of hydrocarbon-based dielectric liquid and molten metal from carbon steel attaches to the surface of the tool in long pulse durations, and wear resistance of the tool is increased due to this deposited layer on the electrode (tool) surface [2, 30]. The increase in pulse duration reduces relative wear drastically.



5.3 Polarity

Electrode polarity has a significant effect on electrode wear rate for moderate current values, but at higher current values it has no significant effect. Electrode wear rate is comparatively more if negative polarity is given to the electrode instead of positive polarity specially in the range of low to medium discharge current values. At high current settings, polarity has no significant effect on electrode wear rate [20] In the case of negative polarity; slight decrease in electrode wear rate is observed with increase in current. But there is drastic decrease in electrode wear rate with increase in current in the case of Positive polarity to the electrode (tool). This shows that at high setting of current in both the polarities, current has no significant effect on electrode wear rate. Lee. S H (2001) observed that better machining performance is obtained generally with the electrode as cathode (-) and work-piece as anode (+). Tool with negative polarity gives higher MRR, lower tool wear & better surface finish [20].

5.4 Tool & work piece Material

An ideal tool material should provide a maximum V_W with minimum V_E. High melting temperature, density, heat conduction coefficient, specific heat, cohesion energy and latent heat of evaporation of the tool material result in high resistance to wear [35]. Khan AA (2007) recorded that brass electrode gives highest wear ratio during machining of steel because of its low thermal conductivity causing less heat loss, and its low melting temperature resulting in fast melting of electrode material. At the same time poor material removal rate is observed because of poor heat absorption and high melting temperature [11]. The V_E is higher for tool materials with low melting temperature. Copper tools give higher V_E values compared with the ones made of graphite and tungsten carbide. It is revealed that V_W increases significantly with discharge current for copper, copper-tungsten (25%Cu) and graphite tools [20], and a maximum value of V_W is obtained with the use of graphite tools. For finishing operations, the copper tools give the best surface quality. Higher melting temperature and cohesion energy of the work-piece material cause higher tool wear [9, 23].

5.5 Dielectric Flushing Method

Injection and suction flushing through the tool gives lower Electrode wear than side flushing. This is due to the lower dielectric temperature, gas volume and contamination in the machining gap for injection and suction flushing compared to that of side flushing [13]. The machining condition turns into an unstable regime when there is no flushing. This condition is called the "static dielectric condition" or "static condition". WR increases rapidly when the flushing pressure is increased beginning from the static condition. Increasing dielectric pressure at high-pressure settings does not result in a significant increase in WR. The increase in dielectric pressure at low-pressure settings results in a significant increase in wear rate, whereas the increase in pressure at high dielectric pressure settings insignificantly affects wear rate [3,40,44]. In an investigation, pressure, velocity and force variations due to forced dielectric flow in the machining gap for injection hole flushing through the tool were formulated theoretically [13]. Jain V.K (1993) reported in his study that effective flushing of the working gap brought about by the rotation of the electrode remarkably improves material removal rate. The reproduction accuracy is least affected despite the prevalent high tool wear rate as the wear gets uniformly distributed over the entire tool surface [8]. In the experimental part of the study, it is found that MRR and WR increase with dielectric flow rate. It is observed that the front-surface inclination angle of the tool (Φ) increases with decreasing diameter of the tool and increasing dielectric flow rate. To stabilize the EDM process an adequate flushing of the gap zone is very important, as increase in the dielectric pressure leads to better behaviour of electrode wear. The Wear of electrode tends to decrease with the increase in flushing pressure. [25]. In another study, the gas injection from the tool is applied instead of a liquid dielectric [17]. It is concluded that gas injection provides faster solidification of molten and evaporated material and more effective removal of debris from the gap. The increasing oxygen pressure results in higher V_W and lower WR values compared with kerosene dielectric use. The vertical and horizontal direction vibrations of the tool generate dielectric liquid movement in the gap. The tool vibration improves the value of MRR, but it leads to an increase in WR [27].

5.6 Use of Powder Suspension in the Dielectric

Various powders like aluminium (Al) chromium (Cr), copper (Cu), and silicon carbide (SiC), are used to improve the MRR and reduce the WR in EDM process because of their significant thermo-physical properties. It is experimentally found that the particle concentration, particle size, the particle density, the particle resistivity and thermal conductivity of powders are having significant effect on the EW & MRR in the EDM process. Proper additions of powder lead to increase in MRR & decrease in the EW. It is investigated that chromium powder gives higher MRR & low EW. [37] At low current setting the reduction in electrically conductive powder concentration leads to a rapid decrease in WR whereas at high current setting it leads to a slow decrease in WR. A very high concentration of powder combined with natural gap contamination (i.e. machining debris) causes frequent occurrence of short-circuits and arc-type pulses. The occurrences of these pulses result in excessively high values of WR [27]. In an investigation where Al, Cr, Cu and SiC powders are mixed with the kerosene dielectric, it is found that Al powder is the most effective and Cu powder is the least effective powder in changing the inter-electrode gap distance. It is also observed that increasing the average size of the suspended powder particles yields an increase in MRR and WR while decrease in WR is observed with an increase in powder concentration [37].

Tzeng Y. F (2001) investigated that generally at low discharge current TWR is decreased when powder suspension in the dielectric is used. It is also observed that increase in particle size leads to increased tool wear. The particle concentration has no significant effect on TWR in the EDM process. [37]

5.7 Tool Geometry

Experiments carried out using square-section copper and graphite tools with through hole injection flushing showed that V_W increases with increasing tool area in roughing and Ra increases with increasing area in finishing conditions [22]. The experiments conducted using a steel work-piece and round tool specimens showed that the tools with small diameter show higher tool wear with increasing current. The study also indicated that increasing discharge voltage yields an increase in V_W and V_E at low discharge current settings [2]. In a study, in which solid and hollow round tools with normal feed and rotational feed are used, it is observed that the V_W and V_E values are maximum for hollow tools and Ra is minimum for solid tools with normal down feed. It is also found that V_W, V_E, Ra and machining depth values are higher for injection flushing applications [40]. In an experimental investigation, in which tools with ultrasonic vibration, rotation and combination of both are used, it is found that high-frequency ultrasonic vibrations of the tool increases the value of V_W in finishing conditions. High values of V_W, V_E and Ra are obtained for low ultrasonic vibration frequency combined with rotation [5].

5.8 Composite Tool Material

In the machining of Al-SiC-based metal composite work-pieces with rotational copper and zinc tools, the increasing content of SiC leads to a decrease in V_W and V_E, and an increase in R_a [33]. Zinc tools give high V_W and R_a, and low V_E values. In another experimental study, in which the same type of composite tools are used, the settings which give high V_W values also result in low yield and ultimate tensile strength of the work material. This is attributed to the annealed soft layer observed at the bottom of the re-solidified work-piece surface. When the work-piece surfaces machined by EDM are compared with the traditionally ground ones, a 15% to 20% reduction in fatigue strength of the work material is found for electrical-discharge-machined surfaces. Mohan B (2002) noted that iirrespective of the electrode material, polarity of the electrode and volume percentage of SiC, the MRR increased with increase in discharge current and for a specific current it decreased with increase in pulse duration. Increase in the volume percentage of SiC had an adverse effect on MRR, and positive effect on TWR and surface finish. [29**]** In the machining of 6061 aluminium alloy and Al_2O_3-

reinforced metal composite work-pieces with rotating round copper tools, a reduction in V_W with an increasing amount of Al_2O_3 is observed [38]. In another study, the diameter of the crater produced by a single discharge on an Al-SiC metal composite work-piece is measured. The measurements indicate that increasing discharge energy and discharge current lead to an increase in the diameter of work-piece craters [40].

6.Conclusions

In this review paper, the effects of various parameters like pulse rate, discharge current, dielectric flushing method, pulse duration, tool geometry and powder particles in dielectric on the performance measures like MRR, EWR, R_a and relative wear are considered. The following conclusions can be drawn:

1. Wear of copper electrode is more as compared to electrodes of other materials like brass, tungsten & carbide.
2. Electrodes undergo more wear along their cross-section compared to that along length.
3. The Electrode wear increases with the increase of current and gap voltage.
4. Increasing the average size of suspended powder particles will increase Electrode wear. But increase in concentration leads to decrease in electrode wear.
5. Long pulses in general give rise to less tool wear than short pulses.
6. Suction flushing gives lower electrode wear rate as compared to injection flushing.
7. Increase in pulse duration decreases the electrode removal rate. The relative wear decreases with increasing pulse duration since the work-piece removal rate increases at faster rate than the electrode wear rate.
8. Electrode Polarities have no significant effect on Electrode (tool) wear rate at high settings of current.

7. References

1. *Chen SL, Yan BH, Huang FY (1999) Influence of kerosene and distilled water as dielectrics on the electric discharge machining characteristics of Ti-6Al-4V. J Mater Process Technol 87:107–111*
2. *Chen Y, Mahdavian SM (1999) Parametric study into erosion wear in a computer numerical controlled electro-discharge machining process Wear 236:350–354*
3. *Cogun C, Akaslan S (2002) The effect of machining parameters on tool electrode wear and machining performance in electric discharge machining. KSME Int J 16(1):46–59*
4. *Crookall JR (1979) A theory of planar electrode face wear in EDM. Ann CIRP 28(1):125–129*
5. *Ghoreishi M, Atkinson J (2002) A comparative experimental study of machining characteristics in vibratory, rotary and vibro-rotary electrodischarge machining. J Mater Process Technol 120:374–384*
6. *Ho KH, Newman ST (2003) State of art electric discharge machining (EDM). Int J Mach Manuf 43(13: 1287-1300*
7. *Hocheng H, Lei WT, Hsu HS (1997) Preliminary study of material removal in electrical-discharge machining of SiC/Al. J Mater Process Technol 63:813–818*
8. *Jain V.K , Lal G.K , Philip Koshy (1993) Experimental investigations into electrical discharge machining with a rotating disk electrode. Precision Engineering, Volume 15, Issue 1, : 6-15*
9. *Jeswani ML (1979) Dimensional analysis of tool wear in electrical discharge machining. Wear 55:153–161*
10. *Jilani ST, Pandey PC (1984) Experimental investigation into the performance of water as dielectric in EDM. Int J Mach Tool Des Res 24(1):31–43*
11. *Khan A.A (2007) Electrode wear and material removal rate during EDM of Aluminium and mild steel using copper and brass electrodes, int. J. Adv. Manuf. Technol .*
12. *Khanra AK, Sarker BR, Bhattacharya B, Parthak LC, Godkhindi MM(2007) Performance of ZRB_2-Cu composite as an EDM electrode. J mater Process Technol 1831: 122-126*
13. *Koenig W, Weill R, Wertheim R, Jutzler WI (1977) The flow fields in the working gap with electro-discharge-machining. Ann CIRP 25(1):71–76 500*
14. *König W, Jörres L (1987) Aqueous solutions of organic compounds as dielectrics for EDM sinking. Ann CIRP 36(1):105–109*
15. *Kruth JP, Stevens L, Froyen L, Lauwers B (1995) Study of the white layer of a surface machined by die-sinking electro-discharge machining. Ann CIRP 44(1):169–172.*

16. *Kunieda M, Muto H (2000) Development of multi-spark EDM. Ann CIPR 49(1) : 119-122.*
17. *Kunieda M, Yoshida M, Taniguchi N (1997) Electrical discharge machining in gas. Ann CIRP 46(1):143–146.*
18. *Lee HT, Tai TY (2003) Relationship between EDM parameters and surface crack formation. J Mater Process Technol 142: 676-683.*
19. *Lee HT, Yur JP (2000) Characteristic analysis of EDMed surfaces using the Taguchi approach. J mater manuf Proc 15: 781-806.*
20. *Lee SH, Li XP (2001) Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide. J Mater Process Technol 115:344–358.*
21. *Liu CC (2003) Microstructure and tool electrode erosion in EDMed of* TiN/Si_3N_4 *composites. Mater Sci Eng A 363:221-227.*
22. *Lonardo PM, Bruzzone AA (1999) Effect of flushing and electrode material on die sinking EDM. Ann CIRP 48(1):123–126.*
23. *Longfellow J, Wood JD, Palme RB (1968) The effects of electrode material properties on the wear ratio in spark-machining. J Inst Met 96:43–48*
24. *Luis CJ, Puertas I, villa G (2005) Material removal rate and electrode wear study on EDM of Silicon carbide. J Mater Process Technol 164-165 : 889-896*
25. *Luis, C. J, Puertas, Villa G., (2005) Material removal rate and electrode wear study on the EDM of silicon carbide, J material processing Technology 164-165 : 889-896.*
26. *Marafona J (2007), Black layer characterization and electrical discharge machining. J Mater Process Technol 184: 27-31.*
27. *Masuzawa T, Heuvelman CJ (1983) A self flushing method with spark erosion machining. Ann CIRP 32(1):109–111.*
28. *Mohan B, Rajadurai A, Satyanarayana KG (2002) Effect of SiC and rotation of electrode on electric discharge machining of Al-SiC composite. J Mater Process Technol 105:1–8.*
29. *Mohan B., Rajadurai A. , Satyanarayana (2002) K. G Effect of SiC and rotation of electrode on electric discharge machining of Al–SiC composite Journal of Materials Processing Technology, Volume 124, Issue 3, 20 : 297-304.*
30. *Mohri N, Suzuki M, Furuya M, Saito N (1995) Electrode wear process in electrical discharge machining. Ann CIRP 44(1):165–168 .*
31. *Mohri N, Takezawa H, Saito N (1994) On-the-machine measurement in EDM process by a calibration system with polyhedra. Ann CIRP.*
32. *Puertas I, Luis CJ, Alvares L (2004) Analysis of influence of EDM parameters on surface quality, MRR and EW of WC-Co. J mater Process Technol 153-154: 1026-1032.*
33. *Ramulu M, Paul G, Patel J (2001) EDM surface effects on the fatigue strength of a 15 vol% SiCp/Al metal matrix composite material. Compos Struct 54:79–86.*
34. *Rebelo JC, Morao DA, Kramer D, lebrun JL (1998) Influence of EDM pulse energy on the surface integrity of martensitic steel. J Mater Process Tcchnol 6:84-90 .*
35. *Samuel MP, Philip PK (1997) Power metallurgy tool electrodes for electrical discharge machining. Int J Mach Tools Manuf 37(11): 1625–1633 .*
36. *Shu KM, Tu GC(2003) Study of electric discharge grinding using metal matrix composite electrode. Int J Mach Tool Manuf 43: 845-854 .*
37. *Tzeng Y. F , Lee C. Y (2001), Effect of powder characteristics on Electric discharge Machining Efficiency, Int J Adv Manuf Technol 17: 586-592 ..*
38. *Yan BH, Tsai HC, Huang FY (2005). The effect of EDM of dielectric of a urea solution in water on modified surface of titanium. Int J Mach Manuf 45(2) : 194-200 .*
39. *Yan BH, Wang CC (1999) The machining characteristics of Al2O3/6061Al composite using rotary electro-discharge machining with a tube electrode. J Mater Process Technol 95:107–111.*
40. *Yan BH, Wang CC, Chow HM, Lin YC (2000) Feasibility study of rotary electrical discharge machining with ball burnishing for Al2O3/6061Al composite. Int J Mach Tools Manuf 40:1403–1421*
41. *Zarepour H, Tehrani AF, Karimi D, Amini S (2007) Statistical Analysis on electrode wear in EDM of tool steel DIN 1.2714 used in forging dies. J Mater Process Technol 187-188 : 711-714*
42. *Kalpakjian S, Schmid SR (2001) Manufacturing engineering and technology, 4th edn. Prentice Hall, Upper saddle River*

43. *McGeough JA (1988) Advanced Methods of machining. Chapman and Hall, New York .*
44. *Cogun C, Poyrazoglu O (2001) The variation of machining performance with machining parameters in EDM. In: Proceedings of the 2nd International Conference on Design and Production of Dies and Molds, Kusadası, Turkey, 2001*
45. *George V, Venktesh V.C.(1980) Investigations on Optimum machining conditions for Electro-discharge machining of 5Cr Die steel, proceeding of the 9th AIMTDR conference IIT-Kanpur, :327-332*
46. *Kruth.JP, Van HJ, Stevans L (1995) Microstructureal investigation and metallographic analysis of white layer of surface machined by electro discharge machining. Proceedings of the conference ISEM-XI, 849-62*

