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Application of CNC Electrical Discharge Turning for Aerospace Materials – A Review

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Abstract: ***Electrical discharge machining (EDM) is considered as an efficient and economical machining tool in machining advanced alloys and composites in the present manufacturing industries. It is widely used non-traditional machining approach to generate complex contours on difficult-to-cut materials. The extensive capabilities such as precision, surface quality, ease of cutting distinct electrical conductive materials irrespective of their hardness, promoted this technique for numerous applications in the fields of aerospace, automobile, medical, die and mold production, precision tooling. During the past decades, a variety of EDM technologies were emerging to comply with the complexity of machined contour, metal removal rate, dimensional tolerances, surface integrity, etc. Among these, electrical discharge turning (EDT) is one of the applications of EDM technology developed to manufacture micro and macro axisymmetric cylindrical components such as miniaturized ejector pins in injection molds, components of micro air turbines and pumps, special needle points for human medicine, micro tools or microstamping dies. Turning by EDM has become an emerging area of research in the present and many experimental investigations were reported in the literature in view to improve its performance. In this article, the experimental and analytical investigation performed on the EDT to machine distinct metals, alloys, and composites during the past two decades is critically reviewed and presented its summary. This paper also presents a brief assessment of future research needs in the same area.***

Keywords: Electrical discharge machining, Wire electrical discharge machining, turning by electric discharge machining technology, strip electrical discharge machining, machining of aerospace materials

1. Introduction

Rapid advancements in the modern aerospace industries have witnessed for a widespread use of advanced engineering materials such as superalloys and ceramic and metal based composites for many of their applications, which includes aircraft gas turbines, combustion chambers, and engine valves. High-temperature mechanical strength, resistance to surface wear and creep [1] are the renowned properties of nickel-iron alloys, cobalt, and titanium in the class of super alloys. On the other hand, the metal matrix composites and inter-metallic compounds with their enhanced properties like lightweight, high strength, superior wear resistance at elevated temperatures become a substitution for metals and alloys given increasing the power and efficiency of gas turbine engines [2]. Currently, the use of advanced engineering materials has become vital for not only the aerospace components, but also many of the other components for automobile, naval, medical and high-speed industrial applications.

Besides of the outstanding properties of advanced materials favourable to the applications above, machining of these materials become challenging for the manufacturing industries today. The need of high dimensional accuracy, the superior surface integrity kind of design considerations involved with the aerospace components increased the complexity of machining these materials greatly. Extreme hardness and brittleness made these materials difficult to cut with conventional machining procedures and involved with special tooling and equipment costs. However, non-conventional machining techniques such as laser beam machining, electrochemical machining, water jet machining, electric discharge machining are proven effective with the capability of machining materials regardless of their hardness [3]. Among these non-conventional methods, electrical discharge machining (EDM) is the extensively adopted machining technique to machine advanced materials for aerospace components having complex geometries and high dimensional accuracy.

EDM is a thermo-electrical process. In this process, a series of discrete transient sparks erodes the unwanted portion of the workpiece at the gap between an electrode tool and workpiece in the presence of dielectric fluid. The dielectric fluid acts as an ionized zone, which facilitates a stable and controlled spark gap and serves as a flushing agent to wash and remove the eroded debris from the spark gap. While generating contours of the workpiece, the controlled movement of the electrode decides the required shape and dimensional accuracy of the component. EDM finds huge applications in a wide variety of fields like aerospace, tooling and dies manufacturing and automotive industries as there is no evidence of residual stresses and cutting tool marks on the workpiece.

The working principle of EDM technique is presented in Fig.1.

Consequently, many EDM technologies have been emerged in the modern manufacturing industries to comply with the complexity of workpiece materials, the machining contours, metal removal rate, dimensional tolerance, and surface integrity.

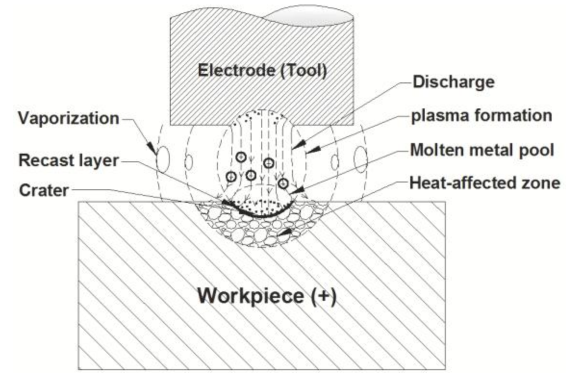

Figure 1: Working principle of Electric discharge machining

The material properties such as hardness, strength, or toughness of the workpiece do not affect the material removal rate in the EDM process since there is no involvement of mechanical energy in its principle. Therefore, to enhance the material removal rate, rotary motion to the electrode in its vertical axis was imparted to incorporate the sufficient flushing conditions in EDM.

By inspiring the results reported in the investigations [4], [5], [6], [7] the electrode rotation in EDM and a gap-flushing method, proved to be really efficient and resulted in a substantial improvement in machining characteristics, e.g. Machining rate, surface finishes and out of roundness. Soni et al. [8], [**9**] Investigated the effect of rotating copper-tungsten electrode and pulse current on the formation of debris during EDM of titanium alloy, and high carbon high chromium dies steel. Ramu et al. [10] used rotary EDM to cut SiC-TiB2 and SiCw/Al with a plate electrode. Mohan et al. [11], [12] used rotating electrode in EDM to machine Al-SiC MMC and found a positive effect with an increasing electrode rotating speed on metal removal rate, tool wear rate, and surface roughness.

Afore discussed investigations are related to the improvement of EDM process performance with the addition of rotating motion to the electrode to drill the workpiece. Turning by electrical discharge machining (EDT) is one of popularly applied EDM technology to manufacture micro and macro axisymmetric cylindrical components such as miniaturized ejector pins in injection molds, components of micro air turbines and pumps, special needle points for human medicine, micro tools or microstamping dies.

This article provides a review of the application of electrical discharge turning (EDT) for various aerospace materials using different EDM process variants.

2. Turning with EDM process variants

This section discusses the working principle of various process variants of electrical discharge machining.

2.1 Electrical Discharge Turning (EDT)

Electrical discharge turning (EDT) is one of the unique configurations of an EDM process is actively developed and applied to fragile, hard to cut materials, especially to machine complex and small cylindrical components. In EDT process, the geometry of the forming tool electrode is reproduced in the rotating workpiece. Ace of the EDM machine's axis is used to rotate the workpiece, and the cutting electrode is fixed stationary on the machine table. The linear feed of the tool imparts the profiled tool geometry onto the circumference of the rotating workpiece.

The concept of EDT process is illustrated in Fig. 1 (a). In EDT process, the metal removal rate depends on the action of thousands of discrete electrical discharges per second between the profiled tool electrode and the rotating workpiece. The produced discharge melts and vaporizes the workpiece material partially and forms tiny craters on the surface of the workpiece. During this process, the tool shape is reproduced onto the workpiece [13].

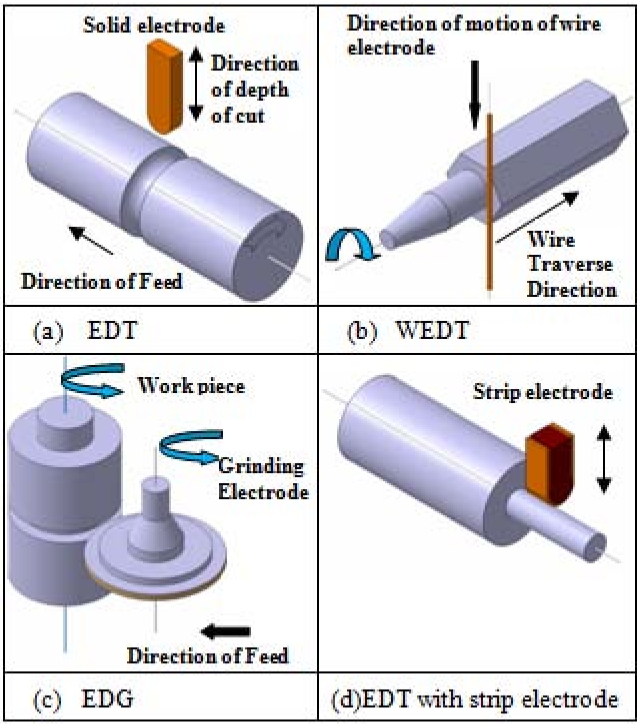

Figure 1: Electric discharge turning using different EDM variants: (a) EDM turning, (b) Wire EDM turning, (c) Electrical Discharge Grinding (EDG), (d) EDT with strip electrode

2.2 Wire electrical discharge turning (WEDT)

Wire electrical discharge turning (WEDT) is part of the novel configuration of a wire electrical discharge machining (WEDM) process developed to produce cylindrical components. A precise rotary spindle is designed and added to the WEDM configuration to enable the generation of free-form cylindrical geometries. The concept of WEDT is illustrated in Fig. 1 (b). In WEDT process, the electrical discharge takes place between the traveling wire and the rotating workpiece (a rotary axis are added to WEDM) that form craters in the presence of dielectric fluid. Discrete spark discharges melt and vaporize the tiny amount of work material. The continuously supplied dielectric fluid flushes away the removed material in the form of debris. In this process, the desired circular forms can be obtained by controlling the electrically charged wire in X and Y directions to remove the unwanted work material.

2.3 Electrical Discharge Grinding (EDG)

Electrical discharge grinding (EDG) and wire electrical discharge grinding (WEDG) are used to machine micro, rotational parts depending on the geometrical complexity of the component. In this process, the electrical discharge machining characterized by a rotating workpiece. WEDG uses fine wire electrodes for their operation and Electrical discharge turning (EDT) uses microstructured tool electrodes and cylindrical electrical discharge grinding (CEDG) uses micro profiled disk electrodes for their operation. In all the above-discussed processes, the working principle is same as of EDM.

3. Literature Review

3.1 Research in CNC EDT for aerospace materials

Several researchers have contributed to the development of the EDT process variant. A high production rate is now possible with the EDT process by introducing four electrodes simultaneously to work on the same profile section. One application of the EDT process of aerospace honeycomb seals were internal, external seals are machined to a burr-free finish with the interior, and outer diameters from 300 to 1400 mm. Speeds are variable between 0-2 rpm. In this process production, time improved by 50% over other, ED machines.

Matoorian and colleagues [14] performed an experimental study of electrical discharge turning (EDT) process on high-speed steel 1.3255. The paper finds the influence of six design parameters, namely, pulse-on time, voltage, pulse-off time, servo, and rotational speed on MRR. Experimental findings indicate that intensity, spindle speed, servo, and pulse-on time are the most important factors affecting the MRR. A mathematical model was derived for MRR using ANOVA, and a good estimate of the material removal rate of EDT parts was found.

3.2 Research in CNC WEDT on aerospace materials

This section discusses the various literature works on WEDT machining of a wide variety of engineering materials such as steels, superalloys, and metal matrix composites.

3.2.1 Steels

Researchers have contributed to the machining of cylindrical steel components using WEDT process. Mohammad et al. [15] carried out a study of surface roughness (Ra), the roundness and material removal rate (MRR) of cylindrical wire electrical discharge turning (CWEDT) of AISI D3 tool steel. In his findings Power, voltage, pulse-off time, and spindle rotational speed are the most influencing parameters on Ra. As the power or voltage will increase, the roughness value also grew. Power, voltage, pulse-off time and spindle rotational speed trailed by the collaboration impacts of power and pulse-off time, voltage and spindle rotation speed.

Haddad et al. [16] investigated the effects of machining parameters on material removal rate (MRR) in cylindrical wire electrical discharge turning (CWEDT) process. AISI D3 tool steel was used as work material for the experiments. The effects of EDM input parameters such as power, voltage, pulse-off time and spindle rotation speed has been analyzed on MRR using analysis of variance (ANOVA). A mathematical model is formulated using response surface methodology (RSM) for MRR.

The same author conducted the next experimental study in the year 2009, [17] based on statistical analysis. The result of input parameters such as force, voltage, pulse-off time and spindle rotational speed was studied experimentally on Ra, roundness, and MRR. Response surface methodology has been used for developing a regression model for MRR, Ra, and roundness. The mathematical models were developed for different machining performance characteristics of the CWEDT process using RSM. These Developed mathematical models are submitted for proper choice of machining parameters for evaluation of Ra, roundness, and MRR under different machining combinations. The same work can be evaluated by the application of Taguchi's method [18]. The machined part surfaces of the CWEDT parts were analyzed to recognize the macro-ridges and craters on the surface using the scanning electron microscope (SEM). EDM parts were analyzed using SEM and micro-hardness tests to measure the sub-surface recast layers and heat-affected zones under particular procedure parameters.

Aravind Krishnan and G.L. Samuel has conducted an observational study on WEDT of AISI D3 (DIN X210Cr12) tool steel [19]. The WEDT is modeled using an artificial network to run forward, backward-propagation algorithm and using the Adaptive Neuro-fuzzy inference system. The writers have been investigated, the combined result of ultrasonic vibration and WEDT process on high-speed steel. During this investigation, the author's has found a 28 % improvement on MRR for the required surface roughness.

An experimental investigation has been constructed to combine ultrasonic vibration and WEDT [20]. The effects of ultrasonic vibration, discharge power, time-off and rotational speed on MRR experimentally investigated. The results show ultrasonic vibration has a substantial impact on MRR in finishing and roughing conditions. The optimal parameter setting results in 2.08026 mm^3/min as MRR. A Mohammadi et al. has investigated the turning of cemented steel with wire electrical discharge machining (TWEDM) [21]. In his findings, Power, Voltage and Servo have the most significant effect on MRR and rotational speed and wire tension have least significant. ANOVA determines wire speed and time-off exhibit no effect on MRR. The same authors [22] has been analyzed the essence of power, time-off, voltage, servo, wire tension, wire speed and rotational speed experimentally on the surface roughness and roundness. The results showed, only power has a significant effect on the surface roughness. The parameter's wire speed, power, and servo on roundness are greater significant than time-off, voltage, wire tension, and rotational speed. Balamurali et al. [23] investigated the effects of machining parameters on MRR and surface roughness in the CWEDT process. Stainless steel of grade (316) was used for the experiments. The machining parameters such as rotational speed, pulse-off time, pulse-on time, wire feed and spark gap have been studied using a

Taguchi method. The author has found, Rotational speed is the most significant parameter on MRR and pulse-on time influences the surface roughness significantly. Anjaneya Prasad et al. [24] studied the Metal removal rate, surface roughness and mechanical evaluation while machining on different materials like En8, En31 and HCHC. The results show that the effect of the impulse on surface finish as the pulse rate increases the surface roughness increases, due to greater crater generated. The material transfer from tool wire affects the surface condition in the machined surface.

3.2.2 Superalloys

The machinability of titanium and its alloys are in general poor in conventional machining due to several inherent properties of the materials. Titanium has a tendency to weld to the cutting tool owing to its chemical reactivity results in chipping and premature tool failure during machining [25]. Moreover, resulting from its low thermal conductivity the heat produced at the tool/workpiece interface increases adversely, which affects the tool life enormously. From the literature, it is found that numerous researchers have tried previously to improve the functioning of the WEDT process such as surface roughness, reducing speed, dimensional accuracy, and material removal rate.

K. Ponappa et al. [26] investigated the influence of EDM parameters on various aspects of the surface integrity of Ti-6Al-4V with different electrode materials. Farnaz Nourbakhsh et al. [27] investigated the WEDM process parameters such as cutting speed, surface roughness and wire rupture of Ti-6Al-4V about processing parameters and different wire electrode materials.

Shajan Kuriakose et al. [28] investigated the surface characteristics of Ti-6Al-4V during the WEDM process by employing the Taguchi method and analysis of variance. Shajan Kuriakose and their colleagues observed that more uniform surface characteristics are obtained with coated wire electrode. Moreover, the time between two pulses has more influence on the formation of a layer consisting of a mixture of oxides. The time gap between two pulses have a lower value, a considerable reduction in the formation of oxides can be obtained.

Naresh et al. [29] conducted an experimental study on the effect of machining parameters on the metal removal rate (MRR) and surface roughness (Ra) of Ti-6Al-4V superalloy in WEDT process. The analysis of variance (ANOVA) is adopted for studying the individual and interaction effects of measured responses. In this experimental study, the responses correlate with each other, so the problem is resolved by considering it as a multi-objective optimization problem. The gray relational analysis as an integrated multi-response optimization technique is adopted to derive the optimal WEDT conditions. The results are found in good correlation.

3.2.3 Metal-matrix Composites

In the last few decades, several attempts have been carried out with the machine, WC-Co with EDM and WEDM. Qu et. al. [30] conducted experiments to explore the maximum MRR for cylindrical and 2D wire EDM of tungsten carbide and brass work-materials. A mathematical model developed for the MRR of cylindrical wire EDM. The outcomes indicate that the MRR for the cylindrical wire EDM was higher than that in 2D wire EDM of the same work-stuff. The practicality of wire-EDM of cemented tungsten carbide was additionally researched by Levy and Wertheim [31] and their test information uncovered that WEDM will be an efficient process to shape the cemented carbide.

On the other hand, Mahdavinejad [32] found some unstable machining during EDM of a tungsten carbide composite. The problem in machining of WC-Co with EDM resides in the differences in melting and evaporation points of the cobalt and tungsten carbide. The melting and evaporation temperature of cobalt is less than the tungsten carbide. Therefore, the energy of the discharge will melt, evaporate and remove the cobalt before even melt of tungsten carbide. Cobalt grains will not hold and the surroundings of tungsten carbide grains and the released grains of tungsten carbide cause instability in the machining process because of their gathering and re-solidification.

Shah et al. [33] investigated the effect of varying seven different machining parameters in addition to varying the material thickness on machining responses such as MRR, kerf and surface roughness of the tungsten carbide machined by WEDM. The author made a comprehensive analysis of the effect of the workpiece thickness along with other important control factors on three critical machining outcomes of WEDT. The results exposed the material thickness has little effect on the MRR and kerf but is a significant factor regarding surface roughness.

Puertas et al. [34] investigated the influence of EDM parameters such as intensity, pulse time and duty cycle on the machining characteristics of tungsten carbide. Machining characteristics were surface roughness, volumetric electrode wear, and MRR. Garg et al. [35] reviewed the work on the EDM and WEDM of a metal matrix composite (MMCs). The review brought out that 29% of the published work deals with WEDM while 71% work is on die sinking EDM.

Jangra K et al. [36] evaluated the WEDM process machinability aspect of tungsten carbide using digraphs and matrix method. The same author [37] reported the WEDM machining of WC-5.3%Co composite. The author investigated six machining parameters, namely taper angle, peak current, pulse-on time, pulse-off time wire tension and the dielectric flow rate. The machining parameters such as taper angle, pulse-on time and pulse-off time affect the MRR and SR. Moreover, Lee and Li [38] have considered the influence of operating parameters on the machining attributes tentatively during EDM of WC. The results proposed that better execution can be stated on the electrode as the cathode and workpiece as anode and devices with negative polarity give higher MRR, lower tool wear and better surface finish.

Jangra et al. [39] conducted experiments on wire electrical discharge machining of four hard to machine materials to examine the rough and trim cutting operations. The results show that surface characteristics may improve by maintaining appropriate wire offset and correct machining parameters in a single trim cutting operation and irrespective of the rough cutting operation. The same author [40] extended the experimental study to investigate the multi-pass cutting operation in WEDM of WC-Co composite. Taguchi method is employed to do the trim cut experiments and to study the influence of machining characteristics such as rough cut history, discharge current pulse-on time and wire offset on two performance characteristics namely the depth of material removed and surface pitting. A technological data have provided in a rough and trim cut on WEDM for efficient machining of WC-5.3%Co composite. Despite the fact that comprehensive reviews on the electrical discharge machining (EDM) [41] wire electrical discharge machining (WEDM) [42] and current research trends in EDM have been described. On the other hand, very few works have been reported on the EDT and its varieties, for the machining of primary and difficult-to-cut tungsten carbide.

4. Research in CNC EDG & WEDG of Aerospace Materials

Shih and Ming Shu [43] investigated the electrical discharge grinding of cold working tool steel AISI D2 using a rotating disk electrode. The experimental results indicate that higher MRR and lower electrode wear rate with a positive polarity electrode and lower roughness with negative polarity with shorter pulse duration. The machining parameters such as rotating speed of electrode, discharge direction and flushing direction effects the MRR and roughness. Electrode with positive polarity with longer pulse duration lowers the electrode wear rate. EDM using negative polarity increases the micro craters density and microhardness values.

Uhlmann et al. [44] investigated an Electrical discharge grinding (EDG) on cold working steel 90MnCrV8 for evaluating the effects of high peripheral speed on process behavior and surface topography. They compared EDM process variants such as EDT, EDG, and WEDG on the influence of the peripheral speed. The investigation revealed that the rotational movement highly influences in all three machining process variants. This inquiry reports that the increasing circumferential speed decreases the crater formation because of the local expansion of the temperature distribution. Moreover, the growing trend of circumferential speed with higher discharge energies increases the MRR and SR increases with rotation.

The same authors [45] extended their investigation on cold working steel 90MnCrV8 material using wire electrical discharge grinding (WEDG). The author talks about the kinematic and technological limitations of the WEDG process influencing the process behavior on the technological requirements of micromachining. The circumferential velocity maintained in the range of 0.25 m/s < V_u <1.25 m/s. The best surface finish was seen with an arithmetic mean deviation of Ra=0.38 µm. There is no surface modifications observed related to the WEDG process. A new method, WEDG for EDM'ing very thin rods is proposed [46]. In this investigation, the results show that the method provides high accuracy and excellent repeatability with the less error than 1µm. Very few works have reported on EDG and WEDG of cylindrical parts made from aerospace materials.

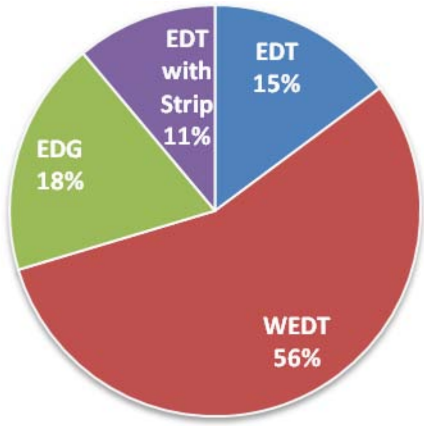

Figure 2: Percentage distribution of various process variants of electrical discharge turning

5. Research in strip EDM Turning on Aerospace Materials

E Ki Young Song et al. [47] developed a new strip EDM Turning method that uses a thin strip electrode. The strip was made of brass and performed the same function as wire in WEDM. The experiments are conducted in stainless steel-304 in strip EDM turning. Under the same machining conditions, the results indicate that the MRR of the strip-EDM turning was 74.3% higher than the MRR for wire-EDM turning and also the EDMed surface was smoother.

The literature shows [48], [49] that only normal turning and taper turning work have been attempted so far; however, no research work has been found on the free - form profile turning in the context of strip EDM Turning. The strip EDM turning has given new hope for manufacturing industries to overcome the limitations of WEDM on MRR and Ra and wire breakage up to a certain extent. Tiny published research is found in this field due to the methodology is novel.

6. Future Directions of Research

Future advancements in the field of EDT process and its variants of advanced materials will continue towards understanding the Science and technology of the process as well as extending the application of the process for the manufacturing industries. Following is a list summarizing an extended probe of the published work, future research opportunities, and challenges in the area of EDT of advanced materials companying conclusions.

- EDT is a powerful machining method for producing intricate cylindrical profiles, in a wide range of materials irrespective of their hardness and strength.
- Figure 3 shows the most of the published research work has been carried out on WEDT of diverse materials and not so much work has been reported on the EDT and EDG.
- WEDT machining of AISI D3 tool steel is identified, in most of the research work published. Very few works have been recorded on a metal matrix composite material.
- Numerous useful MMCs have not meant attempted as work material on the EDT process.

- Very few works reported on the EDT process on aerospace materials.
- Even though research work has been identified on the EDM and WEDM of MMCs, the application of CNC EDT process on many MMCs is yet to be explored since very few research works have been reported in these areas.
- No work has been reported on Electrical discharge turning and research courses for the machining of critical and difficult-to-cut tungsten carbide material.
- Development of newer hybrid EDM machining has the potential to combine the strength and to defeat the weakness of different processes.

7. Summary

A critique of the research works on aerospace material with various CNC EDT process variants are given in this report. A research study on the application of CNC WEDT, EDG, and WEDG on different aerospace materials are discussed. In most of the research work, the CNC WEDT is carried out on AISI D3 steel, carbide steel, stainless steel, Ti-64 titanium alloy. Plenty of future scope for the EDT, WEDT and EDG machining of cylindrical components of MMCs and Ceramics. The development hybrid EDM machine tool can significantly improve the advanced research in the areas of turning with EDM and turning with strip EDM based hybrid machining.

References

[1] Choudhury I, El-Baradie M. “Machinability of nickel-base super alloys: a general review,” Journal of Materials Processing Technology, 77(1), pp. 278-284, 1998.
[2] Weinert K, Biermann D, Bergmann S. “Machining of high strength light weight alloys for engine applications,” CIRP Annals-Manufacturing Technology, 56(1), pp. 105-108, 2007.
[3] Rao TB, Krishna AG. “Simultaneous optimization of multiple performance characteristics in WEDM for machining ZC63/SiCp MMC,” Advances in Manufacturing,1(3), pp. 265-275, 2013.
[4] Soni J, Chakraverti G. “Production of surface finish and accuracies with rotating electrode in electro-discharge machining,” In Proceedings of the Conference 14th AIMTDR, IIT Bombay; 1990.
[5] Erden A. “Role of dielectric flushing on EDM performance,”. In Proceedings of International Machine Tool Design and Research Conference, pp. 283, 1982.
[6] Kagaya K, , Yada K. “Micro-electrodischarge machining using water as a working fluid—I: micro-hole drilling,” Precision Engineering. 8(3), pp. 157-162, 1986.
[7] Sato T, Mizutani T, Yonemochi K, Kawata K. “The development of an electrodischarge machine for micro-hole boring,” Precision engineering. 8(3), 163-168,1986.
[8] Soni J. “Microanalysis of debris formed during rotary EDM of titanium alloy (Ti 6A1 4V) and die steel (T 215 Cr12),” Wear, 177(1), pp. 79,1994.
[9] Soni J, Chakraverti G. “Surface characteristics of titanium with rotary EDM,”. Bulletin of Materials Science, 16(3), pp. 213-227, 1993.
[10] Ramulu M. “EDM sinker cutting of a ceramic particulate composite, SiC-TiB2,” Advanced Ceramic Materials;(USA), 3(4), 1988.
[11] Mohan B, Rajadurai A, Satyanarayana K. “Electric discharge machining of Al-SiC metal matrix composites using rotary tube electrode,: Journal of materials processing technology,153, pp. 978-985, 2004.
[12] Mohan B, Rajadurai A, Satyanarayana K. “Effect of SiC and rotation of electrode on electric discharge machining of Al--SiC composite,” Journal of Materials Processing Technology, 124(3) pp. 297-304, 2002.
[13] Ramasawmy H, Blunt L. “Effect of EDM process parameters on 3D surface topography,” Journal of Materials Processing Technology, 148(2), pp. 155-164, 2004.
[14] Matoorian P, Sulaiman S, Ahmad M. “An experimental study for optimization of electrical discharge turning (EDT) process,” Journal of Materials Processing Technology, 204(1), pp. 350-356, 2008.
[15] Haddad MJ, Tehrani AF. “Investigation of cylindrical wire electrical discharge turning (CWEDT) of AISI D3 tool steel based on statistical analysis,” Journal of materials processing Technology,198(1), pp. 77-85, 2008.
[16] Haddad M, Tehrani AF. “Material removal rate (MRR) study in the cylindrical wire electrical discharge turning (CWEDT) process,” journal of materials processing technology,199(1), pp. 369-378, 2008.
[17] Haddad M, Tajik M, Tehrani AF, Mohammadi A, Hadi M. “An experimental investigation of cylindrical wire electrical discharge turning process using Taguchi approach, International Journal of Material Forming. 2(3), pp. 167-179, 2009.
[18] Haddad MJ, Alihoseini F, Hadi M, Hadad M, Tehrani AF, Mohammadi A. “An experimental investigation of cylindrical wire electrical discharge turning process, The International Journal of Advanced Manufacturing Technology, 46(9-12), pp. 1119-1132, 2010.
[19] Krishnan SA, Samuel G. “Multi-objective optimization of material removal rate and surface roughness in wire electrical discharge turning,” The International Journal of Advanced Manufacturing Technology, 67(9-12), pp. 2021-2032, 2013.
[20] Mohammadi A, Tehrani AF, Abdullah A. Investigation on the effects of ultrasonic vibration on material removal rate and surface roughness in wire electrical discharge turning. The International Journal of Advanced Manufacturing Technology, 70(5-8), pp. 1235-1246, 2014.
[21] Mohammadi A, Tehrani AF, Emanian E, Karimi D. “Statistical analysis of wire electrical discharge turning on material removal rate,” Journal of materials processing Technology, 205(1), pp. 283-289, 2008.
[22] Mohammadi A, Tehrani AF, Emanian E, Karimi D. “A new approach to surface roughness and roundness improvement in wire electrical discharge turning based

on statistical analyses," The International Journal of Advanced Manufacturing Technology, 39(1-2), pp. 64-73, 2008.

[23] Balamurali D, Manigandan K, Sridhar V. "Analysis of the Effect of Machining Parameters on Wire Electrical Discharge Turning of Stainless Steel," Analysis, 2(1), pp. 34-41, 2015.

[24] Anjaneya Prasad, B., A. Chennakesava Reddy, "Regression analysis approach for predicting process output variable in WEDM," National conference on Computer Applications in Mechanical Engineering (CAME), 2005.

[25] Rahman, M., Wong, Y. S., & Zareena, A. R. "Machinability of Titanium Alloys," *JSME International Journal Series C*, *46*(1), 107-115, 2003.

[26] Ponappa K, Aravindan S, Rao P, Ramkumar J, Gupta M. "The effect of process parameters on machining of magnesium nano alumina composites through EDM," The International Journal of Advanced Manufacturing Technology, 46(9-12),pp. 1035-1042, 2010.

[27] Nourbakhsh F, Rajurkar KP, Malshe A, Cao J. "Wire electro-discharge machining of titanium alloy," Procedia CIRP, 5, pp. 13-18, 2013.

[28] Kuriakose S, Shunmugam M. "Characteristics of wire-electro discharge machined Ti6Al4V surface," Materials Letters, 58(17), pp. 2231-2237, 2004.

[29] Baki N, Reddy AC, Rao TB. "SELECTION OF OPTIMAL PROCESS PARAMETERS IN WIRE-ELECTRICAL DISCHARGE TURNING WHILE MACHINING TI-6AL-4V ALLOY," In: International Conference on Advanced Materials and manufacturing Technologies (AMMT); 2014.

[30] Qu J, Shih AJ, Scattergood RO. "Development of the cylindrical wire electrical discharge machining process, part 1: concept, design, and material removal rate," Journal of Manufacturing science and engineering, 124(3), pp. 702-707, 2002.

[31] Levy G, Wertheim R. "EDM-machining of sintered carbide compacting dies," CIRP Annals-Manufacturing Technology, 37(1):175-178, 1988.

[32] Mahdavinejad R, Mahdavinejad A. "ED machining of WC-Co," Journal of materials processing technology. , 162, pp. 637-643, 2005.

[33] Shah A, Mufti NA, Rakwal D, Bamberg E. Material removal rate, kerf, and surface roughness of tungsten carbide machined with wire electrical discharge machining. Journal of materials engineering and performance, 20(1), pp. 71-76, 2011.

[34] Puertas I, Luis C, Alvarez L. "Analysis of the influence of EDM parameters on surface quality, MRR and EW of WC-Co," Journal of Materials Processing Technology, 153, pp. 1026-1032, 2004.

[35] Garg R, Singh K, Sachdeva A, Sharma VS, Ojha K, Singh S. "Review of research work in sinking EDM and WEDM on metal matrix composite materials". The International Journal of Advanced Manufacturing Technology, 50(5-8), pp. 611-624, 2010.

[36] Jangra K, Grover S, Chan FT, Aggarwal "A. Digraph and matrix method to evaluate the machinability of tungsten carbide composite with wire EDM,". The International Journal of Advanced Manufacturing Technology, 56(9-12), pp. 959-974, 2011.

[37] Jangra K, Grover S, Aggarwal "A. Optimization of multi machining characteristics in WEDM of WC-5.3\% Co composite using integrated approach of Taguchi, GRA and entropy method," Frontiers of Mechanical Engineering, 7(3), pp. 288-299, 2012.

[38] Lee S, Li X. "Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide," Journal of materials processing Technology. 115(3), pp. 344-358, 2001.

[39] Jangra KK. "An experimental study for multi-pass cutting operation in wire electrical discharge machining of WC-5.3% Co composite," The International Journal of Advanced Manufacturing Technology, 76(5-8), pp. 971-982, 2015.

[40] Kumar V, Jangra K. "An experimental investigation and statistical modelling for trim cutting operation in WEDM of Nimonic-90." International Journal of Industrial Engineering Computations, 6(3), pp. 351-364, 2015.

[41] Ho K, Newman S. "State of the art electrical discharge machining (EDM)," International Journal of Machine Tools and Manufacture, 43(13), pp. 1287-1300, 2003

[42] Ho K, Newman S, Rahimifard S, Allen R. State of the art in wire electrical discharge machining (WEDM). International Journal of Machine Tools and Manufacture, 44(12), pp. 1247-1259, 2004.

[43] Uhlmann E, Piltz S, Jerzembeck S. Micro-machining of cylindrical parts by electrical discharge grinding. Journal of Materials Processing Technology, 160(1), pp. 15-23, 2005.

[44] Uhlmann E, Piltz S, Oberschmidt D. "Machining of micro rotational parts by wire electrical discharge grinding," Production Engineering,2(3), pp. 227-233, 2008.

[45] Shih HR, Shu KM. "A study of electrical discharge grinding using a rotary disk electrode," The International Journal of Advanced Manufacturing Technology,38(1-2), pp. 59-67, 2008.

[46] Song KY, Chung D, Park M, Chu C. "Development of strip EDM," Procedia CIRP, 6, pp. 53-57, 2013.

[47] Masuzawa T, Fujino M, Kobayashi K, Suzuki T, Kinoshita N. "Wire electro-discharge grinding for micro-machining," CIRP Annals-Manufacturing Technology, 34(1), pp. 431-434, 1985.

[48] Ki Young Song DKCMSPCNC. "Electrical discharge machining using a strip electrode," Precision Engineering, 37, pp. 738-745, 2013.

[49] Ki Young Song DKCMSPCNC. "EDM turning using a strip electrode," Journal of Materials Processing Technology, 213, pp. 1495-1500, 2013.