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Optimization of Process Parameters in Wire Electrical Discharge Machining of MMC: A Review

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ABSTRACT
Wire electrical discharge machining (WEDM) is a specialized thermal machining process capable of accurately machining parts with varying hardness or complex shapes, which have sharp edges that are very difficult to be machined by the main stream machining processes. This practical technology of the WEDM process is based on the conventional EDM sparking phenomenon utilizing the widely accepted non-contact technique of material removal. Since the introduction of the process, WEDM has evolved from a simple means of making tools and dies to the best alternative of producing micro-scale parts with the highest degree of dimensional accuracy and surface finish quality. Metal matrix composites are advanced materials having high specific strength, good wear resistance, and high thermal expansion coefficient. To achieve this task, machining parameters such as pulse on time, pulse off time, peak current, servo voltage, wire feed, wire tension etc. of this process should be selected such that optimal value of their performance measures like Material Removal Rate (MRR), Surface Roughness (SR), Gap current, Dimensional deviation, etc. can be obtained or improved. In past decades, intensive research work had been carried out by different researchers for improvement and optimization of WEDM performance measures using various optimization techniques like Taguchi, Response Surface Methodology (RSM), Artificial Neural Network (ANN), Genetic Algorithm (GA), etc. This paper also highlights the feasibility of the different control strategies of obtaining the optimal machining conditions. This literature review helps to identify the suitable process parameters and their ranges in machining of metal matrix composites.
Keywords - Wire EDM, Metal Matrix Composite, Optimization, MRR, Surface roughness

I. INTRODUCTION
Metal Matrix Composites have proven to be significant highly developed materials that provide as alternatives to many conventional materials, mostly when light-weight and high strength parts are needed such as in the automotive, aerospace, defense and other industries. MMCs have found many successful industrial applications in recent past as high-technology materials due to their exceptional properties such as high strength-to-weight ratio, high toughness, lower value of coefficient of thermal expansion and capability of operating at elevated temperatures. Processed MMC cause serious tool wear due to the presence of abrasive particles and thus reduced tool life when machined using conventional means. Wire - EDM seems to be a better choice as it confirms to easy control and can machine intricate and complex shapes Garg et al. [1].

1.1 Overview of Wire - EDM
Wire EDM (Vertical EDM's kid brother), is not the new kid on the block. 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. WEDM is a spark erosion process used to produce complex two and three dimensional shapes through electrically conductive work pieces. The wire does not touch the work piece, so there is no physical pressure imparted on the work piece compared to grinding wheels and milling cutters. A power supply delivers high-frequency pulses of electricity to the wire and the work piece and material is removed as a result of high energy discharge subjected on the work piece. WEDM has become an important non-traditional machining process, widely used in the aerospace, nuclear and automotive industries. As WEDM process provides an effective solution for machining hard materials (like titanium, ceramics, zirconium and tungsten carbide) with intricate shapes and profiles Kozak et al. [2].

1.2 Wire – EDM process parameters
The most common process parameters and performance measures used by various researchers in their research work regarding optimization of Wire - EDM process is shown in Figure 1.

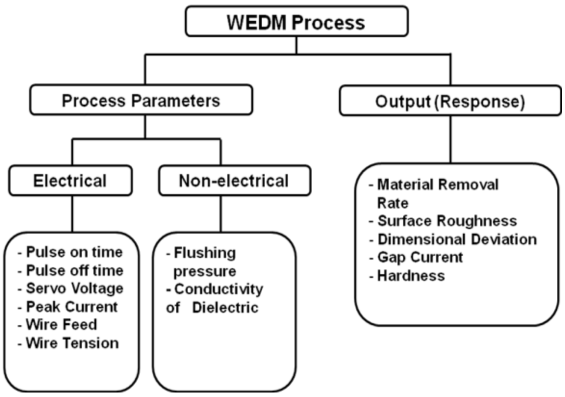

Fig-1: Process parameters and output (response)

II. WIRE CUT EDM ON COMPOSITES

This part discusses the capability of the Wire - EDM improvement in the machining of the different advanced materials.

2.1 Recent MMCs Materials

Wire EDM is considered as an useful and cost-effective tool in the machining of metal matrix composite among the different material removal processes. Several comparative studies have been made in the processing of metal matrix composites (MMC). These studies showed that WEDM yields better cutting edge quality and has better control of the process parameters with fewer workpiece surface damages. Ganpatrao et al. [3] attempted to study the determination of material removal rate of WEDM of metal matrix composites using dimensional analysis. They proposed semi-empirical model of MRR in WEDM based on thermo physical properties of the work piece and pulse-on time, average gap voltage. An empirical model based on response surface method was developed. Lal et al. [4] conducted an experimental study on Wire electrical discharge machining of AA7075/SiC/Al_2O_3 hybrid composite fabricated by inert gas-assisted electromagnetic stir-casting process. The objective of the paper was to investigate the effect of WEDM process parameters like discharge duration, pulse interval time, discharge current and the wire drum speed on the kerf width while machining newly developed hybrid metal matrix composite (Al7075/7.5 % SiC/7.5% Al_2O_3). The discharge current has most significance on kerf than discharge duration. Rozenek [5] analyzed the electrical discharge machining characteristics of metal matrix composites. They studied the influence of discharge current, pulse-on time, pulse-off time and voltage on the machining feed rate and surface roughness during WEDM of metal matrix composite AlSi7Mg/SiC and AlSi7Mg/Al2O3. The analysis of results shows that maximum cutting speed of AlSi7Mg/SiC and AlSi7Mg/Al2O3 composites are obtained to be approximately 3 times and 6.5 times lower than the cutting speed of aluminum alloy. Samy et al. [6] developed a mathematical modeling for wire electrical discharge machining of Aluminium-Silicon Carbide composites. They optimized WEDM characteristics such as the MRR, cutting speed and the surface roughness was developed. The process parameters considered are the average machining voltage, the pulse frequency, the work piece height, the kerf size and the percentage volume fraction of SiC present in the aluminum matrix. Satish Kumar et al. [7] presented an experimental study of wire electrical discharge machining characteristics of Al6063/SiCp composites. In this work, the effect of WEDM parameters such as pulse on time, pulse off time, gap voltage and wire feed on material removal rate and surface roughness in MMCs consisting of Al6063 and SiCp are given. Regression equations are developed to predict the output parameters for Al6063 and composites.

2.2 Highly developed ceramic materials

The WEDM process has also evolved as one of the most promising alternatives for the machining of the advanced ceramics. Sanchez et al. [8] provided a literature survey on the EDM of advanced ceramics, which have been commonly machined by diamond grinding and lapping. In the same paper, they studied the feasibility of machining boron carbide (B_4C) and silicon infiltrated silicon carbide using EDM and WEDM. Cheng et al. [9] also evaluated the possibility of machining ZrB_2 based materials using EDM and WEDM, whereas Matsuo and Oshima [10] examined the effects of conductive carbide content, namely niobium carbide and titanium carbide on the CR and surface roughness of zirconium ceramics (ZrO_2) during WEDM. Lok and Lee [11] have successfully WEDMed sialon 501 and aluminium oxide– titanium carbide (Al_2O3–TiC). However, they realized that the MRR is very low as compared to the cutting of metals such as alloy steel SKD-11 and the surface roughness is generally inferior to the one obtained with the EDM process. Dauw et al. [12] explained that the MRR and surface roughness are not only dependent on the machining parameters but also on the material of the part

2.3 Recent applications in tooling design

WEDM has been gaining wide acceptance in the machining of the various materials used in modern tooling applications. Several authors [13,14] have investigated the machining performance of WEDM in the wafering of silicon and machining of compacting dies made of sintered carbide. The feasibility of using cylindrical WEDM for dressing a rotating metal bond diamond wheel used for the precision form grinding of ceramics has also been studied [15]. The results show that the WEDM process is capable of generating precise and intricate profiles with small corner radii but a high wear rate is observed on the diamond wheel during the first grinding pass. Such an initial high wheel wear rate is due to the over-protruding diamond grains, which do not bond strongly to the wheel after the WEDM process [16]. The WEDM of permanent NdFeB and 'soft' MnZn ferrite magnetic materials used in miniature systems, which requires small magnetic parts, was studied by comparing it with the laser-cutting process [17]. It was found that the WEDM process yields better dimensional accuracy and SF quality but has a slow CR, 5.5 mm/min for NdFeB and 0.17 mm/min for MnZn ferrite. A study was also done to investigate the machining performance of micro-WEDM used to machine a high aspect ratio meso-scale part using a variety of metals including stainless steel, nitronic austentic stainless, beryllium copper and titanium [18].

III. OPTIMIZATION OF WIRE - EDM PROCESS

This segment provides a study on the several machining strategies connecting the design of the process input factors and the mathematical modeling for the optimization of performance measure parameters. The most effectual machining strategy is finalized by identifying the different factors affecting the Wire- edm process and looking for the different behavior of obtaining the most favorable machining condition.

3.1 Design of machining parameters

The settings for the different machining parameters necessary in the Wire - edm process play a key role in producing an most favorable machining performance. This part shows some of the logical and arithmetical methods used to study the effects of the parameters on the output quality characteristics such as Surface roughness, kerf width and Cutting Rate.

3.1.1 Factors influencing the output parameters

WEDM is a complex machining process controlled by a large number of process parameters such as the pulse duration, discharge frequency and discharge current intensity. Any slight variations in the process parameters can affect the machining performance measures such as surface roughness and CR, which are two of the most significant aspects of the WEDM operation [19]. Suziki and Kishi [20] studied the reduction of discharge energy to yield a better surface roughness, while Several authors [21] have also studied the evolution of the wire tool performance affecting the machining accuracy, costs and performance measures.

3.1.2 Machining parameters effects on the cutting rate

Many different types of problem-solving quality tools have been used to investigate the significant factors and its inter-relationships with the other variables in obtaining an optimal WEDM CR. Konda et al. [22] classified the various potential factors affecting the WEDM performance measures into five major categories namely the different properties of the workpiece material and dielectric fluid, machine characteristics, adjustable machining parameters, and component geometry. In addition, they applied 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. Tarng et al. [23] employed a neural network system with the application of a simulated annealing algorithm for solving the multi-response optimization problem. It was found that the machining parameters such as the pulse on/off duration, peak current, open circuit voltage, servo reference voltage, electrical capacitance and table speed are the critical parameters for the estimation of the CR and SF. Huang et al. [24] argued that several published works [25] are concerned mostly with the optimization of parameters for the roughing cutting operations and proposed a practical strategy of process planning from roughing to finishing operations. The experimental results showed that the pulse on-time and the distance between the wire periphery and the workpiece surface affect the CR and SF significantly. The effects of the discharge energy on the CR and SF of a MMC have also been investigated [26].

3.1.3. Machining parameters effects on the MRR

The effects of the machining parameters on the volumetric MRR have also been considered as a measure of the machining performance. Scott et al. [27] used a factorial design requiring a number of experiments to determine the most favorable combination of the WEDM parameter. They found that the discharge current, pulse duration and pulse frequency are the significant control factors affecting the MRR and SF, while the wire speed, wire tension and dielectric flow rate have the least effect. Liao et al. [28] proposed an approach of determining the parameter settings based on the Taguchi quality design method and the analysis of variance. The results showed that the MRR and SF are easily influenced by the table feed rate and pulse on-time, which can also be used to control the discharging frequency for the prevention of wire breakage. Huang and Liao [29] presented the use of Grey relational and S/N ratio analyses, which also display similar results demonstrating the influence of table feed and pulse on-time on the MRR. An experimental study to determine the MRR and SF for varying machining parameters has also been conducted [30].The results have been used with a thermal model to analyze the wire breakage phenomena.

3.1.4. Machining parameters effects on the surface roughness

There are also a number of published works that solely study the effects of the machining parameters on the WEDMed surface. Gokler [31] studied the selection of the most suitable cutting and offset parameter combination to get a desired surface roughness for a constant wire speed and dielectric flushing pressure. Tosun et al. [32] investigated the effect of the pulse duration, open circuit voltage, wire speed and dielectric flushing pressure on the WEDMed workpiece 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. Anand [33] used a fractional factorial experiment with an orthogonal array layout to obtain the most desirable process specification for improving the WEDM dimensional accuracy and surface roughness. Spedding and Wang [34] optimized the process parameter settings by using artificial neural network modeling to characterize the WEDMed workpiece surfaces.

IV. FEASIBILITY OF METAL MATRIX COMPOSITES

Intensive research in MMCs started about thirty years ago to meet the increasing requirements of properties in aerospace materials to achieve higher speed and higher temperature engines for higher efficiencies. Most of these MMCs were used in aerospace applications where weight savings were of paramount importance, and to some extent in selected weapons systems, where cost was hardly of any concern. During the last few years, several developments have occurred in MMCs which have great relevance to India. For instance, the costs of metal-matrix fiber reinforced composites have come down from several hundred thousand dollars per pound to the order of a thousand dollars per pound at this time due to the decrease in costs of continuous fibers. The continuous fibre reinforced MMCs, therefore, still remain quite expensive for widespread use in countries like India, except for certain critical applications where enormous savings in energy or resources can be made: However, there has been a more dramatic decrease in the cost of metal-matrix discontinuous fibre/particulate composites. The costs of particulate composites like aluminium-silicon carbide have come down to the level of two to ten dollars per pound due to the feasibility of using inexpensive particulate reinforcements and the possibility of using conventional casting processes to produce these composites. These composites can be made at even lower costs due to the lower costs of highly skilled manpower in India. The following are the list of selected organization working on MMCs in India.

- National Physical Laboratory, CSIR, New Delhi
- Indian Institute of Technology, New Delhi
- Indian Institute of Technology, Kanpur
- Regional Research Laboratory, CSIR, Bhopal
- Regional Research Laboratory, CSIR, Trivandrum
- National Aeronautical Laboratory, CSIR, Bangalore
- Vikram Sarabhaa Space Centre, Trivandrum
- Indian Institute of Science, Bangalore
- Banaras Hindu University, Varanasi
- University of Roorkee, Roorkee
- Defense Metallurgical Research Laboratory, Hyderabad
- Hindustan Aeronautics, Bangalore
- Indian Institute of Technology, Bombay

V. MMCS FABRICATION METHODS

Fabrication of MMCs is the primary processing route of its production. A basic classification, about the technological methods for MMCs, takes account of the state where the constituents during the primary cycle of production. Fabrication methods of Metal Matrix Composites can be mostly divided into three categories.

5.1 Liquid state Processing

Processing of Metal Matrix Composite using liquid state find wide acceptance as it involves lower cost for getting liquid metals than metal powder. Various complex shapes using liquid metals can be produce with significant ease by adopting methods already developed in the casting industry. Some techniques documented by researchers are infiltration, dispersion, squeeze casting, stir casting and compo-casting etc. On the other hand liquid phase fabrication also suffers from a number of limitations that consist of lack of reproducibility associated with imperfect control of the processing parameters and some adverse chemical reactions at the interface of the reinforcement and the liquid metal.

5.2 Solid phase fabrication

Solid states processing of MMCs are generally used to get the maximum mechanical and physical properties. Excellent grained control over the composite microstructure and the reinforcement distribution can be easily obtained by this process.

Mostly the discontinuous reinforcement Metal Matrix Composites are processed in this route. In present day some adopted methods of MMCs are diffusion bonding and powder metallurgy.

5.3 Vapor phase fabrication

Vapor state processing is a key process where the matrix is deposited from the vapor stage into individual reinforcement parts of the constituent. It may be noted that there is tiny or no mechanical disorder of the interfacial area and large bond in between reinforcement with no any chemical reaction. The matrix is deposited by plasma spraying or by chemical vapor deposition.

VI. OPTIMIZATION METHODOLOGY

Various optimization techniques used by the various researchers' for improvement and optimization of performance measures of WEDM machining on MMCs.

Following are the summary of experimental work carried out by various researchers on Wire-EDM machining of Metal Matrix Composites, effects of machining parameters on output response quality characteristics and their conclusions.

The Material Removal Rate, Cutting Speed and Surface Roughness were analyzed by A. Pramanik [35] for AlSi7Mg/20%SiC reinforced MMC using different non - traditional machining. He analyzed that Vaporization, Chemical dissolution and Mechanical erosion are the most important material removal mechanisms occur during machining. The thermal degradation and the presence of reinforcement particles mainly break the machined surface

Thella Babu rao et al. [36] inspected the effect of machining parameter such as Pulse-on time, Pulse-off time and Wire tension on Surface roughness, Metal removal rate and Wire wear ratio of Al7075/SiCp MMC using Wire-EDM. Response surface methodology is used to build up the empirical models for these WEDM responses. They interpreted that machining responses are conflicting in nature. The problem is formulated as a multi-objective optimization problem and is solved using the Non-dominated Sorting Genetic Algorithm-II.

The MRR, TWR, SR and Circularity were analyzed by D. Puhan et al. [37] using four machining parameters such as Discharge current, Pulse duration, Duty cycle and Flushing pressure and two material parameters (weight fraction of silicon carbide in the composite and mesh size) during the machining of AlSiCp by EDM. The fabrication of MMC was carried out by PM Route. A hybrid approach combining Principal component analysis and Fuzzy inference system coupled with taguchi method to simultaneously optimize multiple responses for desirable parametric conditions.

The Cutting Width (Kerf) were analyzed by Pragya Shandilya et al. [38] using process parameters such as Servo voltage, Pulse on time, Pulse off time and Wire feed rate during the machining of SiCp/6061Al MMC by WEDM. The MMC of Aluminium 6061 reinforced with 10% of SiC particles (by Weight) were prepared by Stir casting method. A mathematical model was developed to analyzed the effects of WEDM parameters using Response Surface Methodology. ANOVA results show that voltage and wire feed rate are highly significant parameters and pulse-off time is less significant. Pulse-on time has insignificant effect on kerf.

D. Satishkumar et al. [39] investigated the effect of wire electrical discharge machining parameters such as Pulse-on time, Pulse-off time, Gap voltage and Wire feed on Material removal rate and Surface roughness in Al6063/SiCp MMC. The Al6063 is reinforced with SiCp in the form of particles with 5%, 10% and 15% volume fractions. The results were analyzed using analysis of variance and response graphs. It was found that different combinations of WEDM process parameters are required to achieve higher MRR and lower SR. It was also found that the increase in volume percentage of SiC resulted in decreased MRR and increased SR.

K.M.Patel et al. [40] investigated the inter-relationships of various EDM machining parameters namely discharge current, pulse-on time, duty cycle and gap voltage on the metal removal rate (MRR), electrode wear ratio (EWR) and surface roughness using the response surface methodology (RSM) on Al2O3–SiCw–TiC ceramic composite. The experimental results reveal that discharge current, pulse-on time and duty cycle significantly affected MRR and EWR while discharge current and pulse-on time affected the surface roughness.

S. Habib [41] carried out experiments on conductive metal matrix composite Aluminium silicon carbide. A comprehensive mathematical model was developed for correlating the interactive and higher order influence of various electrical discharge machining parameters e.g. the pulse on time, peak current, average gap voltage and SiC percentage (5, 10, 20 and 25) on the respective material removal rate, electrode wear ratio, gap size and surface roughness using RSM. The adequacy of the above the proposed models have been tested through the analysis of variance.

VII. DISCUSSIONS AND CONCLUSIONS

After a detailed analysis of the literature, the following conclusions can be drawn.

- The literature review clearly indicates that the Wire EDM on composites are widely reported in literatures. Silicon carbide and Aluminum oxide reinforced composites widely studied in the literatures. Investigation in Wire- EDM on particulate reinforced Metal Matrix Composites is still increasing through as it has made superior evolution in few areas.

- The various applications of Wire-EDM have been found in Aerospace, Automobile, Medical and die manufacturing industries, where precise dimensions is the prime objective. Machining of Al/SiC can be made economical by suitably selecting the machining parameters.
- The attendance of reinforced particles adds extra difficulty and makes the machining process different from that of monolithic matrix material. There are still deficiencies in appreciative the mechanisms of most of the machining processes due to the different capacities of removing reinforced particles. Tool breaking, tool wear and recast layer are the main troubles observed in Wire – EDM.
- Various researchers have made attempts in the machining of Al/SiC in WEDM. The process remains still challenging due to the Distribution and orientation of reinforcement in the metal matrix and Non homogeneous and anisotropic nature of composite as a whole.
- While machining of Aluminium Matrix Composites, Wire breakages are initiate to pose limitations on the cutting speed. Work regarding different wire material has not been fully explored.
- It is also found that most of the research work has been carried out on improvement and optimization of same performance measures like MRR, Surface roughness for different materials, but some performance measures like Gap current, dimensional deviation, hardness, etc. are either not much focused or not focused yet. So, this area is yet to be explored more.
- Most of the researchers have concentrated on optimization of single quality characteristic while in present industries, high productivity and product quality with low production cost are important. To achieve that simultaneously, multi response optimization of machining process is required. This area can be taken up for further research as they required more attention.

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