REVIEW ON PROCESS PARAMETRIC OPTIMIZATION OF WIRE ELECTRIC DISCHARGE MACHINING

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Abstract

Wire electrical discharge machining (WEDM) one of the most used non-traditional machining process for machining difficult to machine materials and can produce intricate shapes with high degree of accuracy and surface finish. WEDM has been emerging from making tools and dies to the best alternative of producing micro scale parts. There are certain limitations which need special attention like wire lag phenomenon and geometrical inaccuracy caused due to wire lag phenomenon. Many researchers have made an attempt to minimize the geometrical inaccuracy. This literature review mainly focused on machining of corner radii, taper cutting and geometrical inaccuracy caused by the WEDM. This paper reports on the various research trends to visualize the effect of various process parameters like pulse duration, gap voltage and wire materials on the process responses namely material removal rate (MRR), surface roughness (R_a), Kerf width and surface integrity factor.

Key words: WEDM, voltage, pulse duration, wire material, surface roughness, MRR, kerf width.

I. INTRODUCTION

Wire Electric discharge machining (WEDM) also known as wire cut EDM is a non-traditional machining process which is mostly used in tool and dies industry, aerospace, surgical, automotive, nuclear industries [1]. The WEDM process plays a predominant role in tool making and dies manufacturing sectors since it has its capability to cut complex and intricate shapes in electrically conducting materials with great accuracy and surface finish [2].Wire EDM was introduced in the late 1960s and has revolutionized the tool and die, mould and metal working industries. The first commercially available numerically controlled (NC) wire cut EDM was built by USSR in 1967. David H. Dulebohn's and his group developed the machines that could able to follow the Andrew engineering companies master line drawn for milling and grinding machines [3]. Master drawings were later produce by computer numerically controlled (CNC) plotters for greater precision and accuracy. A wire cut EDM machine using CNC plotters and optical line follower technique was produced in 1974 [4]. In WEDM a thin single strand metallic wire usually brass is used as a tool electrode and is fed continuously through the work piece submerged in a tank of dielectric fluid usually deionized water [5]. The wire that is continuously fed through the work piece is held between the upper and the lower diamond guides. The guides usually CNC controlled move in x-y plane but in most of the machines the upper guide can also move independently in the z-u-v axis giving rise to the ability to cut tapered an transitioning shapes. This allows the wire cut EDM to be programmed to cut intricate and delicate shapes. The cutting width is greater than the width of the wire because sparking occurs from the side of the wire to the work piece causing erosion [5]. Wire cut EDM is commonly used when low residual stresses are desired because it does not require high cutting forces for material removal. If the energy/power per pulse is relatively low (finishing operations) little changes is expected to occur in mechanical properties of the material. During WEDM, the formed thermal cycle causes recast layer formation and thermal stress on the work piece and this could causes dimensional inaccuracy [6]. WEDM process is applicable on any electrically conductive metals (e.g. steel, graphite, titanium, carbide, polycrystalline diamond and ceramics) irrespective of their hardness so it has vast application in different industries (e.g. medicine, electronics and the automotive industry) [7]. Beside this there are some limitations in WEDM like limited cutting speed because of danger of wire rupture and inaccuracy with machining of corner and small radii portion of the work piece [8].

This paper reviews the research trends in WEDM on different process parameters including pulse on time, pulse off time, gap voltage, servo voltage, dielectric flow rate, wire speed an wire tension on different process responses like material removal rate, surface roughness, kerf width, wire lag and dimensional accuracy and surface integrity fact.

II. WEDM WORKING PRINCIPLE

WEDM is a thermo-electric process in which material removal takes place by a series of discrete electric sparks that occurs between the tool electrode (wire) and the work piece. Dielectric liquid is flushed from the gap between the tool electrode (wire) and the work piece which acts as a coolant and flushes away the remaining debris away. The spark theory in 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 occur more than one hundred thousand times per second. The volume of the metal removal during this short period of sparks discharges depends upon desired cutting speed and surface finish required. The heat of the each electrical sparks estimated at around 15000° to 21000° Fahrenheit erodes away a tiny bit of material that is vaporized an melted from the work piece. These particles (chips) are flushed away from the cut with the stream of deionised water [4, 5].

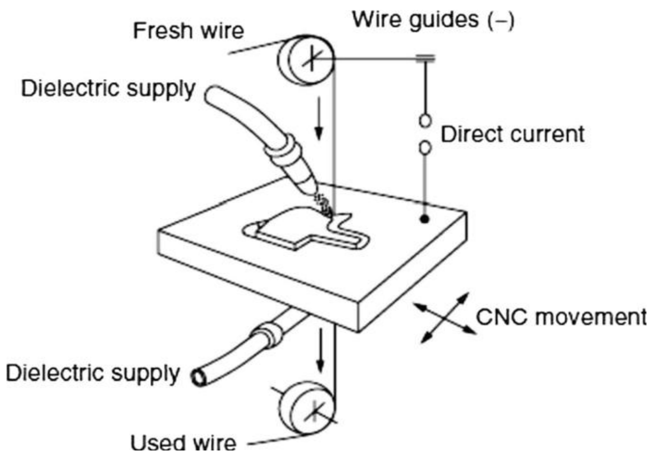

Fig.1. Schematic diagram of WEDM

III. WEDM PROCESS PARAMETERS

A. Pulse duration:

Electrical discharges must occur and stop simultaneously during machining. The pulse on time is referred as T_{on} and pulse off time is referred as T_{off} and is generally measured in μs. In pulse on time the voltage is applied to the gap between the tool electrode and the work piece thereby producing discharges and during off time no voltage is applied. Rao et al. [9] presented the parametric analysis of wire EDM on aluminium alloy. They found that T_{on}, peak current and spark gap voltage shows a significant effect on MRR and surface roughness. Durairaj et al. [10] performed a comprehensive study on WEDM. They used stainless steel, brass wire (0.25 mm ϕ) and distilled water as workpiece, tool and dielectric fluid respectively. The ANOVA of Taguchi optimization method and grey relational analysis shows that T_{on} has a major influence on surface roughness and kerf width. Tilekar et al. [11] investigated the effect of process parameters on surface roughness and kerf width of aluminium and mild steel using single objective Taguchi method for process parameter optimization. The ANOVA shows that T_{on} has major influence on surface roughness in case of aluminium and input current has major influence in case of mild steel. The analysis of variance also resulted that in case of kerf width wire feed rate and Ton has significant effect on aluminium and mild steel respectively. Bobbili et al. [12] investigated the effects different machining variables such as T_{on}, T_{off}, peak current and spark voltage on the performance characteristics such as MRR, surface roughness (R_a) and gap current. In this investigation multi response optimization technique based on Taguchi method coupled with Grey relational analysis on ballistic grade aluminium alloy is used. Results confirmed that T_{on}, IP, and SV are significant variables to Grey relational grade. Singh and Garg [13] investigated the effect of various process parameters of WEDM like, T_{on}, T_{off}, gap voltage, peak current, wire feed and wire tension on material removal rate of hot die steel (H-11) using one variable at a time approach. They found that material removal rate directly increases with the increase in pulse on time and peak current while decreases with the increase in pulse off time and servo voltage. Hascalyk and Cydas [14] presented an experimental investigation of the machining characteristics of AISI D5 tool steel in WEDM process. In experiments parameter such as open circuit voltage, pulse duration, wire speed and dielectric fluid pressure were varied to explore the effects on surface roughness and metallurgical structure. Optical and scanning microscopy, surface roughness and micro hardness tests were conducted to study the characteristics of the machined specimens. They found that the surface roughness varying proportionately with pulse duration and open circuit voltage. Kuruvila and Ravindra presented [15] their study on determining the parametric influence and optimum process parameters using Taguchi technique and a Genetic algorithm on hot die steel. The results reveal that among these machining parameters, smaller T_{off} gives the overall good performance. Higher T_{on} is used for attaining higher MRR and smaller current is suggested for better surface finish/texture control, medium range for error control and high value for MRR.

B. Gap voltage:

Gap voltage or open circuit voltage specifies the supply voltage to be placed on the gap. Prakash et al. [16] investigated the effect of process parameters like gap voltage, T_{on}, T_{off}, wire feed, percentage of reinforcement on the responses material removal rate and surface roughness while machining aluminium alloy (A413)/flash/boron carbides using WEDM and they found that gap voltage is the most influential parameters affecting the MRR an surface roughness. Sivaprakasam et al. [17] investigated the influence of the three different input parameters (e.g. voltage, capacitance and feed rate) on material removal rate, kerf width, and surface roughness using response surface methodology with central composite design the experiments were carried out on titanium alloy (Ti-6Al-4V). ANOVA test results reveals that voltage and feed rate, interaction of voltage and capacitance and pure quadratic effect of all three machining parameters have significant effect on material removal rate. Vijayaraj and Gowri [18] tried to develop an appropriate machining strategy for micro-WEDM of aluminium alloy using zinc coated wire of 70μm diameter. From ANOVA they found that electric capacitance is the main factor affecting the surface finish and the other factor affecting the surface finish are voltage, wire speed, wire tension and feed respectively. Sharma et al. [19] investigated the effects of process parameters on surface roughness, material removal rate for WEDM using HSLA as a work piece and they observed that material removal and surface finish decreases with the increase in T_{off} and servo voltage. Gupta et al. [20] investigated the effects of the process parameters on kerf width for WEDM using HSLA as a work piece. The analysis of results indicated that the spark gap voltage, pulse duration and peak current have a significant effect on kerf width. Singh et al. [21] studied the effects on different parameters of wire EDM like wire feed, pulse off time and servo voltage on EN 8 steel on the dimensional deviation. They found that servo voltage has significant effect on dimensional deviation and then T_{off} and wire feed.

C. Different wire materials:

(i.) *Copper wire:* Being an oldest metal used in WEDM, copper has high electrical conductivity but due its low tensile strength, high melting point and low vapour pressure rating copper wire was replaced by brass wire [22].

(ii.) Brass wire: Brass EDM wire is a combination of copper and zinc, typically alloyed in the range of 63-65% Cu, 35-37% Zn. It is the fact that the addition of zinc improves the cutting ability and speed compared to copper [23]. During machining the zinc contained in the brass wire actually vaporizes, which helps to cool the wire and provides more energy to the work zone. Addition of zinc significantly provides higher tensile strength and vapour pressure rating which offsets the relative loss in the conductivity [24].

(iii.) *Zinc coated brass wire:* Zinc coated brass wires offers a significant increase in cutting speed over a plain brass wire without any damage in any other critical properties [24]. This wire is used for cutting difficult-to-cut materials such as tungsten carbide, polycrystalline diamond and graphite when exceptional surface finish is in demand. Nourbakhsh et al. [25] investigated the effects of different process parameters on cutting speed, wire rupture and surface integrity of wire electro discharge machining of titanium alloy. The Scanning Electron microscopic (SEM) examination of the machined surfaces was performed to understand the effect of different wires on work piece material surface characteristics. Also the influence of zinc-coated brass wire on the performance of WEDM is compared with high speed brass wire. The results reveals that compared with brass wire, zinc coated brass wire results in higher cutting speed and smoother surface finish. Also the SEM photographs proved that uncoated wire produces a surface finish with more cracks, craters and melted drops. Garg et al. [26] presented an experimental investigation for wire EDM of newly developed Al-5%ZrO_2 particulate reinforced metal matrix composite. Experiments were performed to investigate the effects of different input parameters on the process responses spark gap and material removal rate. Comparison of results using different wire electrode has also been presented. The results reveals that the optimum value of maximum material removal rate is more while using diffused wire as compared to brass wire and the optimum value of minimum spark gap is less while using brass wire instead of diffused wire. Antar et al. [27] studied an experimental data for work piece productivity and integrity in WEDM Udimet 720 nickel based super alloys and Ti-6Al-2Sn-4Zr-6Mo titanium alloy using copper coated wires (ZnCu50 and Zn rich brass). The results reveals that productivity can be increased upto 40% for Udimet 720 and 70% for Ti6246 when replaced with uncoated brass wire same operating parameters.

IV. LIMITATIONS OF THE WIRE EDM

Many researchers tried to minimize the wire lag because most of the geometrical inaccuracy is caused by wire lag phenomenon. Several researchers have been of the opinion that the main forces acting along or upon the wire are forces from gas bubbles formed by the plasma of the erosion mechanism, hydraulic forces due to flushing, electrostatic force and electrodynamics force. However, the researchers believe that there is little effect of electro dynamic force on the mechanical behaviour of the wire. Instead, another force acts perpendicular to the wire, which is impact. During every individual spark discharge, the wire experiences an impact, which acts in the reverse direction of the discharge occurrence. Puri et al. [28] investigated the wire lag phenomenon in WEDM and trend of variation of geometrical inaccuracy caused due to wire lag with various types of machining parameters. They found that the significant factors affecting the geometrical inaccuracy due to wire lag are T_{on}, T_{off}, pulse peak current during rough cutting, pulse peak voltage, wire tension, servo spark gap set voltage and constant cutting speed during trim cutting. Zhichen et al. [29] analysed and reduce the geometrical inaccuracy of rough corner cutting first of all the major causes of corner inaccuracy (45◦, 90◦ and 135◦ angle) are analysed in detail. Secondly, an elliptic fitting method is proposed to describe the trajectory of wire electrode centre and the feasibility of model is confirmed by measuring the corner edges of the work piece. They found that the wire deflection and vibration are the main causes of right and obtuse angle corner cutting. Sanchez et al. [30] studied on the corner geometry generated by the successive cuts (roughing and finishing).Errors at different zones of the corner are identified and related to the material removed during each cut. They found that in order to achieve a good fit to the ideal corner geometry limiting cutting speed during the trim must be taken into account the variable excess/lack of material produced by the previous cuts. Firouzabadi et al. [31] investigated on small radius convex and concave corner radii errors and alternate solutions are proposed for the successive cuts (roughing and finishing operations). They concluded that roughing operation is the major stage for corner inaccuracy and curved paths. By controlling the process parameters error can be reduced, it is not possible to eliminate them completely. G. Selvakumar et al. [32] investigated on the responses namely cutting speed, surface roughness and corner inaccuracy during wire EDM of aluminium 5083 alloy. Pulse on time, pulse off time, peak current, wire tension, servo feed setting and corner angle are used as control factors. The results revealed that the geometrical accuracy of the work piece was improved by predicting the dimensional shift and passing the same to the CNC programme as wire offset value. Jangra et al. [33] presented an experimental study on rough and trim cutting operations on wire electric discharge machining (WEDM) using four hard to machine materials namely WC-Co composite, HCHCr steel alloy, Nimonic-90 and Monel-400. Results revealed that in rough cutting operations machining speed and surface roughness increases with the increase in discharge energy across the electrodes. Results also revealed that trim cutting operation under same machining parameters with appropriate wire offset value surface characteristics can be improved irrespective of the rough cutting operations. Plaza et al. [34] proposed the design of experiments methodology to study the influence of WEDM process variables on the angular accuracy of the taper cutting operations. Two original models for the prediction of angular error in WEDM tapper cutting are presented here. Results revealed that part thickness and the taper angle are the most influencing variables in tapper cutting operations.

V. EFFECT ON DIFFERENT RESPONSES

Lots of researchers have tried to maximize the MRR simultaneously reducing the surface roughness by different approaches. MRR determines the machining rate while surface roughness is a component of surface texture. It is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. There are many different roughness parameters in use but R_a is the most common parameters other common parameters include R_z, R_q, R_v, R_p, and is usually expressed in µm. Garg et al. [35] presented the effect of cutting speed and surface roughness in wire electric discharge machining of Ti-6-2-4-2(HSTR aerospace alloy) considering six control factors, pulse on, pulse off, IP, servo voltage and they found that for cutting speed main effects were T_{on}, T_{off}, IP, servo voltage and surface roughness is effected by the main effects of pulse on time, pulse off time, IP, wire feed and wire tension. Srivastava et al. [36] carried out an experimental study on composite of Al2024 reinforced with SiC to investigate the effects of different process parameters on material removal rate and surface roughness. From the SEM image of the machined samples it was observed that surface finish that of unconventional machining process is better than conventional machining process. They also found that surface finish and MRR varying proportionately with peak current, pulse on time, percentage reinforcement. Kanlayasiri et al. [37] investigated the effects of machining variables such as pulse peak current, T_{on}, T_{off} and wire tension on the surface roughness of DC53 die steel. Analysis of variance (ANOVA) technique was used to find out the significant variables affecting the surface roughness and they found that T_{on} and pulse peak current were the significant variables affecting the surface roughness. They also developed the mathematical model using multiple regression method to formulate the T_{on} and peak current to surface roughness. The developed model showed high prediction accuracy within the experimental region. Kerf width (width of the cut) is the measure of amount of material that is wasted during machining. It affects the dimensional accuracy of the finished part.Gupta et al. [38] investigated the effects of process parameters on kerf width for WEDM using HSLA as work piece. HSLA is used in cars, trucks, cranes, bridges, roller coaster and other structures specially designed to handle large amount of stress. They found that kerf width decreases with the increase in T_{on}. Shichun et al. [39] presented a study on the kerf variations in micro-WEDM which is composed of two main parts breakdown distance and wire vibration amplitude, the mathematical model is developed for wire lateral vibrations in machining process. They came to know that open circuit voltage not only determines the breakdown distance but also affects the wire vibration in the process and it is also demonstrated as a key factor to influence the kerf width in the micro-WEDM process. Tosun et al. [40] investigated the effect on kerf width and material removal rate in WEDM. They found that the open circuit voltage and pulse duration was the main factor influencing the kerf width and the material removal rate. Antar and Soo [41] pointed out that changes of surface metallurgy mostly occur in a very small zone near to the surface. Klocke et al. [42] found that surface integrity can be directly related to fatigue life of the machined part which is the principal factor for designing component's which undergo dynamic loading. Kumar et al. [43] presented an experimental investigation of WEDM of pure titanium microstructure analysis in terms of machining parameters such as T_{on}, T_{off}, peak current and spark gap using energy-dispersive X-ray, SEM and X-ray diffraction techniques (XRD). The surface integrity was analysed using SEM. It was observed that T_{on}, T_{off} and peak current deteriorate the integrity of machined samples, which produces the deeper and wider overlapping craters, pockmarks, globules of debris and micro-cracks. Aspinwall et al. [44] investigated on surface integrity after machining Ti-6Al-4V an inconel 718. Roughing and finishing (multiple trim cuts) strategies were employed on two high specification machines with pulse generator designed to provide minimum surface integrity damage. They found that the average recast thickness was <11µm, several trim passes showing no apparent recast or damage. Similarly no significant change in work piece micro hardness variation was observed with cracking confined to the recast layer. Bobilli et al. [45] investigated on multi response optimization technique based on Taguchi method coupled with grey relational analysis is for wire-EDM operations on ballistic grade aluminium alloy for armor applications. Results confirmed that T_{on}, peak current and servo voltage are significant variables to grey relational grade. Mathematical models were developed using response surface methodology for MRR, R_a an IG to determine the relation between machine variables and performance measures. Chalisgaonkar and Kumar [46] studied on WEDM under varying process parameters such as T_{on}, T_{off}, peak current, wire feed, wire tension, servo voltage using pure titanium as a work material. Experiments were planned under Taguchi L_{27} orthogonal array. Multi response optimizations were performed for cutting speed and surface roughness to determine optimal parameter setting. The results revealed that the optimal process parameters setting obtained for both cutting speed and R_a are such that: T_{on} (108 μs), T_{off} (30 μs), IP (140A), WF (10m/min), WT (9 units) and SV (30V). Mahapatra and Patnaik [47] made an attempt to determine the important machining parameter for performance measures like MRR, SF, and kerf separately in the WEDM process. Taguchi experimental design method is used to determine optimal parameter combination for maximization of material removal rate and minimization of surface finish and kerf width. The results revealed that the significant machining parameters affecting the performance measures are identified as discharge current, pulse duration, pulse frequency, wire speed, wire tension, and dielectric flow. Manna and Bhattacharyya [48] presented the experimental investigation to determine the parameter setting for machining aluminium-reinforced silicon carbide metal matrix composite (Al/SiC-MMC). The Taguchi technique is used to optimize the CNC-wire cut EDM parameters. The results revealed that Open gap voltage and pulse on period are the most significant influencing machining parameters for controlling material removal rate, wire tension and wire feed rate are the most influencing process parameters affecting the surface roughness. Wire tension and spark gap voltage are also the most influencing parameters affecting the kerf width. Huang and Liao [49] investigated the optimal machining parameters setting for maximum material removal rate and minimum surface finish. Experiments were conducted as per Taguchi technique, an L_{18} mixed orthogonal array was used to design the experiments. With both grey relational analysis and statistical analysis it was concluded that table feed rate and T_{on} have the main influence on MRR, T_{on} has the significant influence on the surface roughness and gap width. Bagherian et al. [50] presented a comprehensive experimental study of dry WEDM process while machining Al/SiC metal matrix composites. Experiments were designed based on L27orthogonal array to find the effects of various process parameters on process responses cutting velocity and surface roughness. Results revealed that pulse on time and discharge current are the most significant factors compared to other process parameters.

VI. CONCLUSION

WEDM is an advanced electro thermal machining process capable of machining electrically conductive materials with varying hardness and can produce parts with great accuracy and surface finish. It has been commonly applied for machining and micro machining of parts with intricate shapes requiring profile accuracy and tight tolerances. WEDM is an expensive process therefore optimization of this process is very much required. There are various types of forces which act perpendicular to the wire electrode while machining and this types of vibration cause geometrical inaccuracy, corner radii errorand corner angle error. Several researchers have tried to minimize the geometrical inaccuracy caused due to wire lag. It seems that there is a lack of information about the geometrical inaccuracy and wire lag phenomenon. More researchers must focus on this topic to improve the accuracy and efficiency of WEDM. More researchers must focus their work on different electrode materials.

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Place acknowledgments at the end of the text, before the references.

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