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Growth of Electrical Discharge Machining and Its Applications – A Review

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Abstract:-Globalization is making the manufacturers to invest and invent in the manufacture / production of sophisticated and quality products to meet ever changing needs of the customer. Thus, the research in manufacturing has been concentrated towards the high speed machining involving CNC Machines, Robots and Automated Handling Systems with the emergence of computers in Engineering on one side and the development Unconventional Machining such as Chemical Machining, Laser Beam Machining (LBM), Electron Beam Machining (EBM) and Electron Discharge Machining (EDM) on the other side. Out of them, the environment of Chemical Machining is found to be hazardous, whereas LBM and EBM require huge investments in comparison to EDM. Therefore, the EDM is widely used in manufacturing. In the present paper, about 111 research papers are reviewed on the major topics of EDM research. It also reports on the research related to the adoptive monitoring and control of process and the feasibility of different strategies of obtaining the optimal machining conditions. EDM as well as WEDM industrial applications are reported together with the hybrid machining process.

Key Words:- EDM, WireEDM, Growth, Review, Modeling, Experiments.

I. INTRODUCTON

Electric Discharge Machining (EDM) is an Unconventional Machining technique of metal removal process consisting of erosion of material from the work piece due to series of discrete sparks between work piece and electrode separated by a thin film of dielectric fluid medium. The EDM process is generally divided into (i) Die-sinking EDM, (ii) Wire Electric Discharge Machining, (WEDM) (iii) MicroEDM, (iv) Powder Mixed EDM and (v) Dry EDM. What ever may be the type of process, the aim is to remove the metal from the work piece by optimum utilization of the machining parameters to get the required shape with quality surface. In the optimum or better utilisation of the available machining variable parameters through number of techniques either by experimentation or modeling are being used in the research and in practice. The recent observation is being the application of the Wire-EDM in Granite Mining Operations to avoid the heavy manual involvement. The outline of various types of EDM and the techniques used for various materials are given in the Figure – 1. The technique starting from a simple means of making tools and dies has reached the stage as the best alternative of producing micro scale parts. Such EDM process growth is briefly discussed based on 111 contributions ever since its basic principle started with the erosive effect of electric discharges.

II. ELECTRIC DISCHARGE MACHINING (EDM)

The Literature shows the basis of EDM with the discovery of the erosive effect of electric discharges or sparks during the year 1770 by the English Chemist Joseph priestly [1]. However, the destructive nature of properties of electrical discharges has been exploited for constructive purpose in the year 1943 at Moscow University [2]. The development of the system by Lazarenko [2] has been utilized the resistance capacitance type of Power Supply for the widely used EDM in the year 1950 and it became a model for successive development in EDM [3]. At the same time, the work of three American employees became the basis for vacuum tube EDM machine and the electronic servo system has automatically provided the proper electrode-to-work piece spacing for sparking, without the electrode contact [4]. The manufacturing / production technology has taken a revolutionary change in 1980s with the advent of computers and made the conventional machines as Computer Numerical Control (CNC) machines including EDM so as to manufacture sophisticated and quality products with accuracy and better productivity. Since then, the CNC in EDM made the process automatic starting from inserting the electrodes in place of tool till obtaining the finished / polished cavity or cavities [5]. Such CNC-EDM has resulted in enormous benefits and influenced the research area. Thus, it is common in the research to bring-out the contributions of various researchers / manufacturers / experts from time to time. In the process, the EDM operating and performance parameters along with electrode design and manufacture [6], Role of EDM in Unconventional and CNC machining [7] and a Review on EDM in relation to the Aluminum Matrix Composites [8] have been seen. The EDM is further expanded as WEDM. The influence of current, Voltage on MRR, surface roughness in WEDM [9] and its relevant topics with the relationship between the dynamics of electrode and control in WEDM [10] and applications of WEDM [11] have been briefly discussed. Then the trend of research in Die-sinking EDM on (i) Conductive Ceramics [12] and (ii) Silicon Carbide Metal Matrix Composites, {13] have been reviewed. All of them have given future direction on the topics: MRR, surface finish, wire diameter, Tool wear, Current rate, kerf, accuracy, etc. Out of the available EDM processes, the Wire EDM is found to be more flexible and hence the review is briefly brought in the following.

III. DEVELOPMENTS IN EDM

The research has gained importance in various angles in terms of experimental studies, modeling both mathematical and simulation and also other techniques for EDM with the main objective of either to maximise the metal removal rate (MRR) or minimise the machining time and tool wear or optimise the machining cost to obtain better surface finish with either conventional or composite or metal combinations. Though extensive theoretical and experimental studies on various aspects of EDM process such as the machine types, tooling, control circuits, selection of the process conditions and online machine control [14]; the complex nature of EDM process and effect of interacting process parameters make the process analysis quite difficult. Therefore, the Researchers worldwide are focusing attention on modeling and optimization of EDM and its related processes. In the present paper, experimental studies and Modeling of machining parameters on various aspects of EDMs are briefly studied and presented in the following.

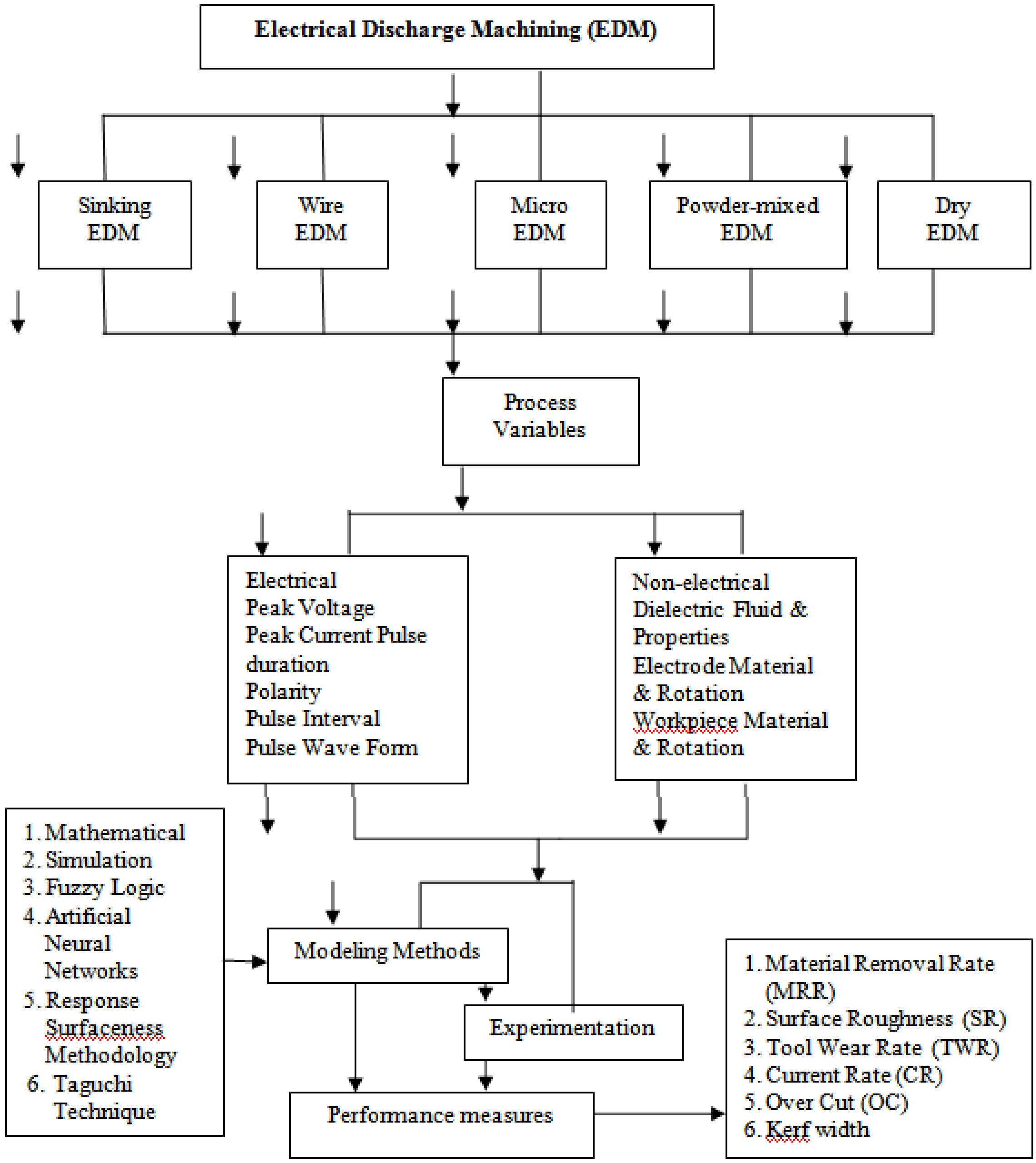

Figure- 1 : Different types, process parameters and Performance measures of EDM

3.1 STUDIES ON EDM

The contributions of researchers have been reviewed in terms of experimental studies on EDM for machining different materials including composite materials. Since the metal removal rate is dependent on the type of electrode used, the powder metallurgy technique for fabricating composite electrode has been tried so as to reduce the crakes and wear resistance, [15]. The feasibility of fabricating micro holes in high nickel alloy using micro EDM has been shown, [16] and the hole making on WC-Co based R-C circuit was experimented, [17]. The copper electrodes give higher MRR than the Al electrodes during machining of stainless steel and carbides since Al electrodes under-go more wear than copper electrode due to their lower melting point and specific thermal energy during EDM, [18]. The graphite electrode is being used during machining of Tungsten Carbide ceramics, [19]. The effect of ultrasonic vibration of the electrode was studied on surface integrity of Tungsten carbide,[20]. The experiments conducted with EDM for surface roughness reveal that smooth machining surface and sharp bottom surface of V groove with PCD tool,[21], theTiCN-20Ni-10TaC cermets results in lower surface roughness than that of other cermets[22]; The surface roughness increases with increase in current [12,23]; the US-EDM helps not only in surface finishing but also increase in MRR,[24]; and also found that the pulse on time factor is most influencing factor in production of quality surface and MRR,[25]. The influence of electrode material, flushing, electrode dimension, depth of cut and planetary motion on EDM performance (material removal rate, the electrode wear, accuracy and texture) is discussed, Lonardo and Bruzzone, [26].

The experiments with Rotary EDM are conducted on Al_2O_{3p} 6061 Al Composite and found that the (i) MRR increases significantly to certain extent and then decline in non-linear pattern with increase in pulse on time and peak current. (ii) Surface roughness increases with increase in current and pulse duration. (iii) Addition of SiC in Al metal matrix composite reduces the electrical conductivity of work material and hence Al-10 % SiCp can be effectively machined using EDM, [8] . The Review Paper of relating to the research work on EDM reveals that the SiC reinforced MMC with sinking EDM and powder mixed EDM have the potential scope to enhance the capability of machining performance so as to obtain better output product under better working conditions and concluded that the research work on dry EDM and using water in EDM as dielecric fluid are the emerging areas followed by MMCs, [13]. The multi objective optimization model on surfaceness of UNS C34000 Brass in EDM helps to identify the Roughness parameters in EDM with offline control of correlated multiple surface quality characteristics, [27] .

IV. WIRE ELECTRIC DISCHARGE MACHINING (WEDM)

A simple WEDM process is shown in the Figure -2.

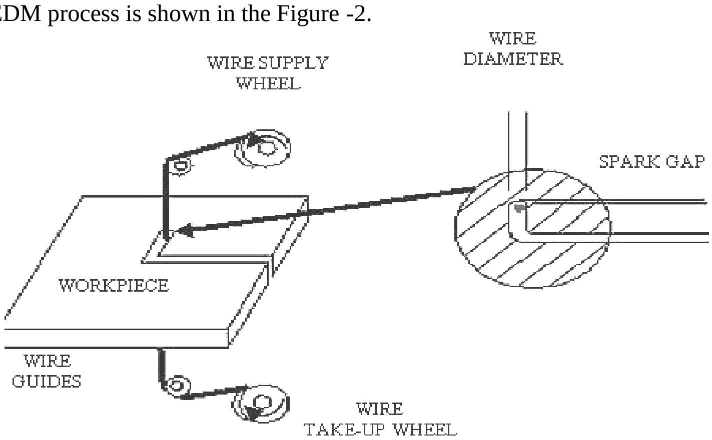

Figure -2: Simple wire EDM process with spark gap details [9]

V. MODELING AND OPTIMISATION

It is essential to produce any product with good quality at low cost with the requirement of customer. To achieve this objective, the influence of various parameters the process parameters have been studied to get the best performance of either EDM or WEDM processes by many researchers and reported briefly in the sub sections.

(i) Mathematical Models

The Mathematical models, the most useful and non-destructive modeling techniques are emerged with the growth of the computer memory. The utilization such techniques in wire EDM is briefly mentioned in the following. To start with, the development of Mathematical models to obtain the surface finish [28,29] and eroding surface [30] based on the discharge parameters. The Mathematical models are widely developed to (i) Calculate the minimum gap distance for the spark generation between the work piece and the electrode [31]; (ii) predict the responses based on constraints of optimization techniques [32]; (iii) correlate the interrelationship and find the best working conditions of various parameters (peak current, duty factor, wire tension and water pressure) during the machining of Iconel-601 to obtain the MRR, wear ratio and surfaceness, [33]; (iv) establish the relationship between the performance measures of the process and its controllable parameters [34]; (v) study and determine the crack zone beyond the crater due to the thermal stresses exceeding the limits due to longer pulse duration, high power and plasma channel radius, [35]; (vi) study the influence of peak current and pulse on time on surface roughness problem solving and optimization of process parameters [36].

(ii) Simulation:

The Simulation is developed on Computer Systems and depend on the speed of the Computer System. The inverse problem of obtaining the appropriate tool electrode shape for achieving the desired final workpiece shape is presented for die-sinking EDM by reverse Simulation and it can also be used in forward simulation,[37].The thermal stresses estimated during the Numerical Simulation of WEDM with FEM exceeded the yield strength of the HSS work piece mostly in the extremely thin zone near the spark, [38]. The design and the obtaining of an experimental database, a preliminary analysis for the selection of process variables and the establishment of wire breakage indicators can be achieved by Simulation [39].

(iii) Fuzzy Logic:

The larger the Gray – Fuzzy reasoning grade the better the multiple process response thereby the electrode wear ratio decreases and MRR increases in WEDM Process, [40]. The Fuzzy Logic model developed is compared and analysed multi response the optimization parameters [41]. The reliable pulse rate in the adoptive control system [42] and thermal analysis with spark erosion in relation to tool / work materials [43] are determined with Fuzzy Logic modeling followed by the prediction of the cutting velocity with in the selected range of machining parameters for higher material removal rate and better surface finish and found that the output results are in good correlation with that of experimental results, [44].

(iv) Artificial Neural Networks (ANN)

ANN models are being used in modeling of machining parameters either independently or combining with other algorithms. To cite: six neural network models, namely the LOGMLP, TANMLP, RBFN, the error TANMLP, the adaptive TANMLP, the adaptive RBFN, and the ANTIS and a neuro-fuzzy model for MRR in EDM and observed that the ANTIS model is more accurate than the other models, [45]. Thus, the ANN models are used to estimate (i) crater shapes and surface roughness, [46, 47] and with back propagation and Feed forward with Back propagation technique to predict MRR, [48] and then it is proved that the BPN is reasonably more accurate than RBFN where as RBFN is faster in comparison to BPN while modeling the surface roughness [49]. The effect of the pulse on time on material removal rate is estimated in combination with Genetic Algorithm hybrid model [50] and then the to study radial basis function of Neural Net works in MRR [51].

The optimum machining process parameters, such as the shape of the crater cavity, MRR and TWR (tool wear rate) are determined by the Intelligent Process Model with FEM and ANN [52]. The cutting speed and surface roughness of Tungsten carbide cobalt composite are predicted Soft computing models, [53]. The computational speed and accuracy are improved on one side and MRR is estimated on other side during the EDM of AISI D_2 Steel by Neuro – Fuzzy Model [54]. The ANN model with back propagation can predict the response parameters such as MRR, Ra and fractal dimensions very accurately while machining HSS of M_2 grade working with electrolyte copper tool, [55]. The surface roughness of AISI 4340 steel is predicted in combination with factorial design. Then the relationship between the ANN models and Mathematical regression analysis are estimated and then compared with the experimental values for their trueness, [56].

(v) Response Surfaceness Methodology (RSM)

The Response Surfaceness Methodology (RSM) is being a technique being used based the output parameters so as to check the quality of the surface obtained in wire EDM and other output parameters. It is established by RS that the (i) Peak current (C) and concentration (D) influence the maximum MRR and smooth SR in a Powder Mixed Electrical Discharge Machining (PMEDM) [57]; whereas the Weighted Principal Component (WPC) method can offer significantly better overall quality than the multi-response signal to noise ratio (MRSN) method [58]; that the peak-on time and peak current significantly affect the MRR and OC during micro-hole machining of Ti-6Al-4V with tungsten carbide electrode and the RSM based experimental data is used to develop the regression based mathematical models [59].

(vi) Taguchi Technique:

The literature reveals that the Taguchi technique is the most effective modeling tool to study the performance characteristics of either EDM or WEDM process and determine the effect of input variables and their levels. Some of the contributions by Taguchi Technique in Wire EDM are brought-out in the following to decide the (i) Ra and MRR by Parametric Optimization [60]; the number of experiments and Optimization of machining parameters in relation to work piece by orthogonal array method [61]; multi-response optimization by weighted principle component method [62]; Surface Removal Rate, cutting radius of workpiece on machining of Al_2O_3 particle Alloy (6061); [63] (Chiang and Chang, 2006); precision and accuracy are by Taguchi Dynamic Experiments with Fuzzy Logic Analysis by 81.5 %, [64]; accuracy and surface roughness by the measured responses of MRR on Incoloy 800 super alloy [65]; the quality design in kerfwidth for machining of Nickel based super alloy Nimonic C263, [66]. The study carried-out with Taguchi for the minimum number of experiments on machining of Aluminum-24345 problem can be solved when compared to full factorial design and proved by experimental results to demonstrate that the machining model is suitable, [67]

(vii) ANOVA

It is common practice to use **An**alysis **o**f **Va**riance (ANOVA) to estimate the performance of any system based on the input parameters and it also used in wire EDM. The influence of wire-EDM machining parameters, (i.e., pulse-on time, pulse-off time, pulse peak current and wire tension) is investigated and established that the surface roughness is affected by multifold regression analysis for MRR, [68]. Further, the EDMed DC53 die steel is very much influenced by Pulse-on time and Pulse-peak current [69]. The optimal solutions to find the MRR and SR are developed and established that the Gaussian Process Regression (GPR) models have the advantage over the regression models [70]. Further, the optimal process parameters, namely peak current affects EWR, SR, [12] where as the pulse-on, pulse-off wire speed and wire tension for simultaneous optimization of cutting speed and dimensional lag are determined by Grey Relational Analysis, [71] followed by the variation of output responses with process parameters are mathematically modeled using Non-linear regression analysis method and then checked for correlation with the experimental results, [72].

EXPERIMENTAL INVESTIGATIONS:

The experimental investigations on Wire EDM are normally conducted by dividing the input variable into two types, namely electrical and non-electrical variables. The normally considered electrical input variables are Peak Voltage

(V), Peak Current (C), Pulse duration (T), Polarity (P), Pulse Interval (t), Pulse Wave (W), etc. The non-electrical parameters are Dielectric Fluid, Electrode Material and Work piece material. After machining, the normal out-put parameters such as Material Removal Rate (MRR), Surface Roughness (Ra), Tool Wear Rate (TWR), Current Rate (CR), Overcut (OC) and Kerf Width (KW) either independently or of combinations of any of them are normally being obtained during the experimentation on WireEDM Process. In the process, wire EDM sparking frequency monitor has been developed to detect the thermal load for on-line control to prevent the wire from rupture by means of a multi-objective model. Then the relationship between the machining rate and surface finish under optimal machine conditions has been proved by experimental investigations,[73]. The experimental investigations are discussed in the following.

5.1 Surface Roughness and MRR

The surface roughness (Ra) and uniformity of the internal surfaces of the holes have been studied in a two stage Micro-EDM machining process consisting of fabrication of electrodes in first stage and by machining of holes in second stage, [74]. It is found in experimentation that the maximum cutting speed while machining with WEDM on the metal matrix composites of AlSi7Mg / SiC and AlSi7Mg / Al_2O_3 is approximately 3 times and 6.5 times lower than the cutting speed of Aluminum alloy, respectively, [75] whereas better straightness, surface roughness, gap length, accuracy in corner cut and electrolytic corrosion-free obtained with the dry-WEDM over the conventional WEDM, [76]. It is also the wet dry wire EDM results in better surface integrity over dry wire EDM during machining on SUS304 Austenitic Stainless steel, [77]. The effects of electrolytic corrosion decreases as the AC the power source increases based on the electrical double layer theory and is proved by experimentation, [78]. The changing the pulse-on time, the cutting speed (material removal rate), the surface roughness and the width of the slit of cutting significantly influence the volume fraction of reinforcement (Al_2O_3 particles) in WEDM on Aluminum matrix composites (Al_2O_3 p/ 6061 Al). It is also found that the frequent breakages of electrodes in machining metals with combination of SiC combinations and thus the usage of thin wires influence the surface wear at various settings of machining parameters WEDM, [79] followed by the effect of cutting parameters on the size of erosion, [80]. Therefore, new assisting electrode material is invented to avoid the breakages and established the WEDM method is also better suited for work pieces of Si_3N_4 insulating ceramics [81]. Average surface finish in relation to wire wear [82], surface smoothness and cracks [83] are reported in the experimental studies.

5.2 Machining of Steels:

Experiments with wire EDM on reciprocating dry sliding pin on plate revealed that the Zro2-WC composite exhibits better tribological characteristics over Zro2-TiCN and Zro2-TiN, [84]. Further, the experimental results revealed that very low wire tension in machining of composites whereas a high flushing rate and a high wire speed were required to prevent wire breakage, [85].

A new concept of specific discharge energy (SDE) is presented. It is observed that the materials having close values of SDE demonstrate very similar machining characteristics, if they are machined under the same machining conditions, [86]. Therefore, the process performance is improved by silver coating on work piece material [87] and it is proved that the Zinc coated Brass Wire gives better performance than brass wire in terms of lower frequency of the breakage of wire, [88]. The hardness of material matrix will not affect whereas the recast layer on the Wire EDM surface has to be mechanically removed to improve the pipe-coupling efficiency and prevent the formation of the deformation cracks during expansion process, [89]. Tests have been conducted on various materials to study the effect of spark cycle and pulse on time of Wire EDM microfeatures so as to understand the root cause for the material fracture mechanism, [90]. An experimental study is carried out on WEDM to identify various significant control factors and their interactions that affect the machining performance such as metal removal rate (MRR) and surface finish (SF) based on Taguchi Method. The relationship between control factors and responses like MRR & SF are established by means of non-linear regration analysis resulting in a valid mathematical model. Genetic algorithm is used to optimize the wire electric discharge machining process with multi objectives. The study demonstrated the wire EDM process parameters can be adjusted to achieve better MRR & SF simultaneously, [91]. A fine quality surface finish has been obtained on tool steel SKD11 by shortening the discharge duration and lowering the peak current in the experimentation of WEDM using RC Pulse Generator, [92] . Reversed polarity machining with the appropriate pulse energy can improve the machined surface roughness, [93].

Further, the analysis has been formulated using multiple regression method to study the effect of pulse-on time and pulse-peak current, on the surface roughness. A model developed by [94] was validated by experimentation within 7% levels of error. An experimental determination method of the convective heat transfer coefficient in wire electro-discharge machining (WEDM) is introduced. A special device is developed to measure the average temperature increment of the wire after a period of short circuit discharges, and the thermal load imposed on the wire is also tracked and recorded. Then based on the thermal model of the wire, the convective coefficient is calculated accurately. The influence of the kerf and the effect of the coolant flushing pressure on the convective coefficient are studied [95]. In finish machining of wire -EDM, in order to study the surface morphology under various pulse duration, thermo-analysis is carried out to investigate the mechanism of erosion of the work piece material using the finite element method. The results are verified with the experimentation and observed that surfaces machined by short pulse duration and long pulse duration have similar roughness values when the pulse energies are almost the same. Also concluded that, during finish machining that has high requirements in surface roughness, long-duration pulses cannot meet the machining requirements and only short-duration pulses can be used to carry out the machining, [96]. It was observed that, the factor servo-voltage has the largest effect on all the response variables irrespective of the materials used in the experiments conducted on three materials (viz., Hot Die Steel, Oil Hardened Non-sinking Steel, and Mild Steel) to optimize the process parameters, [65] and also while machining AI / SiCp metal matrix composites using wire EDM [97]. Further, it is established that the surface finish of composite material is found to be better with increased % of SiC reinforcement.

Experiments have been conducted to study the relationship between the MRR and Electrode Wear Ration (EWR) and surfaceness on an Alumina based ceramic composite, Al_2O_3 / TiC / Si Cw and established that the (i) MRR increases with discharge current, pulse on time and duty cycle time, (ii) EWR increases with discharge current, duty cycle and gap Voltage and (iii) Surfaceness increases with an increase in discharge current and pulse on time, [98]. Experiments are conducted to drill high speed aspect ratio holes on microwave processed magnesium nano composites and established that the MRR and taper mainly depend on the servo speed and pulse on time, [99].

5.3 Machining of Alloys:

Electrode preparation techniques and the machining of micro holes are described in detail and showed that for brass electrodes, an arithmetic average roughness value as low as 1.7 μm is achieved. The technique of preparation in the usage of brass micro electrodes is found result in good quality surface and hence employed directly to machine the micro holes on the same machine using micro-EDM (μ-EDM) attachment, [100]. Further, the effect of discharge conditions on erosion efficiency have been studied in drilling with μ-WEDM using RC relaxation circuit in the melting and evaporation concept of material removal phenomenon,[101]. The tension of the micro wire electrode during the WEDM process is optimized in accordance with the discharge energy based on the coupled thermo-mechanical analysis, (both the three-dimensional temperature and the stress distribution), [102]. The usage of Copper based Graphite Electrodes is established that the (i) formation of microcracks at lower current range of 4 A and Pulse duration of 3.2 μs and (ii) produces crater with poor surface finish, with increases in high discharge current rate and longer pulse duration while machining AISI H13 Steels [103]. To overcome such issues, a mathematical model of wire lateral vibration in machining is suggested to calculate the maximum amplitude of wire vibration [104]. The surface roughness increases with increase in current due to more metal removal in single discharge for a set of process parameters, [105]. With such background, the performance characteristics, such as material removal rate (MRR), tool wear rate (TWR) and over cut (OC) are studied and analysed the usage of different dielectrics (kerosene and de-ionized water) in micro hole machining of Ti-6Al-4V, [106]. The de-ionized water is used in machining of two different materials in the experimental work to find the MRR and Ra, [107]. In doing so, the machined kerf width varies with different machining parameters, which greatly influences the machining precision. The higher the value of thermal conductivity and specific heat capacity of machined material decrease the efficiency have been established by the experiments on WEDM on materials – Titanium Alloys (Ti6A1-4V) and cemented Carbides (B40), [108]. Based on the above observations, two thermal models namely, (i) the random pulse model for machining thin work pieces, and (ii) the clusters model for thicker work pieces are proposed. Further, a transient thermal analysis for the determination of temperature distribution in the wire of a WEDM process under multiple discharge condition is reported by using an explicit finite-difference method. The studies have revealed that the (a) thermal loads of wire EDM with short elapsed time is essential while machining thin work pieces and (b) where as the long elapsed time under multiple spark conditions will increase wire velocity and thus reduces the maximum temperature, [109]. Further, a better surface is obtained by micro electric discharge machining using powder mixed dielectric (PMD) media on SKH-51 tool steels while compared to Tungsten Carbide (WC) [110]. Recently, coatings have been introduced to increase the strength of the copper and composite wires and established that the wires with α-phase, β-phase and γ-phase coatings have significantly increased the wire EDM productivity [111].

VI. CONCLUSIONS

The EDM is an unconventional material removal process and flexible enough to meet the diverse machining requirements posed by the demand in the global metal cutting industries. With emergence of computers, the EDM process has been widely brought under varoius methods. Among them, the wire EDM has become more popular. It has been commonly applied for the machining and micromachining of parts with intricate shapes and varying hardness requiring high profile accuracy and tight dimensional tolerances. However, the main advantage of the process is the relatively low machining speed as compared to other conventional machining process due to its thermal machining technique. The ultimate goal of Wire EDM process is to achieve an accurate and efficient machining operation combined with quality with at most best machining performance by the various factors affecting the process and identifying the optimal machining condition from number of combinations. More than one hundred papers have been reviewed and the salient contributions are brought in the paper. Such contributions will help the researchers but also the manufacturers to cope with the growing production / manufacturing techniques in global manufacturing arena.

REFERENCES

[1]. Webzell, S., The first steps in to EDM in Machinery, 159, (4040) Findlay Publ. Ltd, Kent, p.41, November, 2001.

[2]. Anonymous, History and Development in the techniques and practice of spark Erosion machining, Spar Catron Limited, Gloucester, UK, pp.6, 1965.

[3]. Livshits, A. L., Introduction in Electro-erosion Machining of Metals, Development of Scientific & Industrial Research, London, 1960.

[4]. Jameson, E.C., Description and Development of EDM, Electrical Society of Manufacturing Engineers, Dearbern, Michigan, pp16, 2001

[5]. Houman, L., Total EDM in Jameson (Ed), Electrical Discharge Machining: Tooling, Methods and Applications, SME, Dearborn, Michigan, PP-5-19. 1983.

[6]. Ho, K.H., et al., State of art on EDM, International Jl. of Machine Tools & Manufacture 43, pp.1287-1300, 2003.

[7]. Bhaskar Reddy,C., V.D. Reddy, G. J. Reddy and C. E. Reddy, Unconventional Mchining – Role of Electric Discharge Machining – A Review, Proc. of 4th National Conf. on Emerging Trends in Mechanical Engg., (ETME

– 2011), G.H. Patel College of Engineering & Technology, Vallabha Vidya Nagar, Gujarat, India, March, 18-19, 2011.

[8]. Balbir Singh, Sudhir Kumar and Jatindar Kumar, A Review of Eelctro Discharge Machining of Aluminum Metal Matrix Composites, Proc. of 3rd International Conf. on Advances in Mechanical EngH., S.V. NIT, Surat, India, pp. 993-997, Jan. 4-6, 2010.

[9]. [9] Ho, K.H. et al., State of art in WEDM, International Journal of Machine Tools & Manufacture 44, pp.1247-1259, 2004.

[10]. Altpeter, F. and Perez, R., Relevant topics in wire EDM control, Journal of material processing technology, Vol.149, pp.147-151, 2004.

[11]. Bhaskar Reddy, C. et al., Evolution and Growth of WEDM and Applications – A Review, 2nd AP Science Congress, S.V. University, Tirupati, Nov.14-16, 2009.

[12]. Ms. Shruti Mehta et al, A Review on Current Research Trends in Die- Sinking Electrical Discharge Machining of Conductive Ceramics, International Journal of Recent Trends in Engineering, Vol. 1, No. 5, May 2009,

[13]. Kuldeep Ojha and Singh, K.K., Review and Future Trends of Sinking EDM and Silicon Carbide reinforced Metal Matrix Composites, Proc. of 3rd International Conf. on Advances in Mechanical Engineering, S.V. National Institute of Technology, Surat, India, pp. 821-826, Jan. 4-6, 2010.

[14]. Kunieda, M. etal. Advancing EDM through fundamental insight into the process, Annals of CIRP, 54, pp599-622, 2005

[15]. Simao, J. et al., Work piece surface modification using electrical discharge machining, Int. J. of Machine Tools & Manufacture 43 (2), pp. 121-128, 2003.

[16]. Hung Sung Liu et al., A study on the characterization of high nickel alloy micro-holes using micro EDM and their applications, Journal of Materials Process Tech.,169, pp. 418-426, 2005.

[17]. Hyun-Seok TAK, et al., Comparative study on discharge conditions in micro-hole electrical discharge machining of Tungsten Carbide (WC-Co) material, Trans. Nonferrous Met. Soc. China 19, s114−s118, 2009.

[18]. Ahsan Ali Khan and Safry Ezan Saifuddin, Wear characteristics of copper and Aluminum electrodes during EDM of stainless steel and carbide,ICME2005, Dhaka, Bangladesh, 28-30,Dce,2005.

[19]. Mohd Amri Lajis ,et al The Implementation of Taguchi Method on EDM Process of Tungsten Carbide, European Journal of Scientific Research ISSN 1450-216X Vol.26 No.4, pp.609-617, 2009.

[20]. Mohammad Reza Shabgard, Atanas Ivanov, Andrew Rees**,** Influence of EDM machining on surface integrity of WC-Co, Manufacturing Engineering Centre, Cardiff University, 2006.

[21]. Sadao Sano, et al., Hybrid Processing of EDM and grinding with an ED-T-formed PCD tool, ISAAT2007, Dearborn, Michigan, USA (2007).

[22]. Manoj Kumar, B.V. et al., EDM performance of TiCN - based cermets, International Jl of Refractory Metals & Hard Materials 25, pp-293-299, 2007.

[23]. Krishna Mohan Rao, G. et al., Influence of machining parameters on EDM of Mar aging Steels-An Experimental investigation, Proceedings of The World Congress on Engineering 2008, Vol II, London, U.K.July2-4, 2008.

[24]. Shabgard, M.R. et.al, The effect of Ultrasonic Vibration of Work Piece in EDM of AISIH13 Tool Steel, World Academy of Science, Engg. & Tech. 52, 2009.

[25]. Tomadi, S. H. et al., Analysis of influence of EDM Parameters on Surface Quality, MRR and Electrode Wear of Tungsten Carbide, Proc. of International Conf. of Engineers & Computer Scientists 2009, V2, Hong Kong, 2009

[26]. Lonardo. P.M and Bruzzone. A.A, Effect of Flushing and Electrode Material on Die Sinking EDM, Annals of the CIRP Vol. 48/1/1999.

[27]. Datta, S., Chandra Routana, B., Bandopadhyaya and Mahapathra, S.S., Proc. of 3rd International Conf. on Advances in Mechanical Engineering, S.V. National Institute of Technology, Surat, India, pp. 738-742, Jan. 4-6, 2010.

[28]. DiBitonto, D.D. et al., Theoretical models of EDM process.1. A simple cathode erosion model, Journal of Applied Physics, 66, pp. 4095-4103, 1989.

[29]. Perez, R., et al. Theoretical modeling of energy balance in electro erosion, Journal of Material Processing Technology, 149, pp.198-203, 2004.

[30]. Josko Valentincic. et al., A model for detection of the eroding surface based on discharge parameters, International Jl. of Machine Tools & Manuf. 44, pp-175-181, 2004.

[31]. Yougshun Zhao et al, Geometric modeling of the linear motor driven EDM die sinking process, International Jl of Machine Tools Manuf. 44, pp1-9, 2004.

[32]. Sarkar, S. et al., Parametric analysis and optimization of wire electrical discharge machining of γ-titanium aluminide alloy, Journal of Materials Processing Technology, 159, pp.286-294, 2005.

[33]. Hewidey, M.S., El-Taweel, T.A. and El-Safty, M.F., Modelling the Machining Parameters of Wire Electrical Discharge Machining of Inconel 601 using RSM, Journal of Materials Processing Tech, V. 169, pp. 328 – 336, 2005.

[34]. Taha Ali EI-Taweel., Parametric study and optimization of AL-Cu-TiC-Si P / M composite, International Journal of Machining and Mach inability of materials, 1(4), pp380-395, 2006.

[35]. Deepak Kumar, P. and Rajat Kumar, B., Study of Surface Damage due to the Thermal Stresses in Electro Discharge Machining, Competitive Manufacturing, Proc. of 2nd International & 23rd AIMTDR Conf., IITMadras, Chennai, India, pp. 741 - 746, 2008**.**

[36]. Shabgard, M.R. et al., Mathematical Modeling of Machining Parameters in Electrical Discharge machining of FW4 Welded Steel, World Academy of science, Engineering and Technology 52, 2009.

[37]. Masanori Kunieda, Wataru Kowaguchi and Takashi Takita, Reverse Simulation of Die-sinking EDM, Annals of CIRP, Vol. 48 / 1/ 1999.
[38]. Vinod Yadav, Vijay K. Jain and Prakash M. Dixit, Thermal Stresses due to Electrical Discharge Machining, Inter- national Journal of Machine Tools & Manufacture, 42, pp 877-888, 2002.
[39]. Cabanes, J., Portillo. E., Marcos, M, and Sanche, J.A., An Industrial Application for online Detection of Instability and Wire Breakage in Wire EDM, Journal of Material Processing Technology, 195, pp. 101-109, 2008.
[40]. Lin, J.L. and Lin, C.L., The use of Grey-Fuzzy Logic for the Optimisation of the Manufacturing Process, Journal of Materials Process Technology, Vol. 160, pp.9-14, 2005.
[41]. Kuriakose, S. and Shunmugam, M.S., Multi objective optimization of wire EDM process by non- dominating sorting genetic algorithm, J. of Materials Processing Technology,170, pp.133-141, 2005.
[42]. Oguzhan Yilmiz et al, Auser friendly fuzzy based system for the selection of EDM process parameters, Jl material Process. Tech.172, pp. 363-371, 2006.
[43]. Yeo, S.H., et al. Critical assessment and numerical comparison of electro-thermal models in EDM, Jl. Mater. Process. Technol., 2007.
[44]. Vijaya Bhaskara Reddy, P., Hemachandra Reddy, K and Vikram Kumar, CH. R., Selection of Cutting Velocity in Wire-EDM Process using Fuzzy Logic, Proc. of the 2nd International & 23rd AIMTDR Conference, 2008.
[45]. Kuo-Ming Tsai and Pei-Jen Wang, Comparisons of Neural Network Models on Material Removal Rate in Electrical Discharging Machining, Journal of Materials Processing Technology, 117, pp 111-124, 2001.
[46]. Kuo-Ming Tsai and Pei-jen Wang, Predictions on surface finish in electrical discharge machining based upon neural network models, International Journal of machine tools and manufacture, 41, pp 1385-1403, 2001.
[47]. Joshi, S.N. and Pande,S. S., Integrated process modeling of EDM using FEM and ANN, Proceedings of inter national Conference on Computer Aided Engineering, IIT Madras, Chennai, pp.552-559, December, 2007.
[48]. Panda, D.K. and Bhogi, R.K., ANN prediction of material removal rate in EDM, Materials and Manufacturing process, 20, pp.645-672, 2005.
[49]. Pradhan, M.K., Das, R. and Biswas, C.K., Comparisons of neural network models on surface roughness in electrical discharge machining, Journal of Engineering Manufacture Vol. 223 PP 801-808, 2009.
[50]. Kesheng Wang et al., A hybrid intelligent method for modeling the EDM process, International Jl of Machine Tool Manuf. 43,995-999, 2003.
[51]. Mandal, D. et al., Modeling of EDM using BPNN and multi- objective optimization using non dominating sorting Algorithm-II, Journal of Material Processing Technology,186(1-3),154-162, 2007.
[52]. Joshi, S.N. and Pande, S.S., 2008, Intelligent Process Modeling and Optimisation of EDM, Competitive Manufacturing, Proc. of 2nd International & 23rd AIMTDR Conf., IITMadras, Chennai, India, pp. 475 - 480, 2008**.**
[53]. Probir Saha, et al., Soft computing models based prediction of cutting speed and surface roughness in wire EDM of Tungsten carbide cobalt composite, International Jl. of Advanced Manuf. technology, 39(1-2),pp.74-84, 2008.
[54]. Mohan Kumar Pradhan and Biswas, C.K**.,** Competitive Manufacturing, Proc. of 2nd International & 23rd AIMTDR Conf., IITMadras, Chennai, India, pp. 469 - 474, 2008.
[55]. Amit Kumar Pal, Simul, B. and Laha Dipak, Competitive Manufacturing, Proc. of 2nd Internatiobnal & 23rd AIMTDR Conf., IITMadras, Chennai, India, pp. 481- 487, 2008.
[56]. Esme.U, Sagbas. A, and Kahraman. F, Prediction of Surface Roughness in Wire Electrical Discharge Machining using Design of Experiments and Neural Networks, Iranian Journal of Science and Technology, Transaction-B, Engineering, Vol. 33, No. B3, pp 231-240, 2009.
[57]. Kansal, H. K., Singh, S. and Kumar, P., Parametric Optimisation of Powder Mixed Electrical Discharge Machining by Response Surface Methodology, Journal of Materials Processing Technology, Vol. 169, pp. 427 – 436, 2005.
[58]. Gauri, S. K. and Chakraborty, S., Multi-Response Optimization for WEDM Process Applying Weighted Principal Component, Proc. of the 2nd International & 23rd AIMTDR Conference, 2008.
[59]. Pradann. B.B, Kibia. G and Bhattacharyya. B., Modeling of Micro-EDM Process Parameters through Response Surface Methodology, Proc. of the 2nd International & 23rd AIMTDR Conference, 2008.
[60]. Swarup S. Mahapatra and Amar Patnaik., Parametric Optimization of Wire electric discharge machining (WEDM) process using Taguchi Method, Journal of Brazil Society of Mech. Sci. & Engg, 28(4), pp.422-429, 2006.
[61]. Ramakrishnan, R., Karunamoorthy, L., Multi response optimization of WEDM operations using robust design, International Journal of Advanced Manufacturing Technology, 29, pp.105-112, 2006.
[62]. Liao, H.C., Mult–response optimization using weighted Principal component, International Journal of Advanced Manufacturing Technology,27, pp.720 -725, 2006.
[63]. Chiang, Ko-Ta, and Chang, Fu, Optimisation of the WEDM process of particle re-inforced Material with multiple Performance Characteristics using Grey Relational Analysis, Journal of Materials Processing Technology, V. 180, pp. 96 – 101, 2006.
[64]. [64] Tzeng, Yith and Chen, Fu, Multi Objective Optimisation of High Speed Electrical Discharge Machining Process using a Taguchi Fuzzy based Approach, Materials and Design, Vol, 28, pp. 1159 – 1168, 2007.
[65]. Ravindra, H.V., et al. Optimization of parameters of WEDM using Taguchi's Technique to achieve Good surface finish and better accuracy, Proc. of 2nd International&23rd AIMTDR Conf. IIT, Madras, Chennai, India, 2008.
[66]. Niladri Mandal, Saha, P., Ramesh Kumar, K., and Dr. Yadav., Study on Machining Parameters Optimization for WEDM of Nimonic C263 – A Taguchi Approach, Proc. Of the 3rd International Conference on Advances in Mechanical Engineering, S V NIT, Surat, January 4-6, 2010.

[67]. Srinivasa Rao, P., Ramji, K and Satyanarayana, B., Effect of WEDM Conditions on Surface Roughness : A parametric Optimisation using Taguchi Method, International Jl. of Advanced Engineering Sciences & Technologies, Vol. 6, No.1, pp. 041 – 048, 2011.

[68]. Petropoulos, G., et al. Modeling of surface finish in electro - discharge machining based upon statistical multi-parameter analysis, Journal of Material Processing Technology, 155-156, pp.1247-1251, 2004.

[69]. Kalyanasri, K., and Boonmung,S., An Investigation on effects of wire EDM Machining parameters on Sutface Roughness of newly developed DC53 Die Steel, Jl .of Material Processing Technology, pp. 187-188, pp. 26-29, 2007

[70]. Yuan, J., Wang. K., Tao, Y. and Fang. M., Reliable Multi-objective Optimisation of High-speed WEDM Process based on Gaussian Process Regression, International Journal of Machine Tools and Manufacture, Vol. 48, pp. 47-60, 2008.

[71]. Kamal Jangra, Sandeep Groover, Ajai Jain and Aman Aggarwal, Optimization of Multiple Machining Characteristics in Die Cutting with WEDM using Grey Relational Analysis, Proc. Of the 3rd International Conference on Advances in Mechanical Engineering, S V NIT, Surat, January 4-6, 2010.

[72]. Muthu Kumar. V, Suresh Babu. A, Venkata Swamy. R and Raajenthiren. M, Optimization of the WEDM Parameters on Machining Incoloy800 Super Alloy with Multiple Quality Characteristics, International Journal of Engineering Science and Technology, Vol. 2(6), pp 1538-1547, 2010.

[73]. Rajurkar, K.P., and Wang, W.M,, Thermal Modeling and On-Line Monitoring of Wire-EDM, Journal of Materials Processing Technology, 38, pp 417-430, 1993.

[74]. Allen. D.M, Almond. H.J.A, Bhogal. J.S, Green. A.E, Logan. P.M and Huang. X.X, Typical Metrology of Micro-Hole Arrays Made in Stainless Steel Foils by Two-Stage Micro-EDM, Annals of the CIRP Vol.48/1/1999.

[75]. Rozenek. M, Kozak. J, Dabrowski. L and Lubkowski. K, Electrical Discharge Machining Characteristics of Metal Matrix Composites, Journal of Materials Processing Technology, 109, pp 367-370, 2001.

[76]. Masanori Kunieda and Chika Furudate, High Precision Finish Cutting by Dry WEDM, Annals of CIRP, V 50/1/ 2001.

[77]. Abdulkareem, S., Khan, A.A. and Zain, Z.M., Effect of Machining parameters on Surface Roughness during Wet and Dry wire EDM of Stainless Steel, Journal of applied Sciences, 11 (10), pp. 1867 – 1871, 2011.

[78]. Do Kwan Chung, H.S. Shin, Bo.H. Kim and Ch.N. Chu, High Frequency Micro Wire EDM for Electrolytic Corrosion Prevention, International Jl. of Precision Engineering and Manufacturing, Vol. 12, No.6, pp. 1125 – 1128, 2011.

[79]. Tosun, N. et al., The effect cutting parameters on wire crater sizes in wire EDM, International Jl of Advanced manuf. technology, Vol.21, pp.857-865, 2003.

[80]. Tosun, N. and Cogun,C., An investigation on wire wear in WEDM, Journal of materials processing technology, Vol.134, pp. 273-278, 2003.

[81]. Takayuki Tani, Yasushi Fukuzawa, Naotake Mohri, Nagao Saito and Masaaki Okada, Machining Phenomena in WEDM of Insulating Ceramics, , Journal of Materials Processing Technology, 149, pp 124-128, 2004.

[82]. Takino, et.al., Cutting of Polished single crystal silicon by wire electrical discharge machining, Precision Engineering,Vol.28, pp.314-319, 2004.

[83]. Kruth, J.P. et al., Composites wires with high tensile core for wire EDM, Annals of CIRP, V.53/1, PP-171-174, 2004.

[84]. Liao, Y.S., Study of Specific energy in WEDM and its application, International Journal of Machine Tools and Manufacture, 44, pp.1373-380, 2004.

[85]. Biing Hwa Yan, Hsien Chung Tsai, Fuang Yuan Huang and Long Chorng Lee, Examination of Wire Electrical Discharge Machining of Al_2O_3 p/ 6061 Al Composites, International journal of Machine Tools & Manufacture, 45, pp 251-259, 2005.

[86]. Liao, Y.S and Yu, Y.P., The Energy Aspect of Material Property in WEDM and its Application, Journal of Materials Processing Technology, 149, pp 77-82, 2004.

[87]. Jerzy Kozak, Kamlakar P. Rajurkar and Niraj Chandarana, Machining of Low Electrical Conductive Materials by Wire Electrical Discharge Machining, Journal of Materials Processing Technology, 149, pp 266-271, 2004.

[88]. Kumar, R. and Choudary, S.K., Prevention of wire breakage in Wire EDM, Inter-national Jl. of Machining and Machinability of Materials, V. 9, no. ½, pp. 86-102, 2011

[89]. Lin, H.C., Lin, K. M., Chen, Y.S. and Chu, C.L., The Wire Electro-discharge Machining Characteristics of Fe – 30Mn-6Si and Fe-30Mn-6Si-5Cr Shape Memory Alloys, Jl of Material Processing Technology, Vol. 161, 435-439, 2005.

[90]. Miller, S.F., Chen-C, K and Albert, J. S. and Jun Qu, Investigation of Wire Electrical Discharge Machining of Thin Cross Sections and Compliant Mechanisms,International Jl. of Machine tools&Manufacture,V45,pp1717–1725, 2005

[91]. Mahapatra, S.S and Amar Patnaik, Optimization of Wire Electrical Discharge Machining (WEDM) Process Parameters using Genetic Algorithm, Indian journal of Engineering and Materials Science, 13, pp 494-502, 2006.

[92]. Yan, Mu and Lai, Yi., Surface Quality Improvement of Wire EDM using a fine finish Powder Supply, International Jl. of Machine Tools and Manufacture, Vol. 47, pp.1686 – 1694, 2007.

[93]. Fuzhu Han, Jun Jaing and Dingwen Yu, Influence of Machining Parameters on Surface Roughness in Finish Cut of WEDM, International journal of advanced manufacturing technology, 34, pp 538-546, 2007.

[94]. Kalyanasiri, K. and Boonmung, S., Effects of wire-EDM machining variables on surface roughness of newly developed DC 53 Die Steel: Design of experiments and regression model, Jl. of Materials Processing Technology, 192-193, pp 459-464, 2007.

[95]. Gang Cheng, Fuzhu Han, and Zhijing Feng, Experimental Determination of Convective Heat Transfer Coefficient in WEDM, International journal of Machine Tools & Manufacture, 47, pp 1744-1751, 2007.

[96]. Fhuzu Han, Jun Jiang and Dingwen Yu, Influence of Discharge Current on Machined Surfaces by Thermo-analysis in finish cut of WEDM, International journal of Machine Tools & Manufacture, 47, pp 1187-1196, 2007.

[97]. Patil, N.G. and Brahmankar, P.K., Some Investigations onto Surface Characteristics of Wire Electro Discharge Machined Metal Matrix Composites, Proc. of the 2nd International & 23rd AIMTDR conference, 2008.

[98]. Patel, K., Pande, P.M. and Rao, P.V., Experimental Investigations to study EDM Machinability of TiC particle and SiC Whisker Reinforced Al_2O_3, Ceramic Composite, Competitive Manufacturing, Proc. of 2nd Internatiobnal & 23rd AIMTDR Conf., IITMadras, Chennai, India, pp. 719- 724, 2008.

[99]. Ponappa, K., Aravindan, S., Rao, P.V. & Gupta, M., Competitive Manufacturing, Proc. of 2nd International & 23rd AIMTDR Conf. IITMadras, Chennai, India,pp.665-670, 2008

[100]. Somashekhar. K.P and Jose Mathew, Fabrication of Microelectrodes for Micro EDM Operation Using Micro WEDG, Proc. of the 2nd International & 23rd AIMTDR conference, 2008.

[101]. Somashekhar. K.P, Subba Rao Nuvvula and Jose Mathew, Effect of Discharge Conditions on the Performance of Micro Electrical Discharge Machining, Proc. of the 2nd International & 23rd AIMTDR Conference, 2008.

[102]. Fuzhu Han, Gang Cheng, Zhijing Feng and Soichiro Isago, Thermo-mechanical Analysis and Optimal Tension Control of Micro Wire Electrode, International journal of Machine Tools & Manufacture, 48, pp 922-931, 2008.

[103]. Radhakrishnan, P. and Gowri, S., Study on Surface Integrity of AISI H-13 (improved) in Electrical Discharging Machining, Competitive Manufacturing, Proc. of 2nd International & 23rd AIMTDR Conf., IITMadras, Chennai, India, pp. 753 - 758, 2008**.**

[104]. Di Shichun, Chu Xuyang, Wei Dongbo, Wang Zhenlong, Chi Guanxin and Liu Yuan, Analysis of Kerf width in Micro-WEDM, International journal of Machine Tools & Manufacture, 49, pp 788-792, 2009.

[105]. Gulamali R. Khunt, et al., An Experimental Study on WEDM of Aluminum Wrought Alloy AA 6351 With a Novel Dielectric Fluid, National Conference On Lean Manufacturing Implementations: LEMAN 2009.

[106]. Kibia. G, Pradann. B.B, Sarkar. B.R and Bhattacharyya. B., Influence of Different Dielectrics on Micro-EDM characteristics during Machining of Ti-6Al-4V, Proc. of the 2nd International & 23rd AIMTDR Conference, 2008.

[107]. Bhaskar Reddy, C., Diwakar Reddy, V. and Eswara Reddy, C., Experimental investigations on MRR and Surface Roughness of EN19 and SS420 Steels in Wirw-EDM using Taguchi Method, International Journal of Engineering Science and Technology, Nov. 2012 (Under Review).

[108]. Poros, D. and Zaborski, S., Semi-emperical Model of Efficiency of Wire Electrical Discharge Machining of Hard-to-machine Materials, Journal of Materials Research Technology, Vol. 209, pp. 1247 – 1253, 2009.

[109]. Simul Banerjee and Prasad, B.V.S.S.S., Numerical evaluation of transient thermal loads on a WEDM wire electrode under spatially random multiple discharge conditions with and without clustering of sparks, International Journal of Advanced Manufacturing Technology, 48, pp 571-580, 2010.

[110]. Jahan, M.P., Anwar, M.M., Wong, Y.S. and Rahman, M., Nano finishing of Hard Materials using Micro Electro Discharge Machining, Proc. of International Mechanical Engg., Part – B: Journal of Engineering Manufacture, Vol. 223, pp. 1127 -1140, 2010.

[111]. Jatinder Kapoor, Dr. Sehijpal Singh and Dr. Jaimal Singh Khamba, Recent developments in Wire Electrodes for High Performance WEDM, WCE 2010, June 30 – July2, 2010, London, U.K.