Metal matrix composites machining by Wire electro discharge machining in last decade: A Review

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Abstract- Wire electrical discharge machining (WEDM) has evolved from a simple means of making tools and dies to the best alternative to nascent materials like Metal Matrix Composites, ceramic composites, which have immense applications in automobile, aircraft, railway sectors, defense, aerospace, micro systems industries, agriculture farm machinery, etc. WEDM shows higher ability for cutting complex shapes with high precision for MMCs. Conventional machining of MMC's causes serious tool wear due to greater hardness and the existence of abrasive reinforcement particles. Numerous studies and research are going on in modelling of WEDM since its inception. Most of the researchers thoroughly worked on process modelling, process parameters, materials of electrodes/tool-work-piece, dielectric medium, etc. The process modelling of WEDM is considered as primary objective. There is need to categorize the variety of research for better understanding of research done in this area. This paper reviews machining of MMCs, techniques used, responses, findings and summery of review. The paper also discusses the potential future trends of research work in the same area.

Index Terms- WEDM, MMC, AMC, MRR, Surface Roughness, Kerf width.

1. INTRODUCTION

Metal Matrix Composites have proven to be significant highly developed materials that proved as alternatives to many conventional materials, mostly when light-weight and high strength components are needed such as in the automotive, aerospace, defense and other industries. A metal matrix composite (MMC) is composite material with two or more fundamental parts, one being a metal and other material may be a different metal, ceramic or organic compound. The matrix is the main material into which the reinforcement is implanted, and is completely continuous. The matrix is usually a metal such as aluminum, titanium or magnesium, and provides a compliant support for the reinforcement. The reinforcement can be either continuous, or discontinuous. Table 1 shows different types of MMCs, reinforcements, properties and applications of the same. MMCs have found numerous fruitful industrial applications in recent past as high-technology materials due to their excellent properties such as high strength-to-weight ratio, high toughness, lower value of coefficient of thermal expansion and capability of functioning at high temperatures. Table 1 shows different kinds of MMCs, reinforcements, properties and applications of the same [1].

WEDM is a spark erosion process used to fabricate intricate two and three dimensional shapes through electrically conductive work pieces. WEDM has become a significant 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) like Metal Matrix Composites, ceramic composites, with intricate shapes and profiles which have vast applications in automobile, aircraft, railway sectors, defense, aerospace, micro systems industries, agriculture farm machinery with intricate shapes and profiles[2]. Conventional machining of MMC's causes serious tool wear due to greater hardness and the existence of abrasive reinforcement particles. So there is need to focus on categorization of the variety of research for better understanding of work done in this area.

2. LITERATURE REVIEW

MMC's can be machined by many conventional machining processes but results shows huge amount of tool wear, low accuracy, poor machineability, poor surface quality , more cutting force required which restricts MMC's to be machined by conventional manufacturing processes, most of authors recommended non conventional machining processes for machining of MMC's [2,3,4,5,7,8,34,35,3744]. Table 2 is list of literature review since 2008 to recent ones. Table shows work carried out by authors on different types of MMCs, techniques used, their responses and major findings, which leads to future research scenario.

Table 1. Types of MMCs, reinforcement, properties and applications of MMCs

Sr. No	Type of MMC	Reinforcements	Properties	Applications
1	Aluminum Matrix Composites	Alumina (Al_2O_3); silicon carbide (SiC) particles; Boron Carbide (B_4C)	High stiffness (modulus of elasticity); Low density; High strength even at elevated temperatures; High thermal conductivity; Excellent abrasion resistance.	Brake rotors for high speed trains, bicycles, golf clubs, electronic substrates, cores for high voltage electrical cables, automotive parts (brake components, pistons, and pushrods), and Nuclear plant parts.
2	Magnesium Matrix Composite	Silicon carbide (SiC) particles	High stiffness (modulus of elasticity); High wear resistance; Low density; Good creep resistance; Good strength even at elevated temperatures.	Lightweight automotive brake system, Components for racing cars, aircraft parts for: transmissions, gearboxes, engine and compressors
3	Titanium Matrix Composite	Continuous monofilament silicon carbide fiber; Titanium boride (TiB2) and titanium carbide (TiC) particles	High creep resistance; High strength; High stiffness (modulus of elasticity); High wear resistance; High thermal stability.	Turbine engine components (fan blades, synchronization rings, connecting links, shafts, discs), components of the jet's landing gear, drive train parts, automotive engine components, general machine components.
4	Copper Matrix Composites	Continuous fibers of carbon (**C**), silicon carbon (SiC), tungsten (W), Silicon carbide particles	High stiffness (modulus of elasticity); Low coefficient of thermal expansion; High thermal conductivity; Good electrical conductivity; Good wear resistance.	Electronic relays, electrically conducting springs and other electrical and electronic components, Manufacturing hybrid modules.

Table 2. List of Literature Review

Sr. No	Author	MMC Material	Techniques used	Responses	Findings
1	K. Ravi Kumar et. al. (2018)[10]	Al (6082)/ tungsten carbide composite	Desirability-Based Multi-objective Optimization	MRR, Surface roughness prediction	The influence of process parameters on MRR and SR of aluminum
2	Harmesh Kumar et. al. (2018)[11]	Al/SiCp-MMC	Box–Behnken's design	Cutting speed, Surface roughness, Spark gap	Developed The quadratic regression models
3	Muniappan et. al. (2018) [12]	Particulate Al6061/Sic/Gr	Taguchi's technique	Surface roughness, S/N ratio	Regression models were developed
4	Srivastava et. al. (2018) [13]	A359/B_4C/ Al_2O_3	----	MRR,HAZ	Surface integrity in wire-EDM tangential turning
5	Shamim Haidar et. al. (2018)[14]	Aluminium MMC foam	Taguchi Techniques	Material Removal Rate	Conducted Parametric optimization
6	Harmesh Kumar et. al. (2017)[15]	(Al/SiCp-MMC)	RSM based Box–Behnken design	Surface roughness prediction	Various surface defects and their possible reasons
7	Prashantha et. al. (2017) [51]	Al6061 reinforced with SiC	DOE as per L9 orthogonal layout	Material Removal Rate	MRR decrease with increase in % vol of Silicon carbide particles

8	Mohinder Garga et. al. (2017) [16]	ZrSiO4p/6063 Aluminium MMC	Box–Behnken Design	Dimensional deviation	Dimensional Deviation (DD) increases with increase in pulse on time and peak current
9	P. M. Gopal et. al. (2017) [17]	Magnesium/boron nitride/ CRT(Mg/BN/CRT) hybrid MMC	Taguchi Techniques L27 orthogonal array	MRR, Surface roughness	Ton and wt. % of reinforcement were most significant for Ra and MRR than any other considered parameters
10	Yash et. al. (2017) [52]	composites of ZrO_2, Al_2O_3, Si_3N_4, SiC	Finite element and numerical simulation models	Material Removal Rate and Surface Finish	Hybrid machining can incorporate.
11	Gurupavan et. al. (2017) [91]	Al6061-6%wt. Si_3N_4 composite material	Taguchi's L27 orthogonal array & Artificial Neural Network (ANN).	SR, accuracy, volumetric MMR and electrode wear	Neural network trained with 70% of the data in training set gives good prediction results
12	Karabulut et. al. (2017) [94]	Al 6061 based MMCs reinforced with four different weight fraction of B_4C	Taguchi L18 array and analyzed by ANOVA	Surface roughness	The surface quality of the machined part was decreased with increasing peak current.
13	Pujara et. al. (2017) [95]	LM6 Aluminum MMC	TLBO (Teaching-Learning Based Optimization) technique	Dimensional accuracy	TLBO gives better results at a lower number of iterations
14	Shubhajit Das et. al. (2016)[21]	Al6061/7%SiC/ 3%B_4C Hybrid MMCs	L18 orthogonal array and analyzed by ANOVA	MRR and CLA value surface roughness (Ra)	Voltage and pulse-off time are the most significant parameters for MRR and Ra.
15	Nilesh G. Patil et. al. (2016) [20]	A359/SiCp composite	Experimentation	Cutting rate, surface finish and kerf width.	Coated electrode improve cutting rate, surface roughness while the kerf width was reduced
16	C. Ahilan (2016) [22]	AA7075/TiB_2 (3wt %)	L9 orthogonal array design and ANOVA	MRR and surface roughness	Toff influences more followed by Wire feed and Ton.
17	Pramanik et. al. (2016) [53]	Al-based SiC reinforced MMC	Experimentation	Degradation of wire electrode	Proposed two mechanisms for wire degradation.
18	Garg et. al. (2016) [85]	Al/ZrO2(p)	Mathematical model with RSM	Spark gap and MRR	Proposed Maximum and minimum values of MRR and spark gap for effective machining.
19	Islam Shyha et. al. (2016) [54]	Al matrix reinforced with SiC particle composite	L9 orthogonal array based Modified fractional factorial design	Material removal rate	Higher MRR can be achieved by increasing current. Presence of SiC particles affects surface roughness.
20	Thella Babu Rao (2016) [23]	Al7075/SiCp	integrated approach of PCA weighted GRA based TM	WEDM performance	Derived the optimal process conditions to increase the quality and productivity of WEDM
21	Jamuna et. al. (2016) [93]	Al5052 SiC, Al 6082 Al_2O_3,Al 7075 Fly ash.	Hybrid Approach as greyfuzzy approach	Kerf width, tool wear, process cost and SR	BM and RM are influential parameters for multi response WP and T_{OFF}
22	Dey et. al.(2016) [96]	AA6061/ cenosphere AMCs.	Box Behnken along with ANOVA and a second order quadratic mathematical model	Cutting Speed	The CS increases with an increase in pulse on time and decreases drastically with the increase of Wt.%.
23	Anand Sharma et. al.(2016) [25]	ZrSiO4p/Al 6063 MMC	Box-Behnken design	Cutting rate, surface roughness	Lower SR is obtained at highest levels of T_{ON} and IP and at lower levels of T_{OFF} and spark gap set voltage.

24	A. Pramanik et. al. (2015) [26]	Al 6061 alloy reinforced with 10 vol% SiC particles,	Experimentation	MRR, kerf width, surface finish and electrode wire wear	The pulse-on-time and wire tension were significant factors for the surface roughness.
25	Ali Riza Motorcu et. al.(2015) [27]	$Al/B_4C/Gr$ reinforced hybrid	Taguchi method and response surface methodology	Material removal rate (MRR) , surface roughness	Determined the relations between MRR, Ra and machining parameters.
26	Sivaprakasam et. al. (2015) [63]	A413- B_4C /9%	Response surface methodology and ANOVA	Material removal rate	Voltage, capacitance and feed rate have significant effect on MRR, KW and SR.
27	Kandpal et. al. (2015) [45]	Aluminium based MMC materials	--------	Hybrid machining process	The WEDM processes with combination with surface grinding, abrasive jet machining, and electro chemical machining are advantageous of hybrid machining process.
28	Ergu¨n Ekici et. al. (2015) [28]	Al/B_4C composites	Taguchi L18 orthogonal array	Surface roughness, Material removal rate	Most effective parameters for surface roughness were pulse-on time and for MRR wire speed.
29	Mehdi et. al. (2015) [58]	Al-Mg_2Si	Experimentation with L27 orthogonal array with ANOVA	MMR	Voltage and current are significant factors for Material Removal Rate.
30	Liu et. al. (2015) [75]	Al alloy 6061 with Particulate of 10 vol.-% Al_2O_3 and 20 vol.-% Al_2O_3	Experimentation	Comparison of machining characteristics in air and emulsified oil	MRR increased with an increase of current in both air and emulsified oil medium. A higher percentage of the ceramic phase decreases MRR.
31	Lal et. al. (2015) [79]	Hybrid MMC 7.5% Al_2O_3 and 7.5% SiC	Experimentation with Taguchi-based grey relational analysis	Surface quality characteristics	Decided the optimum parameters for multiple parameters optimization.
32	Kumar et. al. (2015) [87]	Boron Carbide (B_4C) MMC	Experimentation	Crater formation	Improved mechanical properties, increase in kerf width, surface roughness due to inclusion of B4C particles.
33	Pragya shandilya et. al. (2014)[29]	SiC_P/6061 Al MMC	box-behnken design	surface roughness	Voltage is the most significant parameters affecting on surface roughness.
34	Zhenlong et. al. (2014) [77]	SiC/Al particulate MMC	Experimentation by micro-WEDM	Characteristics of recast layer and removal process of ceramic particles	The thickness of recast layer increased with the discharge energy increasing.
35	Thella Babu Rao et. al. (2014)[36]	ZC63/SiC_P	Taguchi method	Surface roughness, MRR, Principal component analysis, and kerf	Concluded that importance of the factors on the multi-performance characteristics was in sequential order of %vol of SiC_P , SiC particulate size , pulse-on time, pulse-off time, wire tension.
36	S K. Garg et. al. (2014)[38]	Al/10 % ZrO_2(p)	Central composite design, multi-objective optimization	Surface roughness.	Developed mathematical models to predict the results for performance characteristics well in advance.
37	Sharma et. al. (2014) [89]	6063/ $ZrSiO_4$(p) (5%) MMC	A Box-Behnken design approach of response surface methodology (RSM)	material removal rate (MRR)	Increasing the pulse off time and servo voltage decreases the cutting rate. Increasing the pulse on time and peak current, the

			and ANOVA		cutting rate increases.
38	Sivaprakasam et. al. (2013) [67]	Aluminum Matrix Composite (A413-9% B_4C).	Modeling by RSM, ANOVA and experimentation	MRR, KW, and SR.	Compared RSM models with ANN models. Concluded ANN model is more accurate than RSM
39	Thella Babu Rao et. al. (2013) [39]	ZC63/SiC_P	composite principal component (CPC)	surface roughness, MRR, wire wear ratio (WWR), kerf (Kw) and white layer thickness	The particulate size, pulse-on time and wire tension has physical significant on the overall quality of the process. Pulse-off time and volume fraction of SiC_P are not significant.
40	Fard et. al. (2013) [86]	Al–SiC metal matrix composite.	Parametric analysis and experimentation by ANOVA and adaptive neuro-fuzzy inference system (ANFIS), artificial bee colony (ABC)	CV and SR.	Pulse on time, discharge current and wire tension are most significant factors for CV and SR.
41	SK. Garg et. al. (2013) [40]	Al/ZrO_2(p)-metal matrix composite	L36-mixed orthogonal array Taguchi method.	spark gap and material removal rate	The significant parameters for MRR are pulse width, pulse off time, servo control voltage, pulse on time, wire feed rate and wire tension
42	Probir Saha et. al. (2013) [41]	5 vol% TiC reinforced austenitic manganese steel MMC	orthogonal and uniform-precision rotatable central composite design ,Neuro-Genetic technique	cutting speed and kerf width	Multi-objective optimization of the process parameters obtained by NN based NSGA-II technique.
43	Shandilya et. al. (2013) [88]	SiCp/6061 Al metal matrix composite	Mathematical model by response surface methodology (RSM) and artificial neural network	Average cutting speed	The prediction accuracy of ANN model was about three times better than RSM
44	Reza Kashiry Fard et. al. (2013) [43]	Al–SiC MMC	L27 Taguchi's orthogonal array, adaptive neuro-fuzzy inference system (ANFIS)	cutting velocity and surface roughness	Pulse on time and discharge current were found to have significant effect on CV and SR.
45	Kumar et. al. (2013) [90]	Al/SiC-MMC.	Mathematical models	Material removal rate and surface finish	Surface roughness and MRR is increases with the increase in peak current, pulse on time, % reinforcement, Peak current.
46	Gupta et. al. [65]	Ti_6Al_4V, HE15, $15CDV_6$ and M-250.	Hybrid modeling and optimization by Artificial Neural Network and Response Surface Methodology.	Surface roughness	To get maximum surface finish hybrid modelling and optimization is carried out.
47	Shandilya et. al. (2012) [68]	SiCp/6061 Al metal matrix composite	Response surface methodology (RSM) and artificial neural network (ANN). Box–	MMR	ANN model is superior for prediction of MMR. This can lead to economical machining.

			Behnken design		
48	Sertan Ozan et. al. (2012) [60]	Al/B_4Cp MMC	Taguchi L9 orthogonal array	surface roughness	The particle reinforcement amount (wt.%) is the most dominant factor on the surface roughness followed by pulse on time and wire feed.
49	Vishwakarma et. al. (2012) [84]	Al-SiC composite	FEA model	MMR	FEA based model developed to analyze the temperature distribution and its effect on MRR.
50	Pragya Shandilya et. al. (2012) [69]	SiCp/6061 Al MMC	Box-Behnken design (BBD)	Cutting width (kerf)	Voltage and wire feed rate are highly significant parameters and pulse-off time is less significant.
51	Pragya Shandilya et. al. (2011) [70]	SiCp/6061 Al MMC	Experimentation	Surface roughness, microstructure and microhardness	The pulse-off time and wire feed rate does not affect the surface roughness significantly. Whereas, Surface roughness is mostly affected by voltage and pulse-on time.
52	Pragya Shandilya et. al. (2011) [71]	SiCp/6061 Al MMC	Box-Behnken design (BBD)	Cutting width (kerf)	Voltage, pulse-off time and wire feed rate have significant effect on kerf where as pulse-on time has insignificant effect.
53	S.N. Joshi et. al. (2010) [7]	---------	Finite element method (FEM).	Shape of crater cavity and the MRR	Crater cavity shapes are predicted.
54	Nilesh Patil et. al.(2010) [31]	Al/Al_2O_3p	Experimentation	Cutting rate, surface finish, and kerf width.	Volume fraction of ceramic reinforcement, pulse on time, off-time, and servo reference voltage are significant for cutting rate, surface finish, and kerf width.
55	Garg et. al. (2010) [72]	Al_2O_3 reinforced MMC	Review	Theoretical models	Very modest work has been reported on MMCs with powder mixed EDM. Little work on theoretical models. Many MMCs have not been tried as work material on WEDM process.
56	Nilesh Patil et. al. (2010) [30]	Silicon carbide particulate reinforced AMC	Model by using technique such as quasi-Newton and simplex	Gap status, surface integrity and Wire performance,	The accuracy of proposed model is more than 99%. MRR decreases with increase in % ceramic particles.
57	Ahmad et. al. (2010) [78]	Aluminium Matrix Composite (AMC) 5 % alumina (Al_2O_3).	Experimentation by regression method	Material removal rate	Very good MRR can be achieved with 5% alumina. Wire breakage and reduced time efficiency of machining observed.
58	Probir Saha et. al. (2009) [80]	5 vol% TiC/Fe in situ MMC	Uniform-precision rotatable CCD of experiments with five levels of each parameter ,normalized radial basis function network (NRBFN)	Cutting speed and kerf width	An increase in the average gap voltage leads to the decrease of the cutting speed and increase in kerf width within considered range.

59	J. W. Liu et. al. (2009) [82]	Al_2O_3 particle-reinforced Al 6061 alloy	L9 orthogonal array design	Material removal rate (MRR)	For the 20% Al_2O_3 reinforced material, the order of importance is current, electrolyte concentration, pulse duration. MMR is influenced by the machining parameters in the order of current, pulse duration, electrolyte concentration.
60	Tran Huu Nam et. al. (2008) [8]	Aluminum-based MMC	FE model and Thermo-elastic models	Creater abnormalities	CTEs were investigated.
61	P C Tan et. al. (2008) [19]	---	Comparison of five EDM models from Snoeys, Van Dijck, Beck, Jilani, and DiBitonto	MRR at the cathode, Temperature distribution and crater geometry	The disk heat source models have a potential to be further development. Shapes of isothermal surfaces for five models were compared.
62	Poros et. al. (2008) [83]	WC-Co B_4C and Ti6Al4V.	Semi-empirical model	Volumetric efficiency	Increase of discharge time increase of volumetric efficiency. The efficiency of cutting is lower.

3. SUMMARY OF LITERATURE REVIEW

Most of the researchers systematically worked on process modelling, process parameters, materials of electrodes/tool-work-piece, dielectric medium, etc. The process modelling of WEDM is considered as major objective since long back to latest one [20,24,51,76,91,94,95].

The regression models [10,11,78] and mathematical models [30,38] were modeled and considered by some authors. The other models are thermo elastic [8], thermo-physical [7,8,32], thermo-electrical [6], electro-mechanical. The models developed are numerical [5,7,48,49], analytical [18], empirical, semi-empirical [24,30,83] for WEDM process. The models considered the area of the contact between plasma channel and electrode as disc heat source model (DHSM) [19], Gaussian heat distribution [5,7] , while considering electrode as finite, semi-finite and infinite in radial and axial direction [32]. Authors also considered a variety of materials as composites, ceramics, monolithic MMC with material properties as uniform, non- uniform and/or isotropic, anisotropic [2-5,18,20,24,30,31,32,70]. The results achieved were compared and validated with experimental data and previous research data [19,31,45,46,70,74,75,76]. Different approaches used as FEM, FDM, FVM to solve the models. Software tools used were ABAQUS, ANSYS, MATLAB, etc [4,7,8,32,43].

Researchers investigated the effect of process parameters on Kerf width [26,31,36,39,41,67,69,71, 80], MRR [10,17,21,27,30,38,47,50,58,81, 82,84, 85, 88,89], Dimensional Deviation [16], Cutting Speed [11,43,80], Electrode wear [26], Spark Gap[40], characterization [77,79,] and surface finish / Surface roughness [8,15,17,24,27,29,32,47,50,60,63,65,68,77, 94,95]. Researches attempted to optimize these process parameters to establish database which can be used in industry or future research [14,25,36,41,64, 65,66,67,80,82,87,88,90,91,93,94,96]. Authors also reviewed literature which gives insight of previous researches done [33,36,52,56,59,61,62,72,74].

4. FUTURE SCOPE

A substantial amount of research has been carried out on WEDM. However very few studies are available on modelling of WEDM process and modelling of Metal Matrix Composites. Research potentials are also available in:

- Modelling of Metal Matrix Composite as a work-piece.
- Process modelling of WEDM.
- Investigation into interaction between electrode, plasma, and work-piece for WEDM.
- Particle removal mechanism in MMC is major parameter in surface roughness which is still a challenge.
- Optimal combination of process parameters for WEDM of MMC also offers another challenge.

5. CONCLUSION

The aim of the review is to lay emphasis on key research studies on WEDM for MMCs. Prior research studies focused on process modelling, process parameters, materials of electrodes/tool-work-piece, dielectric medium, optimization of process parameters, etc. The current review study concludes that modelling of WEDM is considered as prime objective

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