Review of WEDM studies on metal matrix composites

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Abstract. At present, the growing needs and design requirements with significant weight savings as well as high strength-to-weight ratio as compared to conventional materials raised a growing interest towards composite materials. Metal matrix composites (MMCs) are extensively used in fields like aerospace, automobiles and army-defence applications due to their high specific strength, low coefficient of thermal expansion, wear resistance, high durability, excellent physical and mechanical properties. The filler reinforcements like SiC, TiC, Al2O3 improve the stiffness, specific strength, creep properties of MMCs, but the presence of such hard reinforcements makes MMCs difficult to machine through conventional machining processes. Wirecut electrical discharge machining (WEDM) is highly precise thermo electrical process and is considered ideal for machining very hard materials, intricate geometries and tooling. This paper reviews the researches in WEDM of metal matrix composites and the relation between different process parameters like pulse on time, pulse off time, wire feed rate, voltage, wire tension, dielectric flow rate on the machining performances such as material removal rate (MRR), Kerf width and surface roughness (SR). The future trends in WEDM researches were also recommended in this paper.

1. Introduction

Metal matrix composites are materials with two or more constituent parts, one of them being a metal composition called matrix and the other hard materials like ceramic or organic compound known as reinforcement. MMC’s are obtained by dispersing the reinforcing material into the metal matrix. In structural applications, lighter metal such as aluminium, magnesium, or titanium are employed for imparting amenable medium for the reinforcement. In high temperature applications, cobalt and cobalt–nickel alloy matrices are common. Reinforcement generally improves rigidity and greatly obstructs crack propagation. The composite’s strength usually depends on the diameter of the particles, the inter-particle spacing and the volume fraction of the reinforcement. Some of the commonly used reinforcements are Al2O3, SiC, TiC, B4C, etc., impart high hardness to the matrix in the composites. The presence of these hard and abrasive reinforcements makes the production of complex shapes difficult through traditional machining processes.

Among different unconventional process WEDM plays a prominent role in different manufacturing industries and it is mostly used in the aerospace, defence and army applications. WEDM is a typical thermal machining techniquethat can accurately machine parts with varying hardness and intricate shapes. It is a spark erosion process which can able to produce complex 2D and 3D work pieces in which the wire does not touch the work piece resulting in reduction of the physical pressure imparted on the work piece. When compared with the other conventional machining processes like the grinding...
and milling cutters where serious tool wear occurs due the presence of reinforcement, WEDM is considered as an effective non-contact machining process. While other non-conventional methods like abrasive jet, electron beam machining and laser cutting are restricted to linear cutting, WEDM exhibits advanced capability for cutting complex 3D shapes with high accuracy.

Despite of these advantages, WEDM process is limited in terms of material removal rate because of poor surface finish and danger of wire breakage. This calls for the study of WEDM process parameters to obtain maximum material removal rate with better surface finish. This paper primarily reviews the major WEDM research activities on MMCs which include the different process parameters such as pulse on time, pulse off time, servo voltage, peak current, wire feed rate, dielectric flow rate and wire speed. These process parameters have a major effect on the performance characteristics such as material removal rate, surface finish, kerf width, dimensional deviation and wire wear rate.

2. Working principle of WEDM

Wire cut electrical discharge machining is a thermal based process in which spark is generated between work piece and tool material. Here the work piece and electrode are placed in a dielectric medium which are connected through electronic circuit and generates DC pulses from the wire to the work piece. In this WEDM process material removal takes places through continuous repetition of spark discharge between the tool and work piece. By using servo-controlled mechanism the gap of 0.025 – 0.075 is continuously maintained between the tool and work piece. In this process de ionized water is used as coolant. This de ionized water continuously passes between the work piece and the wire. In this process wire feed should be continuous.

Figure 1. Schematic diagram of WEDM process

During this process spark is generated which generate huge amount of heat. This much amount of heat is sufficient to melt the material along with the work piece. This results in removing of molten mass from the work piece. Then the tool profile is transferred to the work piece. Figure 1 shows the schematic diagram of WEDM process. Usually, WEDM is used for machining hard materials such as High-Speed Steel, hardened steel, Metal Matrix Composites etc. WEDM enables machining of different types such as blind, inclined, micro holes and complicated profiles. This is the only machining process that can machine hard materials with high accuracy and good surface finish.

3. WEDM process parameters

The performance WEDM is observed in terms of output responses like material removal rate, kerf width, surface roughness, etc. These responses were mainly affected by input process parameters such
as pulse on time, pulse off time, voltage, feed rate, dielectric flow rate, wire speed etc. Figure 2 shows the cause and effect diagram for various performance measures in WEDM process.

**Figure 2.** Cause and effect diagram for WEDM process

*Pulse on time and pulse off time:* In wire cut electrical discharge machining, the material removal occurs and stops alternately during pulse on time and pulse off time. During pulse on time, the voltage is applied to the gap between the electrode and the inserted work piece, resulting in electric discharges between them. If there is a long duration of electrical discharge then the greatest value of pulse on time is taken, to avoid wire breakage pulse off time is inserted between the pulse on time.

*Peak Current:* Peak current is the amount of power utilized in WEDM process. During pulse on time, the current goes on increasing till it reaches the pre-set level which is expressed as peak current. In case of roughing operations and large surface areas, higher peak current values are used.

*Servo Voltage and feed rate:* The movement of wire is controlled using servo voltage while the table is controlled by the servo feed rate. If the value of servo voltage is higher, the gap between the work piece and electrode is higher. In the case of higher servo voltage, the electric sparks and machining rate is low. Whereas lower servo voltage results electric sparks and machining rate is high.

*Dielectric flow rate:* Dielectric fluid is essential for obtaining stable electric discharge as a result of efficient cooling and chip removal. In WEDM process, de-ionized water is used as dielectric fluid because it is environmental friendly nature. High flushing pressure will result in better material removal rate.

*Wire tension and speed:* The wire remains straight if the wire tension high, otherwise it may get bend and results in breakage. Increased wire speed increases the wire consumption while wire breakage occurs with low wire speed.
4. WEDM performance characteristics

4.1. Effect of process parameters on WEDM Performances

The performance characteristics of WEDM such as materials removal rate, surface roughness, kerf width, etc., were influenced by various parameters such as pulse on time, pulse off time, current, voltage and dielectric flushing pressure. Scott et al. [1] give a methodology to study optimal combination of parameters such as pulse duration, pulse frequency, wire speed and dielectric flow rate in WEDM of D2 tool steel. In this process, the methods used are enumeration and dynamic programming. From the result they conclude that pulse duration and pulse frequency are significant factors for material removal rate and surface finish, whereas dielectric flow rate and wire tension are insignificant. Dhar et al. [2] founded to study the effects of machining parameters like pulse on time and gap voltage on the response parameters like material removal rate, tool wear rate and radial over cut in WEDM of Al4 Cu-6Si alloy reinforced with 10% SiC particles. From the results, they developed the mathematical model to organize bonding among the parameters. The material removal rate and surface roughness were increased by increasing the current [3]. The regulation in pulse off time based on the sparking frequency affects the material removal rate. But, the sudden increase in sparking frequency leads to wire breakage [4].

The other parameters relating the electrode wire and workpiece also play a vital role in WEDM process. The open circuit voltage increases when there is an increase in wire speed and dielectric fluid pressure [5]. However, wire feed rate and wire tension had no effect on MRR. MRR found to be increased when there is an increase in pulse on time and get decreases with the increasing pulse off time [6]. The materials which are used for fabrication of wire electrodes should be characterized by high melting and evaporation temperatures. Metals like Mg, alkaline metals are easily machined by using of copper, brass and steel wires which can increase cutting efficiency of WEDM [7]. The size of craters formed and the MRR are increased with increase in relative speed. Also, high relative speed can produce higher melting efficiencies [8]. Some of properties like electrode wear ratio and surface roughness were better on the conductive materials than insulating materials while MRR is better in insulating materials than conductive materials.

4.2. WEDM on metal matrix composites

WEDM is considered to be one of the ideal methods for machining metal matrix composites with hard reinforcements and varying hardness. Patel and Brahmankar [9] carried out experimental studies on WEDM of the aluminium metal matrix reinforced with alumina particle and found that increased percentage of ceramic particulates reinforcement in the MMC decreases MRR. The pulse on-time and thermo-physical properties like melting point temperature, thermal diffusivity and coefficient of thermal expansion are important parameters influencing MRR. Ahamed et al. [10] investigated EDM performances of hybrid Al-SiC composites in addition with B4C and glass reinforcements. The presence of these ceramic particulate reinforcements acts as a barrier to the machining of hybrid Al-SiCp Composites. It is observed the long sparking duration and high dielectric flushing pressure are required to remove the tightly packed reinforcement like B4C and SiC. The reinforcements with better wettabili ty result in increased pulse on time and reduced flushing pressure.

Lal et al. [11] investigated the influence of parameters such as discharge period, pulse interval, wire drum speed on kerf width during WEDM of Al7075/SiC/Al2O3 hybrid composite obtained by the inert gas assisted electromagnetic stir casting process. The discharge current has the most significant effect on kerf width followed discharge duration and wire drum speed, while the effect of pulse duration is insignificant on kerf width. Rozenek et al [12] studied the WEDM characteristics of metal matrix composites such as AlSi7Mg/SiC and AlSi7Mg/Al2O3. They found that the cutting speed while machining AlSi7Mg/SiC and AlSi7Mg/Al2O3 through WEDM is 3 times and 6.5 times slower than the aluminium alloy respectively. The wire feed rate during WEDM of these composites also depends on the type of reinforcement used. Material removal rate in WEDM and EDM of MMCs is lower than that of the alloy due to decreased the electrical conductivity and thermal conductivity. Yan et al [4] indicated that the surface roughness, kerf width and cutting speed during WEDM of alumina reinforced 6061 aluminium matrix composites were significantly depend on volume fraction of
reinforced alumina particles. It is also revealed from the test results that a slight wire tension, a larger dielectric flushing rate and a high wire speed are important to avoid wire breakage.

4.3. Process modelling and optimization.

The works done until now have not been associated with any modelling and optimization techniques. Therefore, Patil and Brahankar [9] developed two different models of MRR in WEDM of MMCs. The first model is an empirical model employing response surface methodology (RSM) and the second model was a semi-empirical using dimensional analysis based on physical, electrical and thermal properties of the work material in addition to the machining parameters such as pulse-on time and voltage. The predictability of the both the models found to be more than 99%. Liao et al. [13] identified some of machining parameters like voltage, resistance, pulse- generating circuit and capacitance as the significant parameters affecting the surface roughness of WEDM in finishing process with the help of Taguchi quality design, ANOVA and F-test. Rao et al. [14] performed parametric analysis of Wire EDM parameters on surface roughness and material removal rate using Taguchi method. Hybrid genetic algorithm is used to develop linear regression model to optimize the performance measures such as surface roughness and material removal rate simultaneously. The results obtained are in a good agreement with experimental values.

Puri et al. [15] developed mathematical modeling of white layer to correlate the significant input parameters of WEDM with rough cut followed by trim cut through response surface methodology. The second order rotatable central composite design have been used for experimental plan to carry out the investigation employing four variable such as pulse on time in rough cutting, pulse on time in trim cutting, offset and cutting speed with five levels. Iqbal et al. [16] used response surface methodology to investigate the relationships and parametric interactions between the performance measures such as MRR, electrode wear rate and surface roughness in EDM milling. The model coefficients of the factors were estimated using central composite experimental design and ANOVA is performed to obtain significant coefficients.

Datta et al. [17] derived the quadratic mathematical models to represent parametric influence on the process responses of WEDM such as material removal rate, surface roughness and kerf. Response surface method is used for prediction of process responses with different combinations of factor settings. Predicted data obtained by Taguchi’s L27 orthogonal array is used for achieving an optimal combination of parameters to attain maximum MRR, minimum surface roughness and maximum dimensional accuracy. This multi-objective criterion is convert into an equivalent single objective function using grey relational analysis. Overall grey relational grade has been optimized using Taguchi technique and verified through confirmatory test. Kumar et al. [18] investigated WEDM of pure titanium by modelling the response such as surface roughness, machining rate, dimensional accuracy and wire wear ratio using response surface methodology. The experiments were carried by changing the parameters such as pulse on time, pulse off time, gap voltage, peak current, wire tension and feed rate based on Box–Behnken design and the responses were optimized through desirability analysis, while the significance of the model is verified by ANOVA.

Shah et al. [19] optimized the process parameters during WEDM of Inconnel-600 using response surface methodology (RSM). The experimental plan is proposed by Taguchi’s robust design and the experimentation has been carried out using Taguchi’s Mixed L18 orthogonal array. The input parameter such as pulse on time, pulse off time, peak current and wire feed rate were considered for optimizing the response in terms of material removal rate. ANOVA is used to study the significance of the process parameters on the response of WEDM also the response surface model has been developed for the performance characteristic such as MRR. Sharma et al. [20] investigated the effect of parameters such as pulse on time, pulse off time, servo voltage, peak current and wire tension on the responses such as metal removal rate and surface roughness during WEDM of HSLA. The central composite rotatable design (CCRD) is employed in conducting the experiments and response surface methodology is applied in formulating mathematical model to optimize the process parameters.

Lakshmanan et al [21] performed electrical discharge machining of EN 31 tool steel to correlate the process parameters with the responses such as MRR. The performances of the process were modelled using response surface methodology and model adequacy checking is validated using analysis of
variance. Majhi et al [22] presented a hybrid optimization method for the obtaining of the optimal process parameters such as Pulse on time, pulse off time and pulse current for maximizing material removal rate and minimizing surface roughness and tool wear rate. The planned experimental results are applied in the grey relational analysis and the weight of the quality characteristics are obtained through entropy measurement method. The influence of the process parameters on the output responses were predicted by response surface methodology based on the results from optimization.

5. Conclusions
From the above studies on WEDM of metal matrix composites it can be concluded that:

- WEDM is found to be effective and efficient process for the machining of metal matrix composites with varying hardness, intricate shapes and presence of hard reinforcement which can cause serious tool wear when machining through conventional process.
- Most of the studies were carried out mainly on WEDM of tool materials like die steels, hard metals like titanium alloys, MMCs such as aluminium matrix composites reinforced with SiC, Al2O3, B4C, etc.,
- Some of the WEDM process parameters such as pulse on time, pulse off time, voltage, peak current, wire tension and wire feed rate were considered for optimising in many investigations to improve the performance such as material removal rate and surface roughness.
- The effects of other non-electrical parameters such as dielectric flushing pressure, volume % of the reinforcements, workpiece material properties, etc., can also be studied in improving the machining performances of WEDM.
- In most of the investigations, the experimental plan is devised by Taguchi method, mathematical models were derived by response surface methodology to optimize the process parameters using desirability analysis and finally the significance of the different models were tested using ANOVA.
- From the review of various studies carried out in WEDM of MMCs, it is clear that there is a future scope for WEDM of the light materials like magnesium matrix composites reinforced with nano particles such as carbon nanotubes, nano SiC, etc.,

6. References
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