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A REVIEW ON CURRENT RESEARCH TRENDS IN WIRE-ELECTRICAL DISCHARGE MACHINING (WEDM)

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ABSTRACT

A Wire-EDM or Electrical-discharge wire cutting is basically a variation of an EDM process in which a slowly moving wire travels along a prescribed path, cutting the work piece, by discharge sparks which occurs in a small gap between wire & work piece and removes unwanted material from parent metal by melting & vaporization. The wire should have sufficient tensile strength and fracture toughness, as well as high electrical conductivity. Creation of extrusion dies, blanking punches and metal & tool fabrication are performed by WEDM. The paper reviews the research work carried out in the different fields related to WEDM such as modeling & simulation, optimization, ultrasonic vibrations, dry machining, composite materials and other key studies including effects, investigations, improvements and developments carried out in the field of WEDM.

Keywords: Dry Machining, Modelling And Simulation , Optimization, Ultrasonic Vibration, Wire-EDM

I. INTRODUCTION

A wire-EDM process is one of the types of EDM process (the other being Die-Sinking EDM). In wire EDM, the conductive materials are machined with a series of electrical discharges (sparks) that are produced between an accurately positioned moving wire (the electrode) and the work piece.

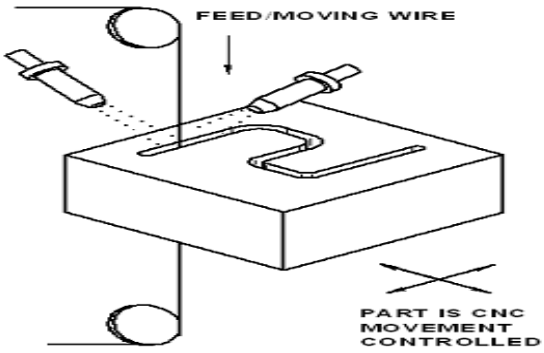

Fig. 1 : Wire-EDM setup

High frequency pulses of alternating or direct current is discharged from the wire to the work piece with a very small spark gap through an insulated dielectric fluid (water). Many sparks can be observed at one time. This is because actual discharges can occur more than one hundred thousand times per second, with discharge sparks lasting in the range of 1/1,000,000 of a second or less. The volume of metal removed during this short period of

spark discharge depends on the desired cutting speed and the surface finish required. The heat of each electrical spark, estimated at around 15,000° to 21,000° Fahrenheit, erodes away a tiny bit of material that is vaporized and melted from the work piece. (Some of the wire material is also eroded away) These particles (chips) are flushed away from the cut with a stream of de-ionized water through the top and bottom flushing nozzles. The water also prevents heat build-up in the work piece. Without this cooling, thermal expansion of the part would affect size and positional accuracy. The wire is usually made of brass, copper, or tungsten; zinc- or brass- coated and multi coated wires are used. The wire diameter is typically about 0.30 mm (0.012 in.) for roughing cuts and 0.20 mm (0.008 in.) for finishing cuts. The wire travels with a constant velocity in the range of 0.15 to 9 m/min, and a constant gap (kerf) is maintained during the cut. In 1969, the swiss firm Agie produced world's first wire-EDM machine. Typically in the early 70's these machines were typically slow, cutting about 2 sq. inches an hour. There speeds went up to 6 sq. inches per hour in early 80's. Today the machines are equipped with automatic wire threading and can cut around 20 times more fast than initial machines. The earliest numerically controlled machines were conversions of punched-tape vertical milling machines. The first commercially available NC machine built as a wire-cut EDM machine was manufactured in USSR in 1967. Machines that could optically follow lines of master drawing were developed by David H. Dulebohn's groupin 1960s(1). It was only towards the mid of the 1970s, when computer numerical control (CNC) drawing plotter and optical line follower techniques were produced. Dulebohn later used the same plotter CNC program to directly control the EDM machine and hence the first CNC EDM machine was produced in1976 that brought about a major evolution of the machining process. As a result, the broad capabilities of the WEDM process were extensively exploited for any through-hole machining owing to the wire, which has to pass through the part to be machined. The review presented in this paper is based upon the major and current research trends carried out by the different researchers of the world who utilized different fields related to the Wire-EDM technology and many ideas were obtained regarding the improvements of the process.

II. MAIN AREAS OF RESEARCH

2.1 Modeling and Simulation

Modeling and simulation always helps to better interpret and predict the results which are otherwise difficult to understand. Here, we use models, prototypes and stimulators, either statically or overtime to develop data as a basis for making managerial or technical decisions without even testing it in Real life.

E. Weingartner, F. Kuster and K. Wegener (2) studied the influence of type of heat source on modeling single discharges as well as influence of temperature dependent material properties and latent heat of fusion and vaporization on simulation results by considering a heat source modeled on three different shapes ; Heat source, disc heat source and time dependent heat source. However the time dependent heat source was found to be more suitable to predict the shape of eroded craters (Depth was decreased when latent heat was considered). Hence latent heat of fusion and vaporization showed to have significant influence on simulation results.

Amit Kumar Gupta and Dr. Sanjeev Kumar (3) Conducted experiments on high carbon chromium Steel with a wire of diameter 0.2 mm and obtained data was analyzed using response surface methodology. The results of ANOVA indicated that proposed a mathematical model can adequately describe the performance within limit of

factors being studied and founded that high pulse on time, low pulse of time and low gives optimal value of cutting rate.

Ravindranath Bobbili, V. Madhu and P. K. Gogia (4) attempted to establish the relation between parameters by employing Buckingham Pi theorem to model the input variables and Thermo physical characteristics of Wire EDM and founded that the results predicted by the model regarding material removal rate and surface roughness work well matching with experiment results.

S. Ben Salem, W. Tebni, E. Bayraktar (5) developed the surface roughness model for parameters of current intensity electrode type and workers material for an EDM process using experimental design method. After confirmation runs were performed, it was found that predicted and measured values were different by 4.5 % which can be said as variation in percentage error for surface roughness. However the mathematical model was itself obtained by experimental design method and relatively small number of designed experiments was required to generate useful information and developing the predictive equations for surface roughness.

Mu-Tian Yan, Chi Cheng Fang (6) proposed a genetic algorithm-based fuzzy logic controller to investigate the dynamic performance of the closed-loop wire tension control system. Experimental results demonstrate that the developed wire transport system can result in satisfactory transient response, steady-state response and robustness. The proposed genetic algorithm-based fuzzy logic controller can obtain faster transient response and smaller steady-state error than a PI controller.

2.2 Optimization

Here optimization signifies the formulation of the best possible output within a given set of elements or conditions. However it involves various methods such as Taguchi's method which can be applied to find optimum process parameters, ANOVA (analysis of variance) to study performance characteristics, Regression analysis for estimating predicted values of the parameters

.**Y.S. Liao, J.T. Huang and H.C.** (7) Proposed an effective and precise way of determining the appropriate machining parameters based on Taguchi design method and ANOVA which was time effective and cost saving as well. The objective was to achieve shortest machining time whilst at the same time, satisfying the requirements of accuracy and surface roughness. They found that the table feed and Pulse on time have a significant influence on material removal rate, gap voltage and total discharge frequency however, gap width and surface roughness are mainly influenced by pulse on time. Hence larger table feed and a smaller Ton will result in higher value of surface roughness.

Pujari Srinivasa Rao, Koonu Ramji and Beelasatyanarayana (8) besides presenting optimal combination of parameters for surface roughness and material removal rate for Aluminum 2014 T6 alloy also developed mathematical models which predicted the SR and MRR with high Regression coefficient value with the help of Optimization of performance measures by hybrid genetic algorithm its results clearly showed that a sacrifice in cutting efficiency is essential for production of Quality Surfaces and vice versa. White layer thickness measurements were made for suggested the combination of parameters whose magnitude or value is relatively high when compared to heavy and other light metals.

Shivkant Tilekar, Sankha Shurva Das, P.K. Patowari (9) included effect on kerf width along with surface roughness of Aluminum and mild steel using single objective Taguchi method. both the parameters were

measured by surface profilometer and optical microscope respectively. Both kerf width and surface roughness were minimized successfully and process parameters word stated ANOVA showed that in case of kerf width wire feed rate and Spark on times have significant effect on Aluminum and mild steel respectively.

2.3 Ultrasonic Vibrations

The introduction of ultrasonic vibrations is one of the method to improve the machining performance of difficult to machine materials. It can cause an easy debris removal as well as enhancement of molten metal ejection due to creation of large pressure change between electrode and work piece .Hence ultrasonic vibrations can be mainly applied for finishing process.

Chaiya Praneetpongrung, Yasush Fakuzawa, Shigeru Nagasawa and Ken Yamashita (10) studied the effects on combined ultrasonic vibrations on machining properties of Si_3N_4. They found that ultrasonic vibrations should be applied after transition time is passed however large amplitude values do not always contribute to large MRR. however surface roughness was increased after introduction of ultrasonic vibration.

Mohammadi, A. F. Tehrani, A. Abdullah (11) Proposed a new method of vibration transfer to wire in ultrasonic assisted wire electrical discharge turning. They observed an optimum output power of ultrasonic transducer below which the effect will be negligible and above which short circuit and wire breakage could occur. significant reduction in sliding friction was observed which was due to instantaneous changes in vector of force finally contributing to higher MRR. In roughing condition ultrasonic vibration effect was found to be more significant.

Guo et al. (12) Studied the machining mechanism of wire EDM along with ultrasonic vibration and found that combined technology of wire EDM and ultrasonic facilitates the form of multiple channel discharge and raise the utilization ratio of energy that leads to improvement in cutting rate and surface roughness. high frequency vibration of wire improves the discharge concentration and reduces the probability of rapture wire.

2.4 Dry Machining

Dry Wire EDM is a modification of oil wire EDM process in which the liquid dielectric is replaced by high velocity gaseous dielectric like Helium, Argon, oxygen, air extra. flow of high velocity air into the gap facilitates removal of debris and prevents the excessive heating of tool and work piece

C.C. Kao, Jio Tao, Sangwon Lee and Alber J (13) investigated the dry wire EDM on thin work Pieces by conducting the experiment in air. the results after experiments showed that not all thin work materials could be machined using dry wire EDM .the increase and work piece thickness and work material melting temperature had an adverse effect on MRR.

S. Abdulkareen, A. A. Khan and Z.M Zain (14) investigated the effects of wire EDM variables on surface topography during wet and dry wire EDM of stainless steel. it was concluded that wet wire EDM gives better surface integrity as compared to dry wire EDM who's poor surface integrity could be because of adhesion of machining debris on enter electrodes surface. however increase in both pulse current and gap voltage can also contribute to poor surface integrity of the work piece during dry wire EDM.

2.5 Machining Investigations

There have been investigation regarding the various terminologies of wire EDM and interesting results have been obtained.

Nihat Tosun and Can Cogun (15) investigated the outcomes on wire wear ratio (weight loss of wire after machining divided by initial wire weight) due to the variations of machining parameters both experimentally and statistically in wire EDM. they found that increasing pulse duration and open circuit voltage increases the WWR where as the increasing wire speed and dielectric fluid pressure decrease the WWR. relation between cutting parameters and WWR were best expressed by using power function. however the most effective parameters on WWR found to be open circuit voltage and Pulse duration.

J. F. Liu, L. Li. U. B. Guo (16) investigated the process capability of wire EDM in machining Nitinol $Ni_{50.8}$ $Ti_{49.2}$ by one main cut (MC) followed by four trim cuts (TC). experimental results show that Six Sigma distributions of surface roughness are very different between MC and TC. roughness distribution shows that MC surfaces have much higher average and random then TC surfaces. The highly discontinuous porous white layer in MC can be reduced to uniform solid white layer in Finish TC. however that significant softening occurred in heat affected zone in MC due to thermal degradation can be minimized by the TC at relatively low discharge energy.

Kruth, et. al. (17) studied and experimentally tested several compositions of wires, with high tensile core and several coatings. They have found that, while cutting with prototype wires, a significant rise in accuracy is obtained, especially in corner cutting, while the cutting rate is at a comparable level as commercial reference wire.

K.P. Rajurkar, W.M. Wang, R.P. Lindsay (18) showed that the wire breakage is correlated to the sudden increase in sparking frequency. It was also found that their proposed monitoring and control system based on the online analysis of the sparking frequency and the real-time regulation of the pulse off-time affects the MRR.

A.Okada, T. Konishi , Y.Okamo, **H. Kurihera** (19) investigated the influence of nozzle jet flushing on wire breakage was experimentally investigated with varying the machined kerf length and machining conditions. Furthermore, the flow fields and debris residence time in the kerf, hydrodynamic stress distributions acting on the wire, and wire deflections were numerically analyzed. Based on the analyzed results, the causes of wire breakage were discussed.

Yanzhen Zhang, Yonghong Liu, Yang Shen, Renjie Ji, Zhen Li, Chao Zheng (20) conducted a systematical and comprehensive investigation of the material removal characteristics of the electrical discharge machining (EDM) process using various dielectrics as the working fluis. Five dielectrics, including gaseous dielectrics, air and oxygen, and liquid dielectrics, de-ionized water, kerosene and water-in-oil (W/O) emulsion were used as the working fluids. The whole geometry parameters of the craters, including the recast material in the craters, were precisely determined by metallographic method. The volume of melted and removed material and removal efficiency in different dielectrics were comparatively investigated. By relating the material removal characteristics to the evolution of the discharge generated bubbles in different dielectrics which was done by computer simulation, it seems that the pressure above the discharge point is an important factor that can affect material removal characteristics.

2.6 Effects

The changes in process parameters always have significant effect on the performance characteristics of wire EDM. some of the studies carried out regarding these effect's have been mentioned here.

J. Prohaszka, A.G. Mamalis, N. M. Vaxevaxevanidis (21) conducted experiments regarding choice of suitable wire electrode materials and influence of properties of these materials on machinability of wire EDM. they found that materials used for fabrication of wire electrodes must be characterized by small work function and high melting and evaporation temperatures. however by coating already used copper, brass, steel and molybdenum wires by a layer of materials processing a small work function such as magnesium, alkaline metals and alkaline earth metals may increase the cutting efficiency during wire EDM.

J. A. Sanchez, J. L. Rodil, A. Herrero, L.N. Lopez De Lacalle and A. Lamikiz (22) studied the corner geometry by successive cuts (roughing and finishing) and effect of cutting speed limitation on the accuracy of wire EDM corner cutting. they found corner radius as an important function in the output results obtained. however in finishing cuts, the value of limitation depends on factors such as work piece thickness, corner radius and number of finishing cuts. it is possible to achieve and optimum fit along the whole corner (bath at 45° and at exit) since the materials are removed by previous cuts were not constant.

H. Singh and R. Garg (23) studied effects of various process parameters on wire EDM on MRR of hot die Steel (H-11) using one variable at a time approach. it was concluded that wires feed and wire tension had no effect on MRR however pulse on time parameter which is increased can also increase the MRR. however MRR will decrease with an increasing pulse of time and peak current also and increase in Servo voltage decreases MRR.

E. Weingartner, K. Wegener and F. Custer (24) after studying the effect of work piece circumferential speed in wire EDM (wire electrical discharge dressing) found that the size of craters formed and MRR are both increases with increase in relative speed. based on simulation results using thermo-electrical model, it was found that higher melting efficiencies can be achieved with high relative speed.

Daniel N. Madyira and Esthar T. Akinlabi (25) studied the effect of wire EDM on fracture toughness of this aero space material (grade 5 Titanium alloy) standard Test procedure using compact tension (CT) specimen is used to measure the fracture toughness. 4 specimens are produced using wire EDM. this includes pre-crack which is easily produced by fatigue cycling. obtained results indicate a slight decrease in fracture toughness. in addition, it was also concluded that wire EDM can be used as an alternative to fatigue pre-cracking and fracture toughness testing of Titanium alloys.

2.7 Improvements and Developments

There is always a scope of improvement in any type of machining process by developing a method or a proper combination of process parameters. wire EDM also improved from its beginning in 1970's till today. some of the recent improvements and development are:-

Oana Dodun, Laurentiu Slatineanu, Lorele, Gherman (26) proposed to devices which should be able to act on the tool electrode in order to improve the machining process efficiency. one of the solution proposes the use

of electromagnetic subsystems, while the second solution is based on the use of a sub assembly electric motor-gear box could be applied for periodically changing the wire tool electrode speed.

Y.S. Liao, J.T. Huang and Y.H. Chain (27) Made an attempt to obtain a good surface roughness with the assistance of taguchi design quality, ANOVA, F-test, machining voltage, current limiting resistance, type of pulse generating circuit and capacitance as significant parameters affecting surface roughness and the traditional circuit using low power for ignition was also modified. they found that DC pulse generating circuit of quality (wire electrode as anode) can achieve better surface roughness. For discharge Spark to take place, low connectivity of dielectric should be incorporated. they were successful in a achieving surface roughness of 0.22µm after analyzing effect of each factor.

K.Y. Song, D.K. Chung, M.S. Park, C.N. Cho (28) developed the concept of strip electrode where a conductive strip moves on the electrode guide. strip electrode uses a continuously applied strip electrode similar to wire electrode in wire EDM. the worn strip is removed and a new one is supplied continuously. this strip EDM method was applied in EDM milling and turning and it was helpful in overcoming errors in machining caused by continuous electrode wear.

T. Tamura (29) developed surface modification technology, both in EDM and Wire EDM for the purpose of completely removing the surface defects. the surface defects in wire EDM was removed by introducing the surface integrity cut (SI cut) after applying a large number of wire EDM finishing cuts. in SI cuts, it was considered that the electrolysis phenomenon occurs between work piece and wire electrode similarly the surface integrity machining (SIME) for EDM was developed after applying finishing EDM which was conducted by applying voltage to constant gap between electrode and work piece and deionized water and used electrolytic action for the purpose.

Kinoshita N., Fukui M, Fujii T (30) have developed a new guide of wire electrode. The guide does not cause locally sharp bending of the wire, and wire runs through the guide smoothly. Hence helps in reducing the defects that arises due to sharp bending of the wire.

Kinoshita et al. (31) 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.

Snoeys et al. (32) proposed a knowledge-based system, which comprises of three modules, namely work preparation, process control and operator assistance or fault diagnosis, enabling the monitoring and control of the WEDM process. The work preparation module determines the optimal machining parameter settings, while the operator assistance and fault diagnostics databases advise the operators and diagnose the machining errors. Thus, the capabilities of these modules increase the amount of autonomy given to the WEDM machine.

Cabanes, E. Portillo, M. Marcos, J.A. Sánchez (33) proposed a methodology that guarantees an early detection of instability that can be used to avoid the detrimental effects associated to both unstable machining and wire breakage. The proposed methodology establishes the procedures to follow in order to understand the causes of wire breakage and instability. In order to quantify the trend to instability of a given machining situation, a set of indicators related to discharge energy, ignition delay time, and peak current has been defined. Wire breakage risk associated to each situation is evaluated comparing the evolution of those indicators with some previously defined threshold values.

2.8 Composite Materials

Composite material is made from 2 or more constituent materials with significantly different physical or chemical properties that when combined, produce a material with characteristics different from individual components. here the process parameter as well as machining capability of composite materials such as ceramic semiconductors carbon materials have been studied with reference to wire EDM and EDM.

B. Lavwers, J.P. Kruth, W. Liu, W. Earaerts, B.Schacht and P. Bleys (34) presented a detailed investigation of the material removal mechanism of some commercially available electrical conductive ceramic materials through analysis of debris and surface/subsurface quality. ZrO_2-based, Si_3N_4-based and Al_2O_3-based ceramic materials with additions of electrical conductive phases like TiN & TiCN were studied. it was found that besides the typical EDM material removal mechanism like melting/ evaporation spalling, other mechanism such as oxidation and decomposition of base material can occur. the latter especially occurs inside EDM of Si_3N_4-Tin using deionized water. Further, spalling effect was proud to be strongly related of formation cracks which was not recognised in machining of ZrO_2-Tin which has higher fracture toughness, compared to others.

S. Lopez, C.F. Gutierrez-Gonzalez, G.Mata-Osore, C. Pecharroman, L.A. Diaz, R.Torrecillas and J.S. Moya (35) presented the properties of ceramic based oxide/semiconductor/ metal nanocomposites and tested. the possibility of turning their composition in order to confer the machinability by EDM. they found that by adding a semiconductor and metal to a high performance ceramic, a composite that combines the good electrical conductivity of both semiconductor and metal, with high Mechanical properties of matrix can be produced the metal place a double role (a) from mechanical point of view the good ceramic/ metal interface confers the composite excellent Mechanical properties. (b) from electrical point of view, Nickel confer the machinability by EDM to samples with sufficient low resistivity.

D. Hanaoka, Y Fukuzawa, C. Ramirez, P.Minrazo, M.J. Osend. M. Belmonte (36) studied the discharge behavior of Si_3N_4 ceramic/carbon nanostructure composite and EDM was carried out using arresting electrode method which help in obtaining a better hole-edge shape as compared to normal method and insulating Si_3N_4 ceramics and $Si_3N_{4/}$ CNT and Si_3N_4/ GNP. Nano composites could be machined by this method. however properties of electrode we're ratio and surface roughness were better in conductive materials but the MRR was found better in insulting materials.

2.9 Other Key Studies

Kapil Gupta, Surjeet K Chaube, NK Jain (37) conducted experiments to find out effect of four important wire EDM parameters namely voltage, pulse on, pulse of time and wire feed rate on wire breakage frequency, surface roughness and machining rate of brass in order to bracket their ranges from available ranges in wire EDM machine for the ease of manufacturing of meso-Gears. they concluded that manufacturing of meso-gears using bracket ranges of parameters resulted in burr-free uniform teeth profile, good roughness characteristics and manufacturing quality DIN standard up to 6 which was much better than quality of gears manufacturer manufactured by conventional process the low discharge energy parameter setting and high voltage and high Pulse on time were suggested here.

Jan Bouquet, Lars Hensgen, Andreas Klink, Tom Jacobs, Fritz Klocke, Bert Lauwers (38) compared the three major Technologies of machining for fast production of gear prototype and found that milling of gears seems to be the most promising process however wire EDM is certainly a potential Technology how to make prototype gears wearing in mind the high quality surface roughness and save accuracy but its Limited flexibility is a big drawback.

H. Gotoh, T. Tani,M. Okada, A. Goto, T. Masuzawa and N. Mobri (39) combine the advantages of electrical discharge milling and Wire EDM and named it wire EDM milling in this method, a wire guide with a hemispherical tip is used. the wire slides along the groove prepared on surface of the tip. the wire guide is reciprocated in rotary state and moved along the designed path for generating the 3D shape. by this method, 3D machining similar to mechanical milling with a ball end mill is realized. this method is free from problems such as tool wear or build up a in mechanical milling.

J.P. Kruth and Ph. Bleys (40) discussed a destructive method for measuring residual stress in the fuction of depth, based on stress relaxation while electrolttically removing in influenced material. measurement of rough and finish wire EDM of tool Steel so that maximum tensile stress and penetration depth of tensile stress and reduce with increasing number of finishing. in some cases ,of rough wire EDM, relaxation of residual stress in time is observed.

Ahsan Ali Khan, Munira Bt. Mohd Ali and Norhashimah, Bt. Mohd. Shaffiar (41) studied the relationship of surface roughness with current and voltage during wire EDM and found that machined surface becomes rougher with increase in current and voltage .craters on unfinished surface become larger as a result of high current and voltage.

III. CONCLUSIONS

From the above literature review, we can hereby conclude that Latent heat of fusion and vaporization influences the simulation results, high pulse on time, low pulse off time and low servo voltage gives optimal value of cutting rate, surface roughness is influenced by pulse on time and ultrasonic vibrations (which were found to be more significant in roughing conditions and probability of rapture wire was reduced because of its introduction), Wet wire-EDM gives better surface integrity as compared to dry Wire-EDM, open circuit voltage and pulse duration were found to be the most effective parameters on WWR, MRR will decrease with increasing pulse off time and peak current, however increase in servo voltage decreases MRR, high melting efficiencies can be achieved with high relative speeds. However, many other conclusions were made related to the different fields in wire-EDM including modeling, dry machining, composite materials, optimization, ultrasonic vibrations and other investigations, effects, improvements & developments suggested were also mentioned.

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. To sum up, we can say enormous research has been done in the past and large amount of work can still be done in the future on the topic, so that WEDM can serve the purpose of high speed machining with good quality products in short time period and at reduced costs.

IV. FUTURE SCOPE

- Need for finding optimal combination of parameters for different tool materials used for work materials.
- Responses like roundness, circularity, cylindricity, machining cost etc may be considered in further research.
- For the estimation of process parameters, the work being carried out can be compared by considering different methods such as multiple relation analyses, ANOVA or F-Test. Similarly comparison can be made between Taguchi analysis Fuzzy control or Orthogonal techniques.
-A lot of research work still needs to be carried out in the field of Wire EDM by machining Super alloys such as Monel K500, Hastelloy composites, Different grades of steel utilizing other process parameters and using deferent Techniques.

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