Review on Current Research Trends in Wire Electrical Discharge Machining (WEDM)

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Abstract

Wire-electro discharge machining (WEDM) has become an important non-traditional machining process, as it provides an effective solution for producing components made of difficult-to-machine materials like titanium, zirconium, etc., and intricate shapes, which are not possible by conventional machining methods. Due to large number of process parameters and responses lots of researchers have attempted to model this process. This paper reviews the research trends in WEDM on relation between different process pa- rameters, include pulse on time, pulse off time, servo voltage, peak current, dielectric flow rate, wire speed, wire tension on different process responses include material removal rate (MRR), surface roughness (Ra), sparking gap (Kerf width), wire lag (LAG) and wire wear ration (WWR) and surface integrity factors. Furthermore, different types of WEDM methods introduced and discussed. In ad- dition the paper highlights different modelling and optimization methods and discussed their advantage and disadvantage. The final part of the paper includes some recommendations about the trends for future WEDM researches.

Keywords: Wire electrical discharge machining (WEDM), Process optimisation; Matenal removal rate; Surface finish; Wire types

1. Introduction:

Wire EDM (Electric Discharge Machining) is a thermo- electrical process which material is eroded by a series of sparks between the work piece and the wire electrode (tool). The part and wire are immersed in a dielectric (electrically nonconduct- ing) fluid which also acts as a coolant and flushes away debris (Kuriakose and Shunmugam, 2004). The movement of wire is controlled numerically to achieve the desired three-dimensional shape and high accuracy of the work piece (Mahapatra and Amar Patnaik, 2006a). Wire EDM, is not the new kid of machining. It was introduced in the late 1960s', and has revolutionized the tool and die, mold, and metalworking industries. It is probably the most exciting and diversified machine tool developed for this industry in the last fifty years, and has numerous advantages to offer. In this process, there is no contact between work piece and electrode, thus materials of any hardness can be cut as long as they can conduct electricity (Kuriakose and Shunmugam, 2004). Whereas the wire does not touch the workpiece, so there is no physical pressure imparted on the workpiece and amount of clamping pressure required to hold the workpiece is minimal. Al- though electrical conductivity is an important factor in this type of machining, some techniques can be use to increase the effi- ciency in machining of low electrical conductive materials (Ko-zak et al. (2004)) .The Spark Theory on a wire EDM is basically the same as that of the vertical EDM process. Many sparks can be observed at one time. This is because actual discharges can oc- cur more than one hundred thousand times per second. The heat of each electrical spark, estimated at around 15,000° to 21,000° Fahrenheit. This process has been widely used in aerospace, nu-clear and automotive industries, to machine precise, complex and irregular shapes in various difficult-to-machine electrically con- ductive materials (Jain, V.K.,(2005), CunShan X.,(2012), Ben-edict, G.F.(1987)). Recently, WEDM process is also being used to machine a wide variety of miniature and micro-parts in met- als, alloys, sintered materials, cemented carbides, ceramics and silicon (Mukherjee,R., et al.(2012)). These characteristics makes WEDM a process which has remained as a competitive and eco-nomical machining option fulfilling the demanding machining requirements imposed by the short product development cycles and the growing cost pressures (Ho, K.H. et al.(2004), Jameson, E.C.(2001)).

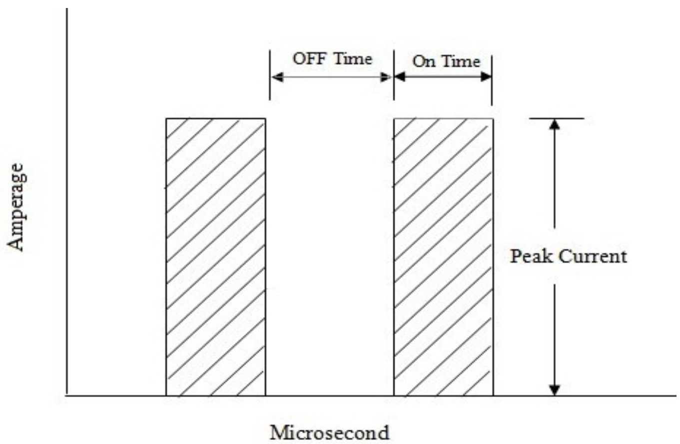
2.Discusson

2.1 Wire EDM Parameters:

2.1.1 Pulse on time and Pulse off time

Electric discharge machining must occur (ON time) and stop (OFF time) alternately during machining. During the ON time, the voltage is applied to the gap between the workpiece and the electrode (wire), while no voltage is placed during the OFF time. Consequently, electric discharge occurs only for the duration of the ON time. To have a long duration of electric discharge, it may be possible to select the great value for the ON time; however, it may cause a short circuit to occur, resulting in wire breakage. To avoid such trouble, the OFF time must be inserted as it shown in figure 1.

Fig.1. *Pulse on time and off time*



2.1.2 Peak current and gap voltage

The peak current is basically a most important machining parameter in WEDM. It is the amount of power used in WEDM and measures in unit of amperage. During each pulse on-time, the current increases until it reaches a preset level, which is ex- pressed as the peak current. In both die sinking and wire-EDM processes, the maximum amount of amperage is governed by the surface area of the cut. Higher amperage is used in roughing op- erations and in cavities or details with large surface areas.

Gap voltage or open circuit voltage specifies the supply volt- age to be placed on the gap. The greater this value is, the greater the electric discharge energy becomes. However; normally these factors are not independent. In the other words as the gap voltage increase the peak current also automatically increases. In some WEDM machines both of these factors show machining voltage.

2.1.3 Servo voltage and Servo feed rate

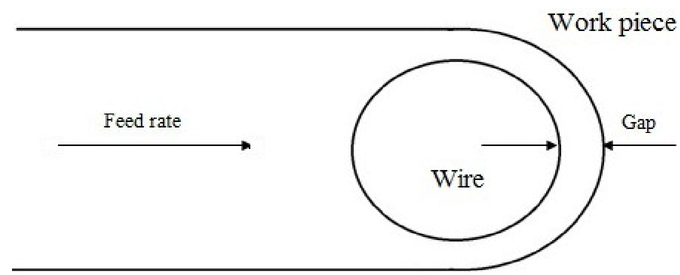
Parameter servo voltage (SV) is used for controlling ad- vances and retracts of the wire. During machining, the mean machining voltage varies depending on the state of the machin- ing between the workpiece and the electrode. SV established the reference voltage for controlling advances and retracts of the wire. If the mean machining voltage is higher than the set voltage level, the wire advances, and if it is lower, the wire retracts (to be precise, the work table advances or retracts instead of wire).

Therefore, a higher the value for SV, the wider the gap be- tween the work piece and the electrode becomes. Higher values for SV also decrease the number of electric sparks, stabilizing electric discharge, although the machining rate is slowed down. When a smaller value is set for SV, the mean gap becomes nar- rower, which leads to an increase in number of electric sparks. It can speed up the machining rate; however, the state of machining at the gap may become unstable, resulting in wire breakage.

Also servo feed rate (SF) specifies the feed rate of the ta- ble during machining. Normally the WEDM machines select this factor automatically with respect to the SV, but this factor also can set manually. In this case machining table has constant speed without regard to the SV.

So both servo voltage and servo feed rate can affect the feed rate as it show in figure2.

Fig.2. *Feed rate and gap size (Roger Kern, 2008)*



2.1.4 Dielectric flow rate

Electro discharge can occur in the air; however, it is not stable and can't be used for rough cut machining. To obtain stable electric discharge, dielectric fluid is required. Within the dielectric fluid, electric discharge machining can be stabilized with efficient cooling and chip removal. The de-ionized water is typically used as a dielectric in wire EDM because it's environmental friendly characteristic. For example due to low thermal conduc- tivity in Titanium alloy material high flushing pressure is absolutely necessary for rough machining, otherwise the short circuit phenomenon will cause to wire breakage. Figure3 show the cut- ting line while machining Titanium alloy (Ti6Al4V) in normal flushing pressure. This figure shows in absence of high flashing pressure cutting line cannot continue more that 1mm.

Fig.3. *Wire broken and small cutting line in Titanium machining due to low flushing pressure*

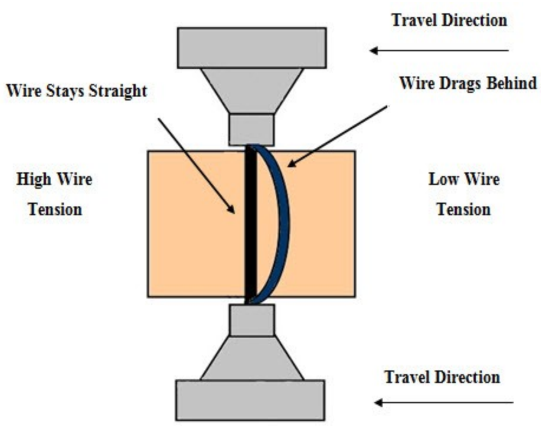
2.1.5 Wire speed or wire feed

Wire speed is another important parameter in WEDM that show the speed of wire in WEDM. As the wire speed increase the wire consumption and in result the cost of machining will increase while low wire speed can cause to wire breakage in high cutting speed.

2.1.6 Wire tension

Wire tension is the factor that can control the tension of wire in WEDM. If the wire tension is high enough the wire stays straight otherwise wire drags behind as it shown in figure 4.

Fig.4. *Relathion between wire drag and wire tension.*



2.2 Wire Type

When wire EDM was first introduced, the main problem was wire material because this material should have lots of properties. The key physical properties of EDM wires include, *Conductivity,* A high conductivity rating is important because, at least theoretically, it means the wire can carry more current, which equates to a 'hotter' spark and increased cutting speed.

Tensile Strength, which indicates the ability of the wire to withstand the wire tension, imposed upon the wire during cutting, in order to make a vertically straight cut.

Elongation, which describes how much the wire "gives" or plastically deforms just before it breaks. *Melting Point,* we would prefer that our wire electrode be somewhat resistant to being melted too quickly by electric sparks. *Straightness*: That can help wire to stay straight. *Flush ability,* the better the flushablity, the faster the wire will cut and the chance of wire breakage will decrease. *Cleanliness,* Wire can be "dirty", due to contamination by residual metal powder left over from the drawing process, drawing lubricant, or paraffin added to the wire by some manufacturers prior to spooling. (Roger Kern, 2007).

2.2.1 Different wire materials

2.2.2 Copper

Was the original material first used in wire EDM. Although its conductivity rating is excellent, its low tensile strength, high melting point and low vapor pressure rating severely limited its potential. Today its practical use is confined to earlier machines with power supplies designed for copper wire.

2.2.3 Brass

Was the first logical alternative to copper when early EDM'ers was looking for better performance? Brass EDM wire is a combination of copper and zinc, typically alloyed in the range of 63–65% Cu and 35–37% Zn. The addition of zinc provides significantly higher tensile strength, a lower melting point and higher vapor pressure rating, which more than offsets the relative losses in conductivity. Brass quickly became the most widely used electrode material for general-purpose wire EDM. It is now commercially available in a wide range of tensile strengths and hardness.

2.2.4 Coated Wires

Since brass wires cannot be efficiently fabricated with any higher concentration of zinc, the logical next step was the development of coated wires, sometimes called plated or "stratified" wire. They typically have a core of brass or copper, for conductivity and tensile strength, and are electroplated with a coating of pure or diffused zinc for enhanced spark formation and flush characteristics. Originally called "speed wire" due to their ability to cut at significantly higher metal removal rates, coated wires are now available in a wide variety of core materials, coating materials, coating depths and tensile strengths, to suit various applications and machine requirements. Although more expensive than brass, coated wires currently represent the optimum choice for top all-around performance. Antar, M.T., *et al.* (2011) presented the work piece productivity and integrity when WED Ming nickel based super alloy and titanium alloy, and it was found that an increase in productivity of about 40% for nickel based super- alloy and about 70% for titanium alloy was possible when replacing standard uncoated brass wire with using Cu core coated wires diffusion annealed under the same operating parameters. In terms of recast layer thickness, better results were achieved using the coated wire for both roughing and trim operation. Actually with machining with coated wire about 25% thinner recast for nickel based super alloy and about 40% thinner for titanium alloy have produced.

In another research Poro´s and Zaborski, (2009) found that increase of discharge time can affect cutting speed and material removal rate significantly by 62% for brass wire electrode and 138% for zinc coated brass wire. Therefore According to differ- ent research the cutting speed of the zinc-coated wire is almost twice of the brass wire because the exterior zinc coating of the electrode has a lower melting temperature than the core mate- rial (brass). Hence, the zinc is overheated and evaporated in the presence of a pulse. The evaporation acts as a heat sink, which means reducing the wire temperature and improving the effectiveness of the WEDM process. Consequently, the cutting speed increases by up to 50% as more intense thermal flows are enabled (Prohaszka *et al.,* 1997). In addition, the coating evaporation increases the gap size and results in better debris removal, which can reduce the surface roughness and the sparking gap (Dauw and Albert, 1992). However, the higher cutting speed of the zinc-coated wire also deteriorates the sparking gap and surface roughness. Composite wires are an advance over zinc-coat- ed as the wire of choice for work pieces. The Composite wires have a plain carbon steel core that is surrounded by a layer of pure copper and coated on the outside with zinc-enriched brass. However for tall work pieces copper clad steel wires have better performance. (Kapoor,J., *et al.,* 2010). In addition Kruth, J.P.,*et al.* (2004) found that composite wires with high tensile core can increase accuracy significantly specially in corner cutting. In terms of resistance to breakage diffusion annealed wires have significant improvement over plain wires.

2.2.5 Fine Wires

Normally the wire diameters are in the range of 0 .006–0.012 inches. High precision work on wire EDM machines, requiring small inside radii, and calls for wire diameters is in the range of 0.001–0.004 inches. Since brass and coated wires are not practical, due to their low load carrying capacity in these sizes, mo- labdanum and tungsten wires are used. However, due to limited conductivity, high melting points and low vapor pressure ratings, they are not suitable for very thick work and tend to cut slowly. Until now, only a few scientific works have been dealing with cutting by W-EDM using wires with a diameter below 50μm. The materials of the wires are tungsten with high tensile strength and melting temperature and brass-coated steel wire. Typical ultra thin wire diameters are 20, 25, 30 and 50μm. These wires can be use to produce micro-parts with wire-EDM. (Klocke, F. *et al*. (2004)).

2.3 Different process responses

2.3.1 Material removal rate and cutting speed:

Lots of research tried to maximize the material removal rate and cutting speed by different approaches. Because these factors can help to increase, economic benefits in WEDM considerably. Almost both of these factors (material removal rate and cutting speed) determine same phenomena which is the machining rate. **MRR value normally obtained by the following equation:**

$$MRR= (W_b - W_a)/(T_m \times p)\ (mm^3/sec) \quad (1)$$

Rajurkar and Wang (1993) analyzed the wire rupture phenomena with a thermal model and experimental investigations. It was found that the material removal rate in WEDM increases initially with the decrease of pulse off time. However, at a very short pulse off time, the gap becomes unstable which leads to a reduction in the machining rate. Singh and Garg (2009) presented the effects of process parameters on material removal rate in WEDM, and it was found that, when pulse on time and peak current increase material removal rate also increase but with the increase of pulse off time and servo voltage, MRR decrease. These results are in agreement with those reported by Po-Huai Yu, *et al.* (2011). Poro´s and Zaborski. (2009) investigate the ef- fects of wire and work piece material on WEDM efficiency, it was found that higher value of thermal conduction, and specific heat capacity of machined material will causes the decrease of efficiency of WEDM. Furthermore, they found that thermal conductivity and specific heat proved to be most significant factors in work piece which can determine MRR and volume of heat af- fected zone. In another work (Mahapatra S. S. and Amar Patnaik, 2006a), an attempt was made to determine the important machining parameters for performance measures like MRR, surface finish and kerf width in the WEDM process. Factors like discharge current, pulse duration, and dielectric flow rate and their interactions have been found to play a significant role in rough cutting operations for maximization of MRR. Shah, A., *et al.* (2011), investigated the effect of work piece thickness on the material removal rate, it was expected that this factor was a significant one while according to this research work piece thickness is not a significant factor for material removal rate. Konda *et al.* (1999) classified the various potential factors affecting the WEDM performance measures into five major cats.Where W and W are weights of work piece material before egories namely the different properties of the work piece material and after machining (g), respectively. T is machining time (sec) and dielectric fluid, machine characteristics, adjustable machine and *p* is the density of work piece material. The cutting speed also computes by dividing the cutting length by the corresponding cutting time. Base on the theory increasing the peak current can increases the energy of each discharge, producing wider and deeper craters that cause to higher material removal rate. Also increasing pulse on time can increase the duration of each discharge that can increase material removal rate. Lots of researches confirm these theories such as, Tosun, N. et al. (2004) presented an investigation on the optimization and the effect of machining parameters on the kerf and the MRR. In this work, the level of importance of the machining parameters on the MRR was determined by using ANOVA. It was found that open circuit voltage and pulse duration were the highly effective parameters whereas wire speed and dielectric flushing pressure were less effective factors. According to this research open circuit voltage for controlling the MRR was about six times more important than the second ranking factor (pulse duration). ing parameters, and component geometry. In addition, they ap- plied the design of experiments (DOE) technique to study and optimize the possible effects of variables during process design and development, and validated the experimental results using noise-to-signal (S/N) ratio analysis. There are other important studies that work on material removal rate, such as (Kozak, J. et al. (1994), Spedding, T.A. and Wang, Z.Q. (1997a), Kuang-Yuan Kung & Ko-Ta Chiang (2008), Parashar, V., *et al*. (2012))

2.3.2 Surface Roughness:

Lots of research tried to minimize the surface roughness by different approaches. Base on the theory surface roughness sig- nificantly affected by the pulse on time and peak current and the cutting speed and surface roughness have an inverse relationship .Base on Sarkar *et al*. (2008) investigation surface roughness de- crease as the cutting speed increase. According to different re- search pulse on time is the most significant factor that affects surface roughness. As the pulse on time increases, the surface roughness increases because of "double sparking". In the other words double sparking and localized sparking become more fre- quent as the pulse on time increases. Double sparking produces a poor surface finish. These results are in agreement with those reported by Sarkar *et al*. (2005); Kanlayasiri and Boonmung (2007a and b) and Kumar *et al*. (2012). Sarkar (2005) confirm that pulse on time is the most important parameters that influence on surface roughness followed by peak current for zinc coat- ed wire .Kanlayasiri and Boonmung (2007a and b) found that pulse on time and peak current have significant effect on surface roughness and as these variable increase the surface roughness become larger. Kumar et al. (2012) also confirm that larger pulse on time and peak current will cause to double sparking which in- crease surface roughness value. Tosun, *et al*. (2003) investigated the effects of the cutting parameters on size of erosion craters (diameter and depth) on wire electrode. An investigation of wire electrode craters is crucial for the understanding of wire rupture, kerf size, and surface roughness of the workpiece. Larger sizes of craters on the wire increase the risk of wire rupture and also result in poor workpiece surface quality and machining accuracy. It is found that increasing the pulse duration, open circuit volt- age, and wire speed increases the crater size, whereas increasing the dielectric flushing pressure decreases the crater size. Rao,P.,S. *et al.* (2011) had stated their effort to optimize surface roughness and it was found that, the parameters like peak current and pulse on time are most significant. Wire tension and servo voltage are significant and pulse off time; flushing pressure and wire speed are less significant factors that affect surface rough- ness.

This result is in the agreement with Vamsi et al. (2010) and Kumar, et al., (2012) investigation. Hasçalýk, A. and Çaydas,U.,(2004) ,investigate the effects of different param- eters on surface roughness .It was reveals that the surface rough- ness increased when the pulse duration and open circuit voltage were increased. It appears that the surface roughness primarily depends on these parameters, dielectric fluid pressure and wire speed not seeming to have much of influence.

Mahapatra and Patnaik (2006b) studied the effects of six factor include, discharge current, pulse duration, pulse frequen- cy, wire speed, wire tension and dielectric flow rate on surface roughness and material removal rate and it was found that fac- tors like discharge current, pulse duration , dielectric flow rate and their interactions play significant role in surface roughness and material removal rate. Tosun et al. (2004) investigated the effect of the pulse dura- tion, open circuit voltage, wire speed and dielectric flushing pres- sure on the WEDMed work piece surface roughness. It was found that the increasing pulse duration, open circuit voltage and wire speed increases with the surface roughness, whereas the increasing dielectric fluid pressure decreases the surface roughness.

There are other important studies that work on surface rough- ness, such as (Spedding, T.A. and Wang, Z.Q.(1997b) ,Liao Y.S. et al. (2004), Yan, M.T. and Lai, Y. P. (2007), Han,F., et al. (2007a and b) Bamberga , E. and Rakwal, D.,(2008), Choi,K. *et al.* (2008), Aspinwall, D.K. et al. (2008), Nishikawa, M. and Kunieda, M.(2009))

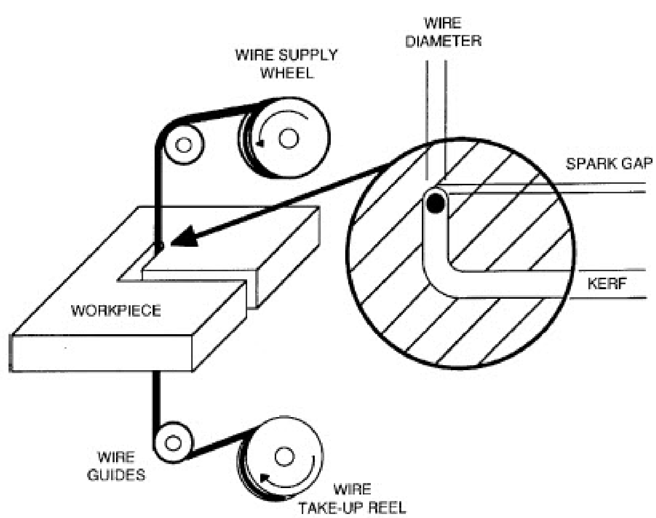
2.3.3 Kerf width and Sparking Gap

Kerf width and sparking gap investigate the same phenom- ena as it shown in figure 5, and it is the measure of the amount of the material that is wasted during machining. It can determine the dimensional accuracy of the finishing part and the internal corner radius of the product in WEDM operations are also limited by this factor (Parashar .et.al, 2010).

Following equation normally use to determine the Sparking gap value:

Sparking gap (mm) = (average of kerf width-diameter of wire)/2 (2)

Fig.5. *Details of Sparking Gap (Scott, 1991)*



There are some conflict reports about pulse off time dura- tion, peak current and dielectric flushing pressure for their influ- ence on kerf width. [a]

Parashar *et.al* (2010) investigate the effects of WEDM pa- rameters on kerf width while machining Stainless steel, it was found that pulse on time and dielectric flushing pressure are the most significant factors, while gap voltage, pulse off time and wire feed are the less significant factor on the kerf width. Tosun, N. *et al*. (2004) presented an investigation on the level of impor- tance of the machining parameters on the kerf width by using ANOVA. It was found that open circuit voltage and pulse dura- tion were the highly effective parameters whereas wire speed and dielectric flushing pressure were less effective factors. According to this research open circuit voltage for controlling the kerf width was about three times more important than the second ranking factor (pulse duration). Swain,A.K., *et al.* (2012) also studied the kerf width and it was found that just gap voltage is the significant factor that affect kerf width and pulse on time and pulse off time are insignificant.

2.3.4 Wire Wear Ratio

Some researches tried to minimize the wire wear ratio by different approaches. Because this factor can help to decrease the wire rupture phenomena considerably.

Wire wear ratio (WWR) value normally obtained by the following equation:

WWR= WWL/IWW (3)

Where WWL is the weight loss of wire after machining and IWW is the initial wire weight. Tosun and Cogun, C., (2003) investigated the effects of different wire EDM parameters on wire wear ratio and it was found experimentally that the increasing pulse duration and open circuit voltage increase the WWR whereas the increasing wire speed and dielectric fluid pressure decrease it. In addition it was found that the high WWR is all. In case of orthogonal corners, the solution to this problem is pretty simple and straight forward which is over travel method however things get complicated when cutting is desired along a curve. (Sinha, S. K., (2010))

Puri, A.B. and Bhattacharyya, B. (2003) investigated the ef- fect of different WEDM parameters on wire lag during rough cut and trim cut process. It was found that pulse on time, pulse off time and pulse peak current during rough cutting; and pulse peak voltage, wire tension, servo spark gap set voltage, during trim cutting are the significant factors. There are other important studies that work on WEDM inaccuracy, such as (Hsue, W. J. (1999), Yan, M. T., and Huang, P. H. (2004), Han, F., *et al*. (2007) and Zhang, X. Y. *et al.* (2012))

2.3.6 Surface Integrity

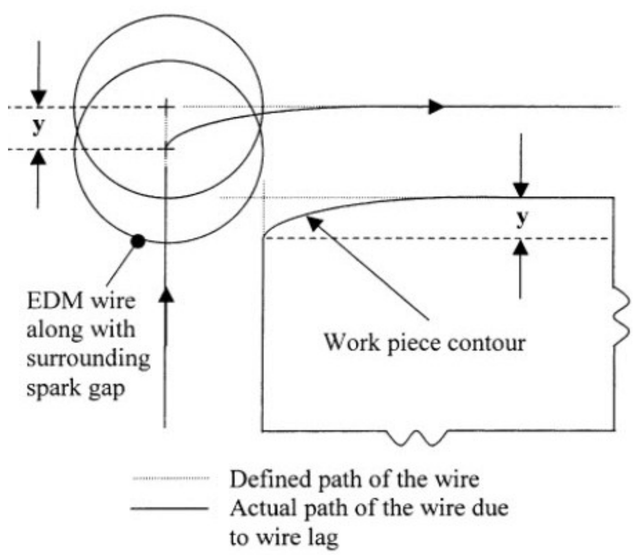
To improve the surface integrity of the WEDM process, fac- tors like the surface roughness, white layer thickness, and surface crack should be considered. High-quality surface roughness can ways accompanied by high MRR and high R value. These repentance the fatigue strength, corrosion and wear resistance of the results are in agree with the other research like Ramakrishnan, R., and Karunamoorthy, L. (2006)

2.3.5 Wire lag and Wire EDM inaccuracy

WEDM is very useful wherever complex geometry with tight tolerances needs to be generated. In this condition geometri- cal inaccuracies are completely unacceptable. Some researches tried to minimize the wire lag because geometrical inaccuracy can caused due to this phenomenon however still there is lack of information about this fact. More research about wire lag can help for improvement of accuracy in contour cutting with wire EDM.

The wire lag phenomena is illustrate in figure 6.

Fig.6. *Wire lag phenomena*



The wires lag normally measure using Profile Projector by measuring the projection image. work piece (Lopez *et al*., 2012).

Kuriakose and Shunmugam, (2004) investigated the effects of different parameters on surface characteristics of Ti6Al4V. It is observed that more uniform surface characteristics are ob- tained with coated wire electrode. Furthermore it was found that pulse off time is the most sensitive parameter that influences the formation of layer consisting of mixture of oxides. With a lower value of pulse of time, a considerable reduction in the formation of oxides can be obtained.

In addition it was reveal that the parameters such as pulse off time, pulse on time, dielectric flushing pressures, wire speed and wire tension are identified as important process parameters of WEDM process, from metallurgical point of view.

Newton, T. R., et *al.* have studied the effect of process pa- rameters on the formation and characteristics of recast layer and in term of recast layer it was found that the peak discharge cur- rent and pulse on time to be the driving factors in determining average recast layer thickness and pulse off time and wire diam- eter did not display a significant effect on average recast layer thickness.

In Puri, A.B. and Bhattacharyya, B. (2005) paper, an attempt has been made to model the white layer depth through response surface methodology (RSM) in a WEDM process comprising a rough cut followed by a trim cut. It was found that the white layer depth increases with increasing pulse on time during the first cut and it decreases with increasing pulse on time during trim cut- ting. In addition with increasing cutting speed in trim cutting, the white layer depth first reduces and then starts increasing. Hassan, M. A *et al.* (2009) studied of the surface integrity of AISI 4140 steel in wire electrical discharge machining and it can be con- cluded that the pulse-on duration has major influence in defining the WEDM surface texture as compared to the peak current.

2.4 Dry and Near-Dry Wire Cut

There is a method in wire EDM which is conducted in a gas atmosphere without using dielectric liquid, this method called dry-WEDM. Recently, new method have introduced in WEDM which called Near-Dry Wire-Cut. In this method the liquid di- electric fluid is replaced by the minimum quantity of liquid with the gas mixture. (Boopathi, S. (2012))

Kunieda and Furudate (2001) conducted studies in dry WEDM. It was found that in dry-WEDM, the vibration of the wire electrode is minimal due to the negligibly small process reaction force. In addition narrower gap distance and no corro- sion for work piece during machining are the other advantages of dry EDM. These characteristics can improve the accuracy and surface quality of workpiece during of finish cutting. The main drawbacks are lower material removal rate compared to conven- tional WEDM and streaks are more likely to be generated in this method. The drawbacks can be resolved by increasing the wire winding speed and decreasing the actual depth of cut. These re- sults are in agreement with other reports. For example Wang, T. et al. (2006 and 2008) Studied finishing cut with Dry-WEDM and it was found that dry-WEDM have some advantage like bet- ter straightness, lower surface roughness and shorter gap length and the main disadvantage of this method was poorer material re- moval rate in compare with conventional method. In conflict with this study Abdulkareem, S., (2011) investigated the effects of machining parameters on surface roughness in dry and wet wire- electrical discharge machining, It was found that wet WEDM gives better surface roughness compared to dry WEDM, it is to be noted that in this study normal machining have studied(not finishing process).

Furthermore, Wang, T. (2006) studied High-speed WEDM (HS-WEDM) in Gas and emulsion liquid and experimental re- sults have shown that WEDM in atmosphere offers a series of advantages such as better straightness accuracy and higher mate- rial removal rate. Figure 7 shows (HS-WEDM) in Gas. There are other important studies that work on dry WEDM, such as (Furu- date C., and Kunieda, M.,(2001),Wang, T., et al. (2004), Wang, T., et al. (2008), Wang, T., et al. (2009), Wang, T., et al. (2012) and Lu, Y. et al. (2012))

Fig.7. *Photo of dry HS-WEDM (Wang,T.,(2011))*

2.5 Process Modelling and Multi Optimization

The modelling of the WEDM process by means of different approach like mathematical techniques has also been applied to effectively relate the large number of process variables to the dif- ferent performance of the process.

2.5.1 Response surface methodology

Response surface methodology or RSM, is a collection of mathematical and statistical technique useful for the modelling and analysis of problems in which responses of interest is influ- ence by several variables and the objective is to optimize these responses. These characteristic makes RSM useful approach for modelling and optimization of wire EDM. In this method if the response is well modelled by a linear function of the independent variables, then the approximating function is the First-order model

$$Y_U = b_0 + b_1X_1 + b_2X_2 + \cdots + b_iX_i + e$$

(4)

If there is curvature in the system, then a polynomial of high- er degree must be used, such as the second order model

$$Y_U = b_0 + \sum_{i=1}^{K} b_i X_i + \sum_{i=1}^{K} b_{ii} X_i^2$$

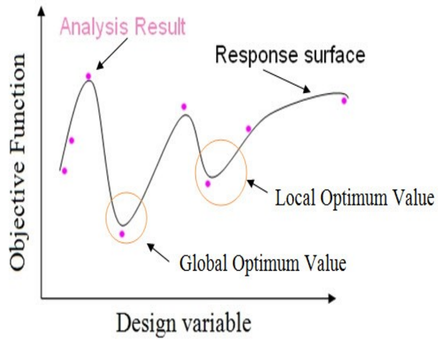
(5)

$$+ \sum_{j>i}^{K} b_{ij} X_i X_j + \cdots + e$$

Where i is the linear coefficient, j is the quadratic coefficient, and β is the regression coefficient, k is the number of studied and optimized factors in the experiment, and e is the random error. Analysis of variance (ANOVA) has taken into account in order to estimate the suitability of the regression model (Montgomery,
2009, Noordin et al. (2004)). In this method the effects of the noise factors have been considered. In addition statistical optimi- zation model can overcome the limitation of classical methods to obtain the optimum process conditions. Furthermore the interac- tions between processes variables are demonstrate. The main disadvantage of this method is the obtained optimum value can be a local optimum value as it shows in figure 7.In figure 7 the goal is minimization of the response. Furthermore this method is quite expensive because lots of experiment needs to be done. For instance if eight factor have considered two to power eight experiment needs to be done in full factorial design(=256) , even if we use half factorial design the number of experiments become
128 which is
still high.

Lots of authors tried to model this process using the Tagu- chi method and response surface methodology approach. Like Hewidy, M.S. et al. (2005), Puri, A.B., Bhattacharyya, B., (2005), Kung, K.Y. and Chiang, K.T. (2008) , Sarkar, S., *et al*. (2008). Ghodsiyeh et al.(2012a,b,c and d), Kumar,A., *et al*. (2012) and Datta, S., Mahapatra S. S., (2010) which utilized response surface methodology coupled with grey-Taguchi technique.

Fig. 8. *Response surface methodology optimization*



2.5.2 Orthogonal array (OA)

This Taguchi method is very useful for modelling and un- derstanding the WEDM process. This Taguchi method allows for the analysis of many different parameters without carry out high amount of experimentation. This characteristic makes OA useful approach for modelling of wire EDM due to large number of pa- rameters in this process. The main disadvantage of this method is that the results obtained are only relative and do not exactly indicate what parameter has the highest effect on the perfor- mance characteristic value. Also, since orthogonal arrays do not test all variable combinations, cannot indicate the significance of different factor interaction which is quit important in WEDM. Lots of authors tried to model this process using this method. Like Anand, K. N., (1996), Huang, J.T *et al.*(1999), Puri, A.B., Bhattacharyya, B., (2003), Kuriakose, S. and Shunmugam, M.S.,(2004), Tosun, N. *et al.*(2004), Wang,C.C., et al. (2009), Vamsi K. P. *et al.*(2010), Parashar, *et al.*(2010) ,Rao, P.S., *et al.* (2011), Kuruvila, N. and Ravindra, H. V. (2011), Satishkumar, D. *et al.*(2011).

2.5.3 Non-Traditional Optimization Algorithms

From early 1960s, various mathematical techniques were de- veloped copying different phenomena of the nature. The attitude of the engineers is that they can learn and know from the nature. Engineers follow natural rules, such as in artificial neural net- work, the study of neurons is involved, and in genetic algorithm, the laws of genetics are transformed to be used as an optimiza- tion tool. These algorithms are very useful for optimization of the process which involves lots of parameters like WEDM. Some- times result suggested by these algorithms cannot be achieved in reality; due to absence of the optimal parameter combination in the machine this could be the main disadvantage of this method. (Mahapatra and Patnaik (2006a)). The rationale behind the use of these algorithms is the capability of these algorithms to find the global optimal parameters whereas the traditional optimization techniques normally tend to be trapped at local optima.(Mahapa- tra , S.S., Amar Patnaik, (2006c)). Some authors tried to optimize WEDM by this method like, Kuriakose, S., Shunmugam,(2005), Jeyapaul, R. *et al.* (2006), Mahapatra and Patnaik (2006c), Debabrata *et al.*(2007),Kuruvila, N. and Ravindra, H. V. (2011).

Mukherjee, R. (2012), compared the performance of differ- ent optimization algorithms on optimizing WEDM process. In this article six non-traditional optimization algorithms have com- pared, including; genetic algorithm, particle swarm optimization, sheep flock algorithm, ant colony optimization, artificial bee colony and biogeography-based optimization for single and mul- ti-objective optimization of WEDM process. It was found that although all these six algorithms have high potential in achiev- ing the optimal parameter settings, but the biogeography-based algorithm outperforms the others with respect to optimization performance, quick convergence and dispersion of the optimal solutions from their mean.

There are some researches that used traditional approach for modelling WEDM like Tarng, Y.S., (1995) which utilized feed forward neural network to model and simulated annealing (SA) algorithm is then applied to the neural network for solv- ing the optimal cutting parameters problem. Other one is Lin, J.L. *et al.* (2000) which used Taguchi method with fuzzy logic for modelling and optimization. In addition, Huang, J. T. and Liao Y. S (2003) studied Wire-EDM based on Grey relational and statistical analyses. Furthermore Kuriakose et al. (2003) used data mining approach and C4.5 algorithm to model this process. Moreover Yuan et al. (2009) used Incorporating prior model into Gaussian processes regression for WEDM process modelling . Also Çaydas, U., *et al.* (2009) used neuro-fuzzy inference system (ANFIS) to model this process. Besides Chen, H.C. (2007) uti- lized a neural network integrated simulated annealing approach for optimizing WEDM.

3. Concluding remarks

(WEDM) is an advanced thermal machining process capa- ble of accurately machining parts with complicated shapes, es- pecially for the parts that are very difficult to be machined by traditional machining processes. It has been commonly applied for the machining and micro-machining of parts with intricate shapes and varying hardness requiring high profile accuracy and tight dimensional tolerances. Optimisation of the WEDM pro- cess parameters is essential because WEDM is an expensive and widely used process. The ultimate goal of the WEDM process is to achieve an accurate and efficient machining operation. Several researchers have studied methods to improve the surface quality and increase the material removal rate of the WEDM process. However, the problem of selecting the cutting parameters in the WEDM process is not fully solved, even though the most up-to- date CNC-WEDM machines are presently available. Still there is lack of information about different WEDM wire types. Hence more research should be done about comparing different wiretypes on different responses. Furthermore there is not enough information about WEDM inaccuracies. More research can im- prove accuracy during WEDM machining specially in contour cutting. In addition it seems that still there is lack of information about dry and near dry-WEDM. Moreover using optimization algorithms can develop the optimization process significantly while just genetic algorithm widely use for optimization of this process up to now and using other algorithm might enhance op- timization. The WEDM process has to be constantly improved to maintain as a competitive and economical machining opera- tion in the modern tool room manufacturing industries. Finally it seems that more researches can enhance the capabilities of WEDM process significantly to improve the machining produc- tivity, accuracy and efficiency.

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