The Scope of Machining of Advanced Ceramics by Electro-Discharge Machining and Its Hybrid Variants

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ABSTRACT

The constraints with the applicability and technological limitation of metal and alloy lead to the origin of advanced ceramics products or devices to enhance the system productivity and effectiveness. Advanced ceramics matrix composites (CMCs), metal nanocomposites are prepared by pressing and high-temperature sintering. The excellent properties of ceramics are preserved by the amalgamation of metal or semiconducting phase with the convention ceramics. Electro-discharge machining (EDM) has the capability to machine very rigid to cut materials that are extremely difficult to the shape by any other regular method. In the past decade, many types of research have explored machining of advanced ceramics by EDM process and came out to be some unique process to machine even non-conventional ceramics and CMCs. Electro-discharge machining (EDM) has the capability to machine very rigid to cut materials that are extremely difficult to the shape by any other regular method. In the past decade, many types of research have explored machining of advanced ceramics by EDM process and came out to be some unique process to machine even non-conventional ceramics and CMCs. Many research have been found in the field of hybrid EDM process to improve the machining outcome and more efficient use of the EDM tool. One of the revolutionary findings is to machining of non-conductive advanced ceramics by EDM process. In the present paper, a critical review of advanced ceramics machining by EDM and its hybrid for ceramics and its composite are presented.

Keywords: advanced ceramics; hybrid-EDM, mechanism

INTRODUCTION

The exposure of the manufacturing and production industries to use engineering ceramics is increasing for the last two decades because of their outstanding mechanical, chemical and thermal properties. Among various ceramics oxides of aluminum and zirconium are widely used for industrial applications that are gas sensors, a component of the pump and medical instruments [1]. Advanced/ engineering ceramics are used as machine tool, aerospace parts, automobile parts and electronics parts [2]. They are mostly used in dental prosthesis such as dental-crown, denture, orthopedics, automotive brakes, sensors, advanced computer memory products [3][4]. Advanced ceramics not only encourage going beyond the performance limit of metal but also overcoming the technological limitation imposed by conventional materials used in industries. Advanced ceramics are the materials of having excellent resistant to thermal degradation and mechanical wear, stronger electromagnetic response, high refractoriness etc. [5]. However such properties are of good signs for application but the fabrication and machinability characteristics such as high rise in machining force, elevated temperature, and substandard surface finish and shorten tool life leads ceramics, as very difficult to cut materials hence results in partial acceptance in the field of industrial application [6][7]. To overcome the problem of machining advanced ceramics, both regular and advanced processes are explored. The
requirements of advanced-ceramics machining are to have good surface integrity, high geometrical characteristics and high material removal rate but these are very difficult to achieve by conventional machining process as high cutting forces causing strength abasement due to the formation of microcracks on the surface. Non-conventional machining process can be used to overcome the machinability limitation of advanced ceramics as their mechanism removal mechanisms are different than that of conventional one as they used mechanical (AJM, USM, WJM AWJM) Electro-thermal (EDM, laser, EBM), chemical (chem. etching, ECM ) etc. energies to machine the part. Among various non-traditional machining process, Electro-Discharge Machining (EDM) is exploring for machining of intricate shaped, hardened parts in recent year in a flexible and accurate manner [8]. EDM is an auspicious technique for production of advanced-ceramics parts. In EDM, the material abrades from the workpiece when a series of discharge takes place between two electrodes i.e. cathode and anode that are submerged in dielectric fluid. The cathode (negative electrode) is progressed toward the workpiece until the gap is minuscule so that, applied voltage ionized the dielectric thus repeated sparking and ionization amidst the two electrodes. The discharge is creating a plasma channel that makes possible the exodus of ions and electrons between cathode and anode, the temperature of the plasma is very elevated i.e. in the range of 20000°C. There is no physical contiguity of cathode (tool) and anode (workpiece) thus mechanical chatter and trembling problem can be eliminated in machining [9] [10]. Material irrespective of their hardness, brittleness softness and fragileness can be machined by EDM [11].

Many researchers have explored ceramics machining by EDM process for developing miniaturized products of hard and difficult to cut materials. These are some characteristics of the EDM process that shows various areas in which the improvement is needed for a better outcome (Table 1).

1.1 Characteristics of EDM process

- **Ultra Miniaturized machine parts**

EDM has the ability to machine miniaturized machined parts of metal, metallic alloy, graphite, and ceramics irrespective of the hardness and brittleness [12]. Liu et al. [13] have developed ultra-miniaturized gas turbine impeller of Si₃N₄-TiN ceramics (diameter 20 mm) for power unit based on micro fuel.

- **High-precision machining**

EDM successfully machined intricate shapes efficiently and precisely irrespective of the dimensions and material of the product Gupta et al. [14] have manufactured miniature spur gears by wire-EDM that are of better geometrical quality than conventional miniature gear.

- **Number of hybrid-variants**

EDM provides the advantage of providing a number of varieties in the process which make it agreeable to be applying for various kinds of materials, with the kinematic change in tooling and setup. ED drilling, Wire
EDM, ED diamond grinding and ED-milling are some of the variants of EDM. Ravinder et al. [15] have modified electrodes by creating inclined micro slots for eliminating the accumulation of debris during machining and ended with better geometrical characteristics i.e. large aspect ratio, low taper angle, the low corner radius of the drilled hole. Koshy et al. [16] have fabricated regular and non-regular polygon shapes with sharp corner using kinematics of the Reuleaux triangle.

- **Machining electrically conducting material**
  EDM is application is limited to metal, advanced ceramics, ceramics matrix composites (CMCs) which possess electrical resistivity of below 100 Ωcm [17][18]. Although, some researchers have successfully worked in the area of EDM of non-conductive ceramics with assisting electrode method. Sabur et al. [19] have machined ZrO2 by copper (Cu) as an assisting electrode and succeed to remove a small amount of material. Schubert et al. [20] have also used starting a conductive layer as a second electrode for micro-machining of insulating ceramics.

- **Low energy efficiency**
  A small amount of energy of total input energy is used for material removal and stored in electrodes in EDM. Maximum amount of input energy is lost in dielectric due small discharge area and temperature gradient in the dielectric fluid. Approximately 18–50% of the total energy is utilized in the EDM. Many researchers are working in the field of optimizing EDM energy in material removal. Obwald et al. [21] observed that only 40% of total energy is distributed to electrodes [22].

- **Costly process**
  EDM is a costly process as compare to the conventional machining process as not only material removal rate is less but also tool fabrication is an exorbitant process [10]. High tool wear in EDM process also added the extra cost of the machining and inaccuracies in machining components. Researchers are trying to compensate for the cost of machining by improving productivity, optimizing the tool wear and surface integrity. In order to enhance the response parameters in the EDM, many augments are provided with the primary configuration. These changes result in developing EDM based hybrid method for further process enrichment.

### Table 1: Research possibility in various areas in EDM and possible outcomes

| Research Area     | Research Need | Possible Outcomes                        |
|-------------------|---------------|------------------------------------------|
| Ceramics          |               | Products of better performance than metal |
| Ceramic composites|               | Better MRR, Lower machining cost          |
| Electrode wear rate|               | Low the ENR, Reduction in machining cost |
| Ceramic composites|               | More surface finish, Less H2O2            |
| Geometrical       |               | Reduction in taper angle, Reduction in radial overcut, Reduction in corner radius |
| characteristics    |               |                                          |
| Aspects           |               | Deep holes, the cavity can be fabricated, Deep features can be fabricated |
| Dieteric          |               | Lower machining cost, Reduction of hazardous effect on the environment |
conducte composite and mechanism of material removal by EDM and its variants. The future direction of research is also presented in the last section.

1. CERAMICS

Advanced ceramics are an emerging class of material recognized for its high strength, chemical inertness, high toughness and excellent wear resistance have a high potential for a wide variety of industrial applications [23]. Although ceramics possess phenomenal physical properties, ceramic's full-scale application is still not achieved due to difficulties in processing and high manufacturing cost [24]. Advance ceramics likely to have extensive application in industries because of its outstanding mechanical, chemical and thermal properties. Industrial machinery products i.e. wear parts, sensors, micro fuel pump, bearings and medical implants are some basic applications of advanced ceramics. A classification of mostly used advanced ceramics based on their applicable field and specific applications is shown in Fig. 1. The main problem with ceramics is that they are very complex in machining [6]. Diamond grinding is used commonly for ceramics machining. But this method is expensive and inefficient. Higher grinding forces induces in this process leads to quick decay in tool edges [25]. Advanced ceramics are facing difficulty in machining as mostly process are slow and expensive. EDM is an appropriate process to machine advanced ceramics because of it's with its near force less non-contact type of machining that is independent of hardness and brittleness of material [20].

EDM allows machining intricate shaped harden conductive parts in a versatile and correct way. The EDM performance of ceramics is affected by various parameters as shown in Fig. 3.
EDM holds the capability of machining and fabrication low cost, tool and parts from conducting ceramic blanks in a precise manner. The capacity of EDM of machining without any physical contact eliminates mechanical chatter and vibration that could damage ceramics during conventional machining [9].

2.1 Research on the EDM of advanced ceramics
Advanced ceramics that possesses electrical conductivity exceeds a particular threshold value of the order of 0.01 S/cm (or resistivity less than 100 Ωcm) [26] could be machined by EDM. While machining by EDM in advanced ceramics, the thermal spalling mechanism is more predominant material removal mechanism [1]. There are no. of EDM variant are possible as shown in Fig. 4, showing the feasibility of machining various different type of shape and properties of the material.

In the case of ceramics that are originally nonconductive in nature with an alumina (Al₂O₃), silicon nitride (Si₃N₄) or Zirconia (ZrO₂) matrix, electrically conductive foreign particles need to be added in the parent ceramics matrix for originating electrical conductivity and enhancing specific property [27].

| Advanced ceramics Machining by EDM for Last Ten Year |
|------------------------------------------------------|
| 2010 | Hybridization [38] |
| 2007 | Insulator design [37], hybridization of process [30], composite research [36,35,34], surface treatment [33,32], insulation design [31], surface layer control [30], micro machining, applications [37] |
| 2016 | Composite ceramics [4], hybridization of process, surface improvement [51], parameter optimization, Micro machining [4], research study, insulator design [30] |
| 2015 | Ceramic machining [59], hybridization of process [59,58,57,56], mechanism of material removal [41], Insulation parameter study [40] |
| 2014 | Hybridization of process [49], composite composite Machining [47,45], effects of coated parameter [44] |
| 2013 | Insulated insulator [3,2], Advanced design control [3,2], micro machining [20], mechanism of material removal [29], hybridization of process [29] |
| 2012 | Hybridization of process |
| 2011 | Mixed electrode improvement [27], ceramic composite [25,26], hybridization of process |
| 2010 | Material removal study [22], parameter optimization study [22] |
| 2009 | Machining characterization [21,20], Hybridization of process, insulated surface study [19,18], insulated design [17] |
| 2010 | Hybridization of process, insulated surface study [17,16], new technology development [15], ceramic composite [14] |
| 2007 | Insulated surface characterization, enabling [15,14], micro machining |

2.2 Nonconductive ceramics machining in EDM
Non-conductive or insulated ceramics possess excellent physical and chemical properties. Metallic and non-metallic elements are present in the basic composition of insulating ceramics. They are used in a no. of industrial applications in automotive spark plug as an electrically and thermally insulator. They are also used in industrial, domestic and building products. The applications are including cutting-tools, bearing, turbine blade, heat exchanger, automotive brake, diesel particulate filters, prosthetic products, dental implants and ceramic-sensors etc. [68]. Machining of insulated ceramics can also be done by the EDM process. But as we know the workpiece should be conductive in nature to carry out the process. So while machining insulated ceramic an assisting electrode has to be used as shown in Fig. 2. The development of secondary electrode (assisting layer, conductive layer) has enabled
insulating ceramics for machining by EDM\textsuperscript{12}. In assisting the electrode method of machining non-conductive ceramics, the surface of the material is coated with highly electrically conductive material like silver or copper paint. Conductive layer makes possible for spark and that leads to the removal of the materials as spark energy causing cracks on the work-piece\textsuperscript{68}. As the assisting conductive layer machined, a new rebuilt conductive layer (pyrolytic carbon) is formed by carbon particles from the particles of dissociation of dielectric (kerosene, hydrocarbon) molecule at high plasma energy\textsuperscript{20}. The process of deposition of conductive rebuilt layer greatly enhances spark stability\textsuperscript{72}. This pyrolytic carbon layer provides the necessary electrical conductivity to progress the process as shown in Fig. 4\textsuperscript{4}. Some researchers have successfully machined non-conductive ceramics by using copper foil\textsuperscript{68}, silver paint\textsuperscript{20}, metal mesh\textsuperscript{74}, carbon baked layer\textsuperscript{75}. Some primary characteristics of non-conductive ceramics machining by EDM are shown in Table 2.
In the EDM process, melting, vaporization, and evaporation are the mechanism of material removal that occur at a very high temperature between the electrodes i.e. cathode and anode \[^{78}\][79]. EDM of non-conductive ceramics, the main mechanisms that occur due to spark erosion of ceramic materials are fracture-related spalling and microcracking that purely depends on properties of ceramics and EDM parameters (Fig. 3).

Numbers of attempts have been made to interpret the basic physics of material removal during EDM of ceramic matrix composites (CMCs). In ceramics machining EDM, Spalling is observed to be another important EDM material removal mechanism. In spalling a very little portion of parent material will be part. The regimes with high discharge energy tend to have larger microcracks. Perpendicular and parallel microcracks are generated due to the spalling effect on the top surface \[^{80}\][81]. Successive discharge of EDM leads to removal of large volume of material much easier. Lower toughness or strength of cracked surface facilitates an increase in cutting speed. A relatively large particle removal in the form of flakes takes place in spalling \[^{69}\]. It is better to have spalling during machining of ceramics because less amount of discharge energy is needed for generating subsurface cracks and for flakes detachment than that of melting, vaporization \[^{82}\]. If irregular size debris, micro flakes, microcracks are observed on the machined surface those are due to spalling effect.
Sabur et al. [83] have machined ZrO₂ ceramics by EDM process and clearly indicated melting and spalling in the Fig. 6. The melting region shows spherical resolidified surface on the other hand spalled area is filled with irregular debris and microcracks. The thermal spalling area with high energy results in larger microcracks. Due to spalling-effect, larger microcracks generated are mostly perpendicular and parallel to the top surface [81].

Schubert et al. [20][4] have machined zirconia ceramics by assisting conductive layer EDM method. It is observed that sparking were steady even after the electrically conducting starting layer has been removed. They also compare the machined surface of steel and zirconia ceramics and observed surface roughness values were factor 2.5 higher than those of steel as shown in Fig. 5. In the case of insulated ceramics machining by EDM, the machined surface found to be rougher than metal as removal mechanism was not only melting or evaporation but also thermal spalling.

### 2.3 Conductive ceramics machining by EDM

A secondary conducive phase has to be added to increase the electric ‒ conductivity of the advanced ceramics. The resultant ceramic-matrix composites (CMCs) possess better fracture toughness, hardness and strength [6] [27]. Lauwers et al. have concluded that the fracture toughness remains modest and such composite cannot be used in high tensile force applications as they may fracture and explode in a brittle manner. To avoid such failure due to change in a mechanical property of CMC, a limited amount of secondary phase has to be added [84] [27]. Many researchers have been working in the area of EDM and its variant of CMC. The fundamentals of EDM process mechanism and research works carried have been discussed with primary characteristics in Table 4.
The material removal process of conductive ceramics by EDM is illustrated in Fig. 8 that shows the two principal mechanisms i.e. melting, evaporation and thermal spalling depending on the properties of advanced ceramics or ceramics matrix composite (CMC) and the process parameters of EDM [65]. Pitman et al. [80] have studied die-sink EDM while machining zirconia-based CMCs that contains 30 vol.% of TiN and concluded that the rapid increase in temperature subsurface crack formation. Hu et al. [67] have studied the mechanism of material removal of Ti₃SiC₂ ceramic during EDM. They explained that melting and decomposition were contributing in removing material during EDM of CMC. The thermal spalling also led to strength degradation for the workpiece.

Spalling is observed to be another important EDM material removal mechanism in ceramic-composite or conductive ceramics along with melting as shown in figure 8 (a), 8 (b) and 8 (c). The thermal shock induced cracks also improve the MRR as lower toughness or strength of work material [227][82]. In spalling large portion of material removed in the form of flakes thus spalling is an important mechanism of material removal while working ceramics and CMCs. The amount of discharge energy needed to propagate subsurface cracks and to remove the material in the form of flakes is much less as compared to discharge energy required in melting and [80].

### Table 1 Major conclusion and finding of EDM of conductive ceramics

| Machining process | Work material  | Major conclusion/finding: benchmark |
|-------------------|----------------|-----------------------------------|
| EDM               | Ti₃SiC₂ ceramic [67], melting, evaporation, thermal spalling | Material removal process of conductive ceramics by EDM is illustrated in Fig. 8 that shows, the two principal mechanisms i.e. melting, evaporation and thermal spalling depending on the properties of advanced ceramics or ceramics matrix composite (CMC) and the process parameters of EDM [65]. Pitman et al. [80] have studied die-sink EDM while machining zirconia-based CMCs that contains 30 vol.% of TiN and concluded that the rapid increase in temperature subsurface crack formation. Hu et al. [67] have studied the mechanism of material removal of Ti₃SiC₂ ceramic during EDM. They explained that melting and decomposition were contributing in removing material during EDM of CMC. The thermal spalling also led to strength degradation for the workpiece. |
| EDM               | Al₂O₃ metal matrix composites [14], melting, evaporation, thermal spalling | |
| EDM               | Cu₃Al₂O₆ metal matrix composites [39], melting, evaporation, thermal spalling | |
| EDM               | Ba₅Ca₁ₓSr₂₋ₓTi₁₀O₃₊₄ metal matrix composites | |

![Figure 8 Illustration of material removal process of conductive ceramic composite by EDM](image-url)
The material removal mechanisms are mainly recognized as melting as spherical shape debris are observed on the CMC surface. The foamy porous layer is resultant of oxidation and decomposition of the non-conductive part of the composite \cite{80}. Trueman et al. \cite{82} have introduced the concept of rough regime machining for advance ceramics they explained that mechanisms of material removal are melting and vaporization and also by thermal spalling. There are subsurface cracks and flakes as shown in Fig. 8, the presence of such overhung surface of leading edge as crack penetrates into the material. The undermining the surface and producing flakes of machining area confirm the spalling mechanism.

3. Conclusions

Electro-discharge machining process and its variants enable us to machine advanced ceramics and ceramics matrix composite (conductive ceramics). EDM process facilitates to fabricate complex microdevices of hard to cut material with the precision in micron. It is evident that insulated ceramics could be machined by assisted electrode method in EDM. The ED machining of non-conductive ceramics by various assisting electrode needs to be explored further in terms of the exact mechanism of material removal. Once the process is established the process parameters are required to be optimized for their use in industry as non-conductive ceramic machining is currently limited to lab experiments only. The author believed that assisted electro method of machining insulated ceramics has a great potential for machining non-conductive advanced ceramics with high accuracy, precision and surface quality that are very difficult and costly to the machine by any conventional machining process. Insulated ceramics machining area need to explore more precisely so that ample opportunities for its industrial use can be open. Moreover conductive advanced ceramics or ceramic-metal matrix (CMCs) machining by EDM and its variants are needed to investigate in term of developing novel hybrid machining process that
leads to better-machined surface and material removal rate in a cost-effective manner. The process physics of machining advanced ceramics (conductive and non-conductive) in terms of simulations models, metrology techniques and industrial implementation should be taken into consideration.

**Future trends for research**

The present study reviewed of the EDM of advanced in various aspects such as state of art, mechanism of material removal of and nonconductive ceramics. The future research trends are based on fundamental understanding of the science of material removal in ceramics by EDM and its variants.

1. Study on a fundamental understanding of electro-discharge machining and its variants of both insulated ceramics and ceramics matrix composite.
2. Study on the development of control algorithm and technological table for insulating ceramics that are capable of controlling major EDM process parameters as they are affecting the rebuild conductive layer on the insulating material.
3. Study on developing a numerical and analytical model that considers material removal mechanism or physics in insulating ceramics and conductive ceramics both as the presence of secondary insulating phase makes material removal unanticipated.
4. Study on the improvement in surface finish, accuracy and precision of the machined ceramics part.
5. Development of newer technology for multi-purpose micromachining of ceramics and its composite.
6. Advancement in on machine tool fabrication facility and one machine measurement to meet the accuracy and precision requirements.
7. Study on characteristics of the machined surface needs to determine for a particular application as properties are change after machining.
8. Advancement of hybrid micromachining technologies to overcome the limitation faced during micromachining of ceramics and its composite.
9. Miniaturizations of ceramics part developed by micro-EDM or its variants with energy optimization.
10. Cost-effectiveness of micro-EDM and hybrid micro EDM needs to be considered.

**References**

[1] Y. K. Lok and T. C. Lee, "Materials Processing Technology Processing of Advanced Ceramics Using the Wire-Cut EDM Process," 1997.

[2] B. Bhattacharyya, B. N. Doloi, and S. K. Sorkhel, "Experimental investigations into electrochemical discharge machining (ECDM) of non-conductive ceramic materials," vol. 95, pp. 145–154, 1999.

[3] A. Schubert, H. Zeidler, R. Kühn, M. Hackert-Oschätzchen, and N. Treffkorn, "Investigation of ablation behaviour in micro-EDM of nonconductive ceramic composites ATZ and Si3N4-TiN," Procedia CIRP, vol. 42, pp. 727–732, 2016.

[4] A. Schubert, H. Zeidler, R. Kühn, M. Hackert-Oschätzchen, S. Flemmig, and N. Treffkorn, "Investigation of Ablation Behaviour in Micro-EDM of Nonconductive Ceramic Composites ATZ and Si3N4-TiN," Procedia CIRP, vol. 42, no. 115, pp. 727–732, 2016.

[5] D. Bhaduri, A. S. Kuar, S. Sarkar, S. K. Biswas, and S. Mitra, "Electro Discharge Machining of Titanium Nitride-Aluminium Oxide Composite for Optimum Process Criterial Yield," Mater. Manuf. Process., vol. 24, no. 12, pp. 1312–1320, 2009.

[6] M. H. Baghel R and B. S. K, "Parameter Optimization of Diamond Grinding Assisted EDM of TiN-Al 2 O 3 Ceramics using Taguchi Method," pp. 272–275, 2016.

[7] C. J. Luis, I. Puertas, and G. Villa, "Material removal rate and electrode wear study on the EDM of silicon carbide," J. Mater. Process. Technol., vol. 164–165, pp. 889–896, 2005.

[8] N. Mohd Abbas, D. G. Solomon, and M. Fuad Bahari, "A review on current research trends in electrical discharge machining (EDM)," Int. J. Mach. Tools Manuf., vol. 47, no. 7–8, pp. 1214–1228, 2007.

[9] Y. Fukuzawa, N. Mohri, H. Gotoh, and T. Tani, "Three-dimensional machining of insulating ceramics materials with electrical discharge machining," Trans. Nonferrous Met. Soc. China (English Ed.), vol. 19, no. SUPPL. 1, pp. 150–156,
[10] Y. Pachaury and P. Tandon, “An overview of electric discharge machining of ceramics and ceramic based composites,” J. Manuf. Process., vol. 25, pp. 369–390, 2017.

[11] K. K. Saxena, S. Agarwal, and S. K. Khare, “Surface Characterization, Material Removal Mechanism and Material Migration Study of Micro EDM Process on Conductive SiC,” Procedia CIRP, vol. 42, pp. 179–184, 2016.

[12] I. Puertas, C. J. Luis, and G. Villa, “Spacing roughness parameters study on the EDM of silicon carbide,” J. Mater. Process. Technol., vol. 164–165, pp. 1590–1596, 2005.

[13] D. Pma, “Micro-EDM process investigation of Si 3 N 4 – TiN ceramic composites for the development of micro-fuel-based power units Kun Liu *, Eleonora Ferraris , Jan Peirs , Bert Lauwers and Dominiek Reynaerts,” Mach. Des., vol. 3, no. 1, 2008.

[14] K. Gupta and N. K. Jain, “On surface integrity of miniature spur gears manufactured by wire electrical discharge machining,” vol. 38, pp. 1735–1745, 2014.

[15] R. Kumar and I. Singh, “Productivity improvement of micro EDM process by improvised tool,” Precis. Eng., no. April, pp. 1–7, 2017.

[16] Y. Ziada and P. Koshy, “Rotating curvilinear tools for EDM of polygonal shapes with sharp corners,” CIRP Ann. - Manuf. Technol., vol. 56, no. 1, pp. 221–224, 2007.

[17] B. Bhattacharyya, B. N. Doloj, and S. K. Sorkhel, “Experimental investigations into electrochemical discharge machining (EDCM) of non-conductive ceramic materials,” J. Mater. Process. Technol., vol. 95, no. 1–3, pp. 145–154, 1999.

[18] H. Baghel, R. Mali and S. K. Biswas, “Study of Vibration Assisted Micro Electro-Discharge Milling of Titanium Nitride-Aluminium Oxide Composite,” pp. 276–279, 2016.

[19] A. Sabur, M. Y. Ali, A. Maleque, and A. A. Khan, “Investigation of material removal characteristics in EDM of nonconductive ZrO2 ceramic,” Procedia Eng., vol. 56, pp. 696–701, 2013.

[20] A. Schubert, H. Zeidler, M. Hahn, M. Hackert-oschätzchen, and J. Schneider, “Micro-EDM milling of electrically nonconducting zirconia ceramics,” Procedia - Soc. Behav. Sci., vol. 6, pp. 297–302, 2013.

[21] K. Oßwald, S. Schneider, L. Hensgen, A. Klink, and F. Klocke, “CIRP Journal of Manufacturing Science and Technology Experimental investigation of energy distribution in continuous sinking EDM,” CIRP J. Manuf. Sci. Technol., vol. 19, pp. 4–11, 2017.

[22] D. D. DiBitonto, P. T. Eubank, M. R. Patel, and M. A. Barrufet, “Theoretical models of the electrical discharge machining process. I. A simple cathode erosion model,” J. Appl. Phys., vol. 66, no. 9, pp. 4095–4103, 1989.

[23] R. Landfried, F. Kern, and R. Gadow, “Electrically conductive ZTA-TiC ceramics: Influence of TiC particle size on material properties and electrical discharge machining,” Int. J. Refract. Met. Hard Mater., vol. 49, no. 1, pp. 334–338, 2015.

[24] I. Puertas and C. J. Luis, “A study on the electrical discharge machining of conductive ceramics,” J. Mater. Process. Technol., vol. 153–154, no. 1–3, pp. 1033–1038, 2004.

[25] Y. K. Lok and T. C. Lee, “Processing of advanced ceramics using the wire-cut EDM process,” J. Mater. Process. Technol., vol. 63, no. 1–3, pp. 839–843, 1997.

[26] C. J. Luis, I. Puertas, and G. Villa, “Material removal rate and electrode wear study on the EDM of silicon carbide,” vol. 165, pp. 889–896, 2005.

[27] B. Lauwers, J. P. Kruth, W. Liu, W. Eeraerts, B. Schacht, and P. Bleys, “Investigation of material removal mechanisms in EDM of composite ceramic materials,” J. Mater. Process. Technol., vol. 149, no. 1–3, pp. 347–352, 2004.

[28] R. Baghel, H. S. Mali, and S. K. Biswas, “Parametric optimization and surface analysis of diamond grinding-assisted EDM of TiN-Al2O3 ceramic composite,” Int. J. Adv. Manuf. Technol., 2018.

[29] F. Zeller, C. Müller, P. Miranzo, and M. Belmonte, “Journal of the European Ceramic Society Exceptional micromachining performance of silicon carbide ceramics by adding graphene nanoplatelets,” J. Eur. Ceram. Soc., vol. 37, no. 12, pp. 3813–3821, 2017.

[30] S. Tripathy and D. K. Tripathy, “Surface Characterization and Multi-response optimization of EDM process parameters using powder mixed dielectric,” Mater. Today Proc., 2019.
[31] M. Shabgard and B. Khosrozadeh, "Investigation of carbon nanotube added dielectric on the surface characteristics and machining performance of Ti6Al4V alloy in EDM process," J. Manuf. Process., vol. 25, pp. 212-219, 2017.

[32] S. Tripathy and D. K. Tripathy, "An approach for increasing the micro-hardness in electrical discharge machining by adding conductive powder to the dielectric," Mater. Today Proc., vol. 4, no. 2, pp. 1215–1224, 2017.

[33] M. A. Singh, D. K. Sarma, O. Hanzel, J. Sedláček, and P. Šajgalík, "Machinability analysis of multi walled carbon nanotubes filled alumina composites in wire electrical discharge machining process," J. Eur. Ceram. Soc., vol. 37, no. 9, pp. 3107–3114, 2017.

[34] Y. Zhao, M. Kunieda, and K. Abe, "Approaches for improvement of EDM cutting performance of SiC with foil electrode," Precis. Eng., 2017.

[35] A. Torres, C. J. Luis, and I. Puertas, "EDM machinability and surface roughness analysis of TiB2 using copper electrodes," J. Alloys Compd., vol. 690, pp. 337–347, 2017.

[36] S. S. Sidhu and P. S. Bains, "ScienceDirect Study of the Recast Layer of Particulate Reinforced Metal Matrix Composites machined by EDM," Mater. Today Proc., vol. 4, no. 2, pp. 3243–3251, 2017.

[37] R. Bamber, R. Morrell, C. Waldon, and M. Shannon, "confinement boundaries," pp. 1–7, 2017.

[38] H. Gotoh, T. Tani, and N. Mohri, "EDM of Insulating Ceramics by Electrical Conductive Surface Layer Control," Procedia CIRP, vol. 42, no. Isem Xviii, pp. 201–205, 2016.

[39] H. K. Yoo, J. H. Ko, K. Y. Lim, W. T. Kwon, and Y. W. Kim, "Micro-electrical discharge machining characteristics of newly developed conductive SiC ceramic," Ceram. Int., vol. 41, no. 3, pp. 3490–3496, 2015.

[40] R. Bajaj, A. K. Tiwari, and A. R. Dixit, "Current Trends in Electric Discharge Machining Using Micro and Nano Powder Materials- A Review," Mater. Today Proc., vol. 2, no. 4–5, pp. 3302–3307, 2015.

[41] H. Marashi, A. A. D. Sarhan, and M. Hamdi, "Employing Ti nano-powder dielectric to enhance surface characteristics in electrical discharge machining of AISI D2 steel," Appl. Surf. Sci., vol. 357, pp. 892–907, 2015.

[42] J. Qian, F. Yang, J. Wang, B. Lauwers, and D. Reynaerts, "Material removal mechanism in low-energy micro-EDM process," CIRP Ann. - Manuf. Technol., vol. 64, no. 1, pp. 225–228, 2015.

[43] M. Kolli and A. Kumar, "Effect of dielectric fluid with surfactant and graphite powder on Electrical Discharge Machining of titanium alloy using Taguchi method," Eng. Sci. Technol. an Int. J., vol. 18, no. 4, pp. 524–535, 2015.

[44] G. Talla, D. K. Sahoo, S. Gangopadhyay, and C. K. Biswas, "Modeling and multi-objective optimization of powder mixed electric discharge machining process of aluminum/alumina metal matrix composite," Eng. Sci. Technol. an Int. J., vol. 18, no. 3, pp. 369–373, 2015.

[45] V. Aggarwal, S. S. Khangura, and R. K. Garg, "Parametric modeling and optimization for wire electrical discharge machining of Inconeal 718 using response surface methodology," Int. J. Adv. Manuf. Technol., vol. 79, no. 1–4, pp. 31–47, 2015.

[46] S. L. Chen, M. H. Lin, G. X. Huang and C. C. Wang, "Research of the recast layer on implant surface modified by micro-current electrical discharge machining using deionized water mixed with titanium powder as dielectric solvent," Appl. Surf. Sci., vol. 311, pp. 47–53, 2014.

[47] Y. Zhao, M. Kunieda, and K. Abe, "Study of EDM cutting of single crystal silicon carbide," Precis. Eng., vol. 38, no. 1, pp. 92–99, 2014.

[48] P. J. Liew, J. Yan, and T. Kuriyagawa, "Fabrication of deep micro-holes in reaction-bonded SiC by ultrasonic cavitation assisted micro-EDM," Int. J. Mach. Tools Manuf., vol. 76, pp. 13–20, 2014.

[49] C. Zhang, "Effect of wire electrical discharge machining ( WEDM ) parameters on surface integrity of nanocomposite ceramics," Ceram. Int., vol. 40, no. 7, pp. 9657–9662, 2014.

[50] Y. Zhao, M. Kunieda, and K. Abe, "Study of EDM cutting of single crystal silicon carbide," Precis. Eng., vol. 38, no. 1, pp. 92–99, 2014.

[51] P. J. Hou, Y. F. Guo, L. X. Sun, and G. Q. Deng, "Simulation of temperature and thermal stress filed during reciprocating traveling WEDM of insulating ceramics," Procedia - Soc. Behav. Sci,
[52] A. Sabur, M. Y. Ali, M. A. Maleque, and A. A. Khan, “Investigation of material removal characteristics in EDM of nonconductive ZrO2 ceramic,” Procedia Eng., vol. 56, pp. 696–701, 2013.

[53] P. J. Liew, J. Yan, and T. Kuriyagawa, “Carbon nanofiber assisted micro electro discharge machining of reaction-bonded silicon carbide,” J. Mater. Process. Technol., vol. 213, no. 7, pp. 1076–1087, 2013.

[54] P. Jun, J. Yan, and T. Kuriyagawa, “Applied Surface Science Experimental investigation on material migration phenomena in micro-EDM of reaction-bonded silicon carbide,” Appl. Surf. Sci., vol. 276, pp. 731–743, 2013.

[55] D. Hanaoka, Y. Fukuizawa, C. Ramirez, P. Miranzo, M. L. Osendi, and M. Belmonte, “Electrical discharge machining of ceramic / carbon nanostructure composites,” Procedia - Soc. Behav. Sci., vol. 6, pp. 95–100, 2013.

[56] F. Q. Hu et al., “Surface properties of SiCp/Al composite by powder-mixed EDM,” Procedia CIRP, vol. 6, pp. 101–106, 2013.

[57] Y. Perez Delgado et al., “Impact of wire-EDM on dry sliding friction and wear of WC-based and ZrO2-based composites,” Wear, vol. 271, no. 9–10, pp. 1951–1961, 2011.

[58] E. Ferraris, D. Reynaerts, and B. Lauwers, “Micro-EDM process investigation and comparison performance of Al 302 and ZrO2 based ceramic composites,” CIRP Ann. - Manuf. Technol., vol. 60, no. 1, pp. 235–238, 2011.

[59] S. Mitra, S. Sarkar, G. Paul, D. Bhaduri, S. K. Biswas “Pareto optimization of electro discharge machining of titanium nitride-aluminium oxide composite material using genetic algorithm,” vol. 265, pp. 985–990, 2011.

[60] A. Sommers, Q. Wang, X. Han, C. T’Joen, Y. Park, and A. Jacobi, “Ceramics and ceramic matrix composites for heat exchangers in advanced thermal systems-A review,” Appl. Therm. Eng., vol. 30, no. 11–12, pp. 1277–1291, 2010.

[61] S. Lopez-Esteban et al., “Electrical discharge machining of ceramic/semiconductor/metal nanocomposites,” Scr. Mater., vol. 63, no. 2, pp. 219–222, 2010.

[62] S. Clijsters, K. Liu, D. Reynaerts, and B. Lauwers, “EDM technology and strategy development for the manufacturing of complex parts in SiSiC,” J. Mater. Process. Technol., vol. 210, no. 4, pp. 631–641, 2010.

[63] D. Bhaduri, A. S. Kuar, S. Sarkar, S. K. Biswas, and S. Mitra, “Electro discharge machining of titanium nitride-aluminium oxide composite for optimum process criterial yield,” Mater. Manuf. Process., vol. 24, no. 12, pp. 1312–1320, 2009.

[64] K. Liu, D. Reynaerts, and B. Lauwers, “Influence of the pulse shape on the EDM performance of Si3N4-TiN ceramic composite,” CIRP Ann. - Manuf. Technol., vol. 58, no. 1, pp. 217–220, 2009.

[65] K. M. Patel, P. M. Pandey, and P. Venkateswara Rao, “Surface integrity and material removal mechanisms associated with the EDM of Al2O3 ceramic composite,” Int. J. Refract. Met. Hard Mater., vol. 27, no. 5, pp. 892–899, 2009.

[66] S. Kumar, R. Singh, T. P. Singh, and B. L. Sethi, “Surface modification by electrical discharge machining: A review,” J. Mater. Process. Technol., vol. 209, no. 8, pp. 3675–3687, 2009.

[67] C. F. Hu, Y. C. Zhou, and Y. W. Bao, “Material removal and surface damage in EDM of Ti3SiC2 ceramic,” Ceram. Int., vol. 34, no. 3, pp. 537–541, 2008.

[68] Y. H. Liu, X. P. Li, R. J. Ji, L. L. Yu, H. F. Zhang, and Q. Y. Li, “Effect of technological parameter on the process performance for electric discharge milling of insulating Al2O3 ceramic,” J. Mater. Process. Technol., vol. 208, no. 1–3, pp. 245–250, 2008.

[69] B. Lauwers, K. Brans, W. Liu, J. Vleugels, S. Salehi, and K. Vanmeensel, “Influence of the type and grain size of the electro-conductive phase on the Wire-EDM performance of ZrO2 ceramic composites” CIRP Ann. - Manuf. Technol., vol. 57, no. 1, pp. 191–194, 2008.

[70] B. Lauwers, J. P. Kruth, and K. Brans, “Development of technology and strategies for the machining of ceramic components by sinking and milling EDM,” CIRP Ann. - Manuf. Technol., vol. 56, no. 1, pp. 225–228, 2007.

[71] C. J. Luis and I. Puertas, “Methodology for developing technological tables used in EDM processes of conductive ceramics,” J. Mater. Process. Technol., vol. 189, no. 1–3, pp. 301–309, 2007.

[72] H. Gotob, T. Tani, and N. Mohri, “EDM of Insulating Ceramics by Electrical Conductive Surface Layer Control,” Procedia CIRP, vol. 42, no. Isem Xviii, pp. 201–205, 2016.
[73] T. Hösel, P. Cvancara, T. Ganz, C. Müller, and H. Reinecke, "Characterisation of high aspect ratio non-conductive ceramic microstructures made by spark erosion," *Microsyst. Technol.*, vol. 17, no. 2, pp. 313–318, 2011.

[74] N. Mohri, Y. Fukuzawa, T. Tani, N. Saito, and K. Furutani, "Assisting Electrode Method for Machining Insulating Ceramics," *CIRP Ann. - Manuf. Technol.*, vol. 45, no. 1, pp. 201–204, 1996.

[75] A. Muttamara, Y. Fukuzawa, N. Mohri, and T. Tani, "Probability of precision micro-machining of insulating Si 3 N 4 ceramics by EDM," vol. 140, pp. 243–247, 2003.

[76] Y. Zhao, M. Kunieda, and K. Abe, "Experimental investigations into EDM behaviors of single crystal silicon carbide," *Procedia CIRP*, vol. 6, pp. 135–139, 2013.

[77] Y. H. Liu, R. J. Ji, X. P. Li, L. L. Yu, H. F. Zhang, and Q. Y. Li, "Effect of machining fluid on the process performance of electric discharge milling of insulating Al203 ceramic," *Int. J. Mach. Tools Manuf.*, vol. 48, no. 9, pp. 1030–1035, 2008.

[78] C. P. Li, M. Kim, M. Islam, and T. J. Ko, "Journal of Materials Processing Technology Mechanism analysis of hybrid machining process comprising EDM and end milling," *J. Mater. Process. Tech.*, vol. 237, pp. 309–319, 2016.

[79] A. P. Dwivedi and S. K. Choudhury, "Improvement in the Surface Integrity of AISI D3 Tool Steel Using Rotary Tool Electric Discharge Machining Process," *Procedia Technol.*, vol. 23, no. 10, pp. 280–287, 2016.

[80] A. Pitman and J. Huddleston, "Electrical discharge machining of ZrO2/TiN particulate composite," *Br. Ceram. Trans.*, vol. 99, no. 2, pp. 77–84, 2000.

[81] B. Lauwers, J. P. Kruth, W. Liu, W. Eeraerts, B. Schacht, and P. Bleys, "Investigation of material removal mechanisms in EDM of composite ceramic materials," vol. 149, pp. 347–352, 2004.

[82] C. Trueman and J. Huddleston, "Material removal by spalling during EDM of ceramics," *J. Eur. Ceram. Soc.*, vol. 20, pp. 1629–1635, 2000.

[83] A. Sabur, M. Y. Ali, M. A. Maleque, and A. A. Khan, "Investigation of material removal characteristics in EDM of nonconductive ZrO2 ceramic," *Procedia Eng.*, vol. 56, no. August 2014, pp. 696–701, 2013.