International Journal of Advanced Technology in Engineering and Science
Vol. No.3, Issue 08, August 2015
www.ijates.com
ijates
ISSN 2348 - 7550

OPTIMIZATION & APPLICATION OF WEDM IN INDUSTRIES-A REVIEW

Amit Chauhan[1], Onkar Singh Bhatia[2]

[1,2]Mech. Engg.Deptt., HPTU Hamirpur, (India)

ABSTRACT

In modern engineering applications we are looking for technologies which are less time consuming, cost–effective and ease in handling, Wire-cut electrical discharge machining (WEDM) is one of the most emerging non conventional manufacturing processes for hard to machine materials and intricate shapes which are not possible with conventional machining methods. This paper reviews the effects of various WEDM process parameters such as pulse on time, pulse off time, servo voltage, peak current, dielectric flow rate, wire speed, wire tension on different process response parameters such as material removal rate (MRR), surface roughness (Ra), Kerf (width of Cut), wire wear ratio(WWR)and surface integrity factors. Also reviews various optimization methods applied by the researchers and finally outlines the recommendations and future trends in WEDM research.

Keywords: Optimization, Process Parameters, Review, Wire-Cut EDM

I. INTRODUCTION

Wire Electrical Discharge Machining (WEDM) is the most widely recognized and non-traditional machining process used in industry today. WEDM is a thermo electrical process in which material is eroded from the work piece by a series of discrete sparks between the work piece and the wire electrode (tool), separated by a thin film of dielectric fluid (distilled water) that is continuously fed to the machining zone to flush away the eroded particles. The tool electrode and the work are held at an accurately controlled distance from one another, which are dependent on the operating conditions and referred to as spark gap. This gap prevents the mechanical contact of the tool and work. The movement of wire is controlled numerically to achieve three dimensional shape and accuracy of the work piece. The schematic diagram of WEDM is shown in Fig. 1. Wire electrode is generally made of copper, brass or tungsten of diameter 0.05mm to 0.3mm, which is capable to achieve very small corner radii. When the equipulsed voltage is applied across the two electrode separated by dielectric fluid, the latter break down. The electron, so liberated are accelerated in presence of the electric field and collide with the dielectric molecules, causing the latter to be robbed off their electrons. The process grows and multiples with secondary emission followed by an avalanche of electrons and ions. The resistance of the dielectric layer drops as it is ionized resulting into ultimate breakdown. The electric energy is discharged into the gap and multifarious action takes place. Electro-dynamic wave set in and travel at high speed causing shock-impact and high temperature rise at the electrodes surfaces. The instantaneous temperature may reach as high as 10,000^{o}C causing localized vaporization of the electrodes.

Since the introduction of the process, WEDM has evolved from a simple means of making tools and dies to the best alternative of producing micro-scale parts with the highest degree of dimensional accuracy and surface finish quality. WEDM has greatly altered the tooling and manufacturing industry, resulting in dramatic improvements in accuracy, quality, productivity and profit. Over the years, the WEDM process has remained as a competitive and economical machining option fulfilling the demanding

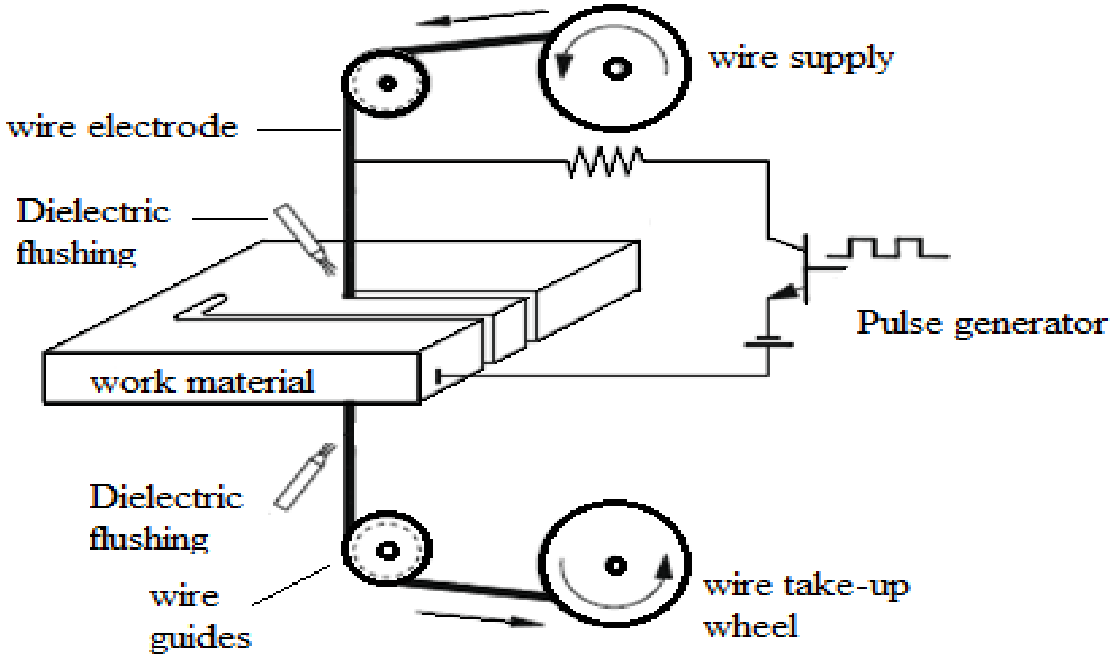

Fig. 1: Schematic Diagram of Working of Wire-EDM

machining requirements imposed by the short product development cycles and the growing cost pressures. However, the risk of wire breakage and bending has undermined the full potential of the process drastically reducing the efficiency and accuracy of the WEDM operation. A significant amount of research has explored the different methodologies of achieving the ultimate WEDM goals of optimizing the numerous process parameters analytically with the total elimination of the wire breakage thereby also improving the overall machining reliability.

II. AIMS AND OBJECTIVES OF WORK

The main objective of present work is to investigate of the influence of input WEDM (Wire Cut Electro Discharge Machining) parameters on machining characteristics like cutting speed and surface roughness and the effects of various WEDM process parameters such as pulse on time, pulse off time, servo voltage, peak current, dielectric flow rate, wire speed, wire tension on different process response parameters such as material removal rate (MRR), surface roughness (Ra), Kerf (width of Cut), wire wear ratio(WWR)and surface integrity factors.

III. LITERATURE REVIEW

WEDM is an essential manufacturing process in some industries, which gives importance to variety, precision and accuracy. Since the inception of the WEDM process in late 1960's to till date, a lot of research works have been done by several researchers. The amount of research work can be divided into two major areas namely WEDM process optimization and process monitoring and control. Several researchers have attempted to improve the performance characteristics namely the surface roughness, cutting speed, dimensional accuracy and material removal rate, in WEDM process. Some of the work related to the present study is discussed in the following paragraphs.

Lin, et al [1] optimized the multiple performance characteristics in wire electrical discharge machining by combining the orthogonal array and grey relational analysis. Machining parameters were work piece polarity, pulse on time, duty factor, open discharge voltage, discharge current, and dielectric fluid are optimized with considerations of multiple performance characteristics including material removal rate, surface roughness, and electrode wear ratio. Experimental results have shown that machining performance in the EDM process can be improved effectively through this approach.**Lin and Lin [2]** investigate an efficient Ti6Al4V electrical discharge machining (EDM) process with a bundled die-sinking electrode. The feasibility of machining Ti6Al4V with a bundled electrode was studied and its effect on EDM performance was compared experimentally using a solid die-sinking electrode. The simulation results explain the high performance of the EDM process with a bundled electrode by through the use of multi-hole inner flushing to efficiently remove molten material from the inter-electrode gap and through the improved ability to apply a higher peak current. A 3-factor, 3-level experimental design was used to study the relationships between 2 machining performance parameters (material removal rate: MRR, tool wear ratio: TWR) and 3 machining parameters (fluid flow rate, peak current and pulse duration). The main effects and influences of the 2-factor interactions of these parameters on the performances of the EDM process with the bundled electrode are discussed.

Sridhar et al. [3] described the residual stress variation in titanium alloy IMI-834 as a function of depth following milling at different feeds, speeds and depths of cut was determined by a strain-gauge technique involving blind-hole drilling. The residual stresses were found to be compressive in nature and to be dependent upon the milling parameters. Heat treatment was found to relieve the residual stresses, the degree of stress relief being found to increase with increase in temperature. Optimum temperatures were determined at which significant relaxation occurred without adversely affecting the microstructure and mechanical behavior of the material.**Newman, et al [4]** reviewed the vast array of research work carried out from the spin-off from the EDM process to the development of the WEDM. It reports on the WEDM research work involving the optimization of the process parameters surveying the influence of the various factors affecting the machining performance and productivity. They also highlight the adaptive monitoring and control of the process investigating the feasibility of the different control strategies of obtaining the optimal machining conditions. A wide range of WEDM industrial applications and future research work is reported.

Kim and Rumulu [5] optimize drilling feed and speed to maximize each hole quality parameter to the greatest extent possible as well as to minimize machining cost. Optimum process conditions for achieving desired whole quality and process cost were found to be a combination of low feed and low speed when using carbide drills, and high feed and low speed in drilling with HSS-Co drills in titanium alloy stacks. **Zhang et al [6]** focused on using ultrasonic to improve the efficiency in electrical discharge machining (EDM) in gas medium. The new method is referred to as ultrasonic-assisted electrical discharge machining (UEDM). In the process of UEDM in gas, the tool electrode is a thin-walled pipe, the high-pressure gas medium is applied from inside, and the ultrasonic actuation is applied onto the work piece. In their experiments, the work piece material was AISI 1045 steel and the electrode material was copper. The experiment results indicate that (a) the Material Removal Rate (MRR) is increased with respect to the increase of the open voltage, the pulse duration, the amplitude of ultrasonic actuation, the discharge current, and the decrease of the wall thickness of electrode pipe; and (b) the surface roughness is increased with respect to the increase of the open voltage, the pulse duration, and the discharge current. Based on experimental results, theoretical models to estimate the MRR and the surface roughness are developed.

Mahapatra and Patnaik [7] described the optimization of WEDM process parameters using Taguchi method. In this paper author optimized metal removal rate (MRR), surface finish and cutting width for a rough cut. Taguchi's L_{27} is used to optimize the individual response characteristic. Finally, genetic algorithm, a popular revolutionary approach, is employed to optimize the wire electric discharge machining process with multiple objectives. The study demonstrates that the WEDM process parameters can be adjusted to achieve better metal removal rate, surface finish and cutting width simultaneously. The confirmation experiments are carried out that shows the error associated with MRR, SR and kerf is less than 5 percent.**Singh et al [8]** described the Taguchi's approach and utility concept to optimize the multi-machining characteristics simultaneously. They discussed a case study on En24 steel turned parts using titanium carbide coated tungsten carbide inserts. They had chosen the three process parameters as, cutting speed, feed and depth of cut. After optimization they found a single optimal condition to get near optimal value of all the response characteristics simultaneously. The response characteristics optimizes were MRR, tool wear rate, power consumption and surface finish.**Kanagurajan et al [9]** studied the influence of operating parameters of EDM such as pulse current, pulse on time, electrode rotation and flushing pressure on material removal rate and surface roughness with tungsten carbide and cobalt.**Jatinder Kumar et al [10]** investigated the tool wear rate during the Ultrasonic machining of pure titanium. Tool material, abrasive material, slurry concentration, abrasive grit size and power rating of the Ultrasonic machine were included as input factors in this investigation. The optimal setting of these parameters were determined through experiments planned, conducted and analyzed using the Taguchi method.

Aman Aggarwal et al [11] optimized the multiple characteristics, in CNC turning of AISIP-20, such as tool life, cutting force, surface roughness and power consumption. Four controllable factors of the turning process viz. cutting speed, feed, depth of cut and nose radius were studied. Face centered composite design was used for experimentation. **Sarkar et al [12]** studied the trim cutting operation in Wire EDM of γ-titanium aluminide. A second order mathematical model was developed for surface roughness, dimensional shift and cutting speed using response surface methodology (RSM). The experimental plan was based on the face centered, central composite design. It was observed that the performance of the developed Pareto optimization algorithm is superior compared to desirability function approach.**Puri and Bhattacharya [13]** presented the study of geometrical inaccuracy caused due to wire lag with various machine control parameters. In this study authors considered all the machine control parameters simultaneously for a rough cut followed by a trim cut. They carried out an experimental investigation based on the Taguchi method involving thirteen control factors with three levels for an orthogonal arrayL_{27} (3^{13}). They described the influence of each control parameter on every response. **Gauri and Chakraborty [14]** used the principal component analysis (PCA) for the multi response optimization. In this paper, some modifications in the PCA based approach are suggested and two sets of experimental data published by past researchers are analyzed using modified procedure. It is observed that PCA based optimization can give better results than constrained optimization.

Shandilya et al. [15] used a RSM and artificial neural network based mathematical modelling for average cutting speed of Si Cp/6061 Al metal matrix composite during WEDM. Four WEDM parameters namely servo voltage, pulse-on time, pulse-off time and wire feed rate were chosen as machining process parameters. They developed a back propagation neural network to establish the process model. The performance of the developed artificial neural network models was compared with the RSM mathematical models of average cutting speed.**Kumar et al. [16]** investigated effect of various WEDM parameters on four response variables, i.e., machining rate, surface roughness, dimensional deviation and wire wear ratio on pure titanium (Grade-2) using RSM. The experimental plan is based on Box–Behnken design. The six parameters, i.e., pulse on time, pulse off time, peak current, spark gap voltage, wire feed and wire tension have been varied to investigate their effect on output responses. The ANOVA has been applied to identify the significance of developed model.**Sharma et al [17]** investigated the effect of parameters on metal removal rate for WEDM using high strength low alloy as work-piece and brass wire as electrode. They observed that material removal rate and surface roughness increase with increase in pulse on time and peak current. RSM is used to optimize the process parameter for material removal rate and surface roughness. They developed a mathematical model which correlates the independent process parameters with the desired metal removal rate and Surface Roughness. The central composite rotatable design has been used to conduct the experiments.**Sorabh et. al. [18]** Studied reveals that Surface finish can be improved by decreasing both pulse duration and discharge current. This indicates short pulse durations.

Davies et. al. [19] Reviewed several temperature measurement methods and used them in temperature monitoring during material removal in WEDM. There study outlines the physics of each method, detailing the sources and evaluation of uncertainty. Finally, using critical criteria in measuring material removal rate, methods were compared and the results were presented in guide-format for participants in this field of work. **G.Krishna et. al. [20]** Applied Taguchi technique to analyzed optimum input parameters corresponding output result. The obtained results were presented trough graph for selected aluminum alloy (HE 20). **Jennes and Snoey [21]** Believed that the traditional research purpose was not to improve machining efficiency, but to prevent from wire rupture during the machining process. Hence, one possible new WEDM challenge and future work area will be steered towards attaining higher machining efficiency by acquiring a higher CR and MRR with a low wire consumption and frequency of wire breakage.

Dekeyser et al. [22] developed a thermal model integrated with an expert system for predicting and controlling the thermal overload experienced on the wire. Although the model increases the level of machine autonomy, it requires a large amount of computation, which slows down the processing speed and undermines the online control performance..**Kinoshita et al. [23]** observed the rapid rise in pulse frequency of the gap voltage, which continues for about 5–40 ms before the wire breaks. They developed a monitoring and control system that switches off the pulse generator and servo system preventing the wire from breaking but it affects the machining efficiency. **Kinoshita et al. [24]** investigated the effects of wire feed rate, wire winding speed, wire tension and electrical parameters on the gap conditions during WEDM. As a result, many conventional control algorithms based on explicit mathematical and statistical models have been developed for EDM or WEDM operations.

Han et al. [24] developed a simulation system, which accurately reproduces the discharge phenomena of WEDM. The system also applies an adaptive control, which automatically generates an optimal machining condition for high precision WEDM. **Suziki and Kishi [25]** studied the reduction of discharge energy to yield a better surface roughness, while **Luo [26]** discovered the additional need for a high-energy efficiency to maintain a high machining rate without damaging the wire. **Nihat Tosun et al. [27]** A study on kerf and material removal rate in wire electrical discharge machining based on Taguchi method. This paper presented an investigation on the effect and optimization of machining Parameters on the kerf (cutting width) and material removal rate (MRR) in wire electrical discharge machining (WEDM). The experimental studies were conducted under varying pulse duration, open circuit voltage, wire speed and dielectric flushing pressure. The settings of machining parameters were determined by using Taguchi experimental design method. The level of importance of the machining parameters on the cutting kerf and MRR is determined busing analysis of variance (ANOVA). The optimum machining parameter combination was obtained by using the analysis of signal-to-noise (*S*/*N*) ratio. The variation of kerf and MRR with machining parameters is mathematically modeled by using regression analysis method. The optimal search for machining parameters for the objective of minimum kerf together with maximum MRR is performed by using the established mathematical models. **Fuzhu Han et al. [28]** Describes the Influence of machining parameters on surface roughness in finish cut of WEDM. According to them Surface roughness is significant to the finish cut of wire electrical discharge machining (WEDM). This paper describes the influence of the machining parameters (including pulse duration, discharge current, sustained pulse time, pulse interval time, polarity effect, material and dielectric) on surface roughness in the finish cut of WEDM. Experiments proved that the surface roughness can be improved by decreasing both pulse duration and discharge current. When the pulse energy per discharge is constant, short pulses and long pulses will result in the same surface roughness but dissimilar surface morphology and different material removal rates. The removal rate when short pulse duration is used is much higher than when the pulse duration is long.

Mustafa Ilhan Gokler and Alp Mithat Ozanozu [29] present the experimental study to select the most suitable cutting and offset parameter combination for the wire electrical discharge machining process in order to get the desired surface roughness value for the machined work pieces. A series of experiments have been performed on 1040 steel material of thicknesses 30, 60 and 80 mm, and on 2379 and 2738 steel materials of thicknesses 30 and 60 mm. **Nihat Tosun and Can Cogun [30]** In this study, the effect of cutting parameters on wire electrode wear was investigated experimentally in wire electrical discharge machining(WEDM). The experiments were conducted under different settings of pulse duration, open circuit voltage, wire speed and dielectric fluid pressure. Brass wire of 0.25 mm diameter and AISI 4140 steel of 10 mm thickness were used as tool and work piece material. It is found experimentally that the increasing pulse duration and open circuit voltage increase the wire wear ratio (WWR) whereas the increasing wire speed decreases it. The variation of work piece material removal rate and average surface roughness were also investigated in relation to the WWR. The variation of the WWR with machining parameters was modeled statistically by using regression analysis technique. The level of importance of the machining parameters on the WWR was determined by using analysis of variance (ANOVA) method.

IV. DISCUSSION

The ultimate goal of the WEDM process is to achieve an accurate and efficiency machining operation without compromising the machining performance. This is mainly carried out by understanding the inter-relationship between the various factors affecting the process and identifying the optimal machining condition from the infinite number of combinations. The adaptive monitoring and control systems have also been extensively implemented to tame the transient WEDM behavior without the risk of wire breakages. Moreover, several monitoring and control algorithms based on the explicit mathematical models, expert's knowledge or intelligent systems have been reported to reduce the inaccuracy caused by the vibration behavior and static deflection of the wire. With the continuous trend towards unattended machining operation and automation, the WEDM process has to be constantly improved to maintain as a competitive and economical machining operation in the modern tool-room manufacturing arena. WEDM process due to its ability to efficiently machine parts with difficult-to-machine materials and geometries has its own application area unmatched by other manufacturing processes.

V. CONCLUSION

Wire-cut electrical discharge machining is one of the most Emerging non conventional manufacturing processes for machining hard to machine materials and intricate shapes, which are not possible with conventional machining methods. This is more efficient and economical for machining hard to machine materials. The effect of various parameters and Setting of various parameters at their optimal levels is very much required for manufacturers. From the literature, the parameters and their effects observed are given as under:

- Higher the pulse-on time, higher will be the energy applied there by generating more amount of heat energy during this period. Material removal rate and wire wear rate increase with increase in pulse on time where as surface finish will decrease.
- Reducing pulse off time can increase cutting speed, by allowing more productive discharges per unit time. However, reducing off time, can overload the wire, causing wire breaks and instability of the cut by not allowing enough time to evacuate the debris before the next discharge.
- Servo voltage acts as the reference voltage to control the wire advances and retracts. At higher value of SV the gap between work piece and wire becomes wider and it decreases the no of sparks, stabilizes electric discharge and the rate of machining slows down. Whereas at smaller value of SV, the mean gap becomes narrow which leads to an increase in number of electric sparks, speed up the machining rate and unstable discharge results in wire breakage.
- Peak current is the amount of power used in discharge machining and is measured in unit of amperage. The current increases until it reaches a preset value during each pulse on time, which is known as peak current. Peak current is governed by surface area of cut. Higher peak current is applied during roughing operation and details with large surface area. MRR directly increases with increased peak current.
- Gap voltage is also called open circuit voltage and specifies the supply voltage to be placed on the gap, greater this value, the electric discharge becomes greater. If the gap voltage increases, the peak current will also increases, which leads to higher MRR.
- Dielectric flow rate is the rate at which the dielectric fluid is circulated. Flushing is important for efficient machining.
- As the wire feed rate increases, the consumption of wire and cost of machining will increase. Low wire speed will cause wire breakage in high cutting speed.
- If the wire tension is high enough the wire stays straight otherwise wire drags behind. Within Considerable range, an increase in wire tension significantly increases the cutting speed and accuracy. The higher tension decreases the wire

REFRENCES

[1] C. L. Lin, J. L. Lin and T. C. Ko, "Optimization of the EDM Process Based on the Orthogonal Array with Fuzzy Logic and Grey Relational Analysis Method " International Journal of Advance Manufacturing Technology,19,pp.271–277, 2002.

[2] J.L. Lin, C.L. Lin, "The use of the orthogonal array with grey relational analysis to optimize the electrical discharge machining process with multiple performance characteristics" International Journal of Machine Tools & Manufacture 42, pp. 237–244, 2002.

[3] B.R. Sridhar, G.Devananda, K. Ramachandra, Ramaraja Bhat, "Effect of machining parameters and heat treatment on the residual stress distribution in titanium alloy IMI-834" Journal of Materials Processing Technology 139, pp.628–634, 2003.

[4] K.H. Ho, S.T. Newman, S. Rahimifard, R.D. Allen, "State of the art in wire electrical discharge machining (WEDM)" International Journal of Machine Tools & Manufacture 44, pp.1247–1259, 2004.

[5] D.Kim,M. Ramulu," Drilling process optimization for Graphite/bismaleimide–titanium alloy stacks" Composite Structures 63,pp. 101–114, 2004.

[6] Q.H. Zhang, R. Dub, J.H. Zhang, Q.B. Zhang, "An investigation of ultrasonic-assisted electrical discharge machining in gas" International Journal of Machine Tools & Manufacture 46 ,1582–1588, 2006.

[7] S.S.Mahapatra & Amar Patnaik, "Optimization of wire electrical discharge machining(WEDM) process parameters using Taguchi method" International Journal of Advance Manufacturing Technology 34,pp. 911–925, 2007.

[8] R. Singh, J.S. Khamba, "Investigation for ultrasonic machining of titanium and its alloys" Journal of Materials Processing Technology 183,pp.363–367, 2007.

[9] D. Kanagarajan & R. Karthikeyan & K. Palanikumar &J. Paulo Davim, "Optimization of electrical discharge machining characteristics of WC/Co composites using non-dominated sorting genetic algorithm (NSGA-II)" International Journal of Advance Manufacturing Technology,36,pp.1124–1132, 2008.

[10] Jatinder Kumar & J. S. Khamba & S. K. Mohapatra, "Investigating and modeling tool-wear rate in the ultrasonic machining of titanium", International Journal of Advance Manufacturing Technology 41, pp. 1107–1117, 2009.

[11] Aman Aggarwal, Hari Singh, Pradeep Kumar, Manmohan Singh, "Optimization of multiple quality characteristics for CNC turning under cryogenic cutting environment using desirability function", journal of materials processing technology , 2 0 5, pp.42–50, 2008.

[12] S. Sarkar, M. Sekh, S. Mitra, B. Bhattacharyya, "Modeling and optimization of wire electrical discharge machining of -TiAl in trim cutting operation", journal of materials processing technology 2 0 5,pp. 376–387, 2008.

[13] A.B. Puri a, B. Bhattacharyya, "An analysis and optimization of the geometrical inaccuracy due to wire lag phenomenon in WEDM", International Journal of Machine Tools & Manufacture 43, pp.151–159, 2003.

[14] Susanta Kumar Gauri & Shankar Chakraborty, "Multi-response optimization of WEDM process using principal component analysis", International Journal of Advance Manufacturing Technology 41, pp.741–748, 2009.

[15] Pragya Shandilya, P.K Jain, N.K.Jain, "Modeling and analysis of surface roughness in WEDC of SiCP/6061 Al MMC through response surface methodology" International Journal of Engineering Science and Technology, Vol.-3, pp.531-535, 2011.

[16] Anish Kumar & Vinod Kumar & Jatinder Kumar," Multi-response optimization of process parameters based on response surface methodology for pure titanium using WEDM process", International Journal of Engineering Science and Technology, 68, pp.2645–2668, 2013.

[17] Neeraj Sharmaa, Rajesh Khanna, Rahuldev Gupta," Multi Quality Characteristics of WEDM Process Parameters With RSM", Procedia Engineering 64 pp.710 – 719,2013.

[18] Sorabh., Manoj, Neeraj Nirmal., "A literature review on optimization of machining parameters in wire EDM", International Journal of Research in Management, Economics and Commerce, pp-492-494, 2013.

[19] Davies M.A., Ueda.T. Saoubi, and Mullany, "On the measurement of temperature in material removal process", Annals of the CIRP vol. 56, pp. 581-604, 2007.

[20] G. Krishna Mohan Rao. G. Ranga. Janardhan, and M. Srinivasa Rao,"optimal machining parameters on Diesinking EDM using Taguchi technique on Aluminum Alloy (HE 20)", pp. 103-116, 2007.

[21] M.Jennes,R. Snoey,"Correlation between EDM data and machining settings", Ann. CIRP 24 (2) pp. 83–88. 1984.

[22] W. Dekeyser, R. Snoeys, M. Jennes,"Expert system for wire cutting EDM based on pulse classification and thermal model-ling", Robotics Computer. Integrated Manuf. 4 (1–2) pp.219–224, 1984.

[23] N. Kinoshita, M. Fukui, G. Gamo,"Control of wire-EDM preventing electrode from breaking" Ann. CIRP 31 (1) ,pp.111–114, 1982 .

[24] N. Kinoshita, M. Fukui, H. Shichida, G. Gamo, T. Sata,"Study on E.D.M. with wire electrode, gap phenomena", Ann. CIRP 25, pp.141–145, 1976.

[25] F. Han, M. Kunieda, T. Sendai, Y. Imai,"High precision simu-lation of WEDM using parametric programming", Ann. CIRP 51,pp.165–168, 2002.

[26] Y. Suziki, M. Kishi,"Improvement of Surface Roughness in wire EDM" (ISEM-9), Nagoya, Japan, 1989.

[27] Nihat Tosun, Can Cogun and Gul Tosun, "A study on kerf and material.removal rate in wire electrical discharge machining based on Taguchi.method", Journal of Materials Processing Technology, Volume 152, pp.316-322, 2004.

[28] Fuzhu Han, Jun Jiang and Dingwen Yu,"Influence of machining parameters on surface roughness in finish cut of WEDM", The International Journal of Advanced Manufacturing Technology, Volume 34, pp.538-546, 2007.

[29] Gokler, Mustafa Ilhan ,Ozanozgu, Alp Mithat,"Experimental investigation of effects of cutting parameters on surface roughness in the WEDM process", International Journal of Machine Tools and Manufacture, Volume 40,pp.1831-1848, 2000.

[30] Nihat Tosun and Can Cogun,"investigations on wire wear in WEDM",.Journal of Materials Processing Technology Volume 134, pp. 273-278, 2003.