Machinability of Non-Conductive Ceramic by EDM: A Review

Rupali Baghel
Department of Mechanical Engineering, Vivekananda Global University Jaipur
rupali.baghel@vgu.ac.in

Abstract
Advanced Ceramics are gaining a foothold in the lightweight aerospace, electronics, and structural engineering component markets. These ceramics could be extensively used in modern industry, such as ballistic body armour, ceramic carbon fibre composite automotive brakes, diesel particulate filters, prosthetic limbs, piezoelectric sensors, and computer memory products, due to their higher compressive strength, resistance to abrasion, lower thermal expansion coefficient, higher density, and chemical stability. Ceramics are notoriously difficult to handle due to the increased hardness and brittleness. Low electric-conductive ceramics, on the other hand, can be machined using the EDM technique, in which plasma energy is used to accurately remove the material by continuous sparking between the surface and the electrode submerged in dielectric. It is observed that EDM can be applied to the material having electrical resistivity below 100 Ω.cm. Most recently it has been observed that EDM could be applied to insulating ceramics too. An attempt has been made in this paper to critically review the machining of ceramics by the EDM process.

1. Introduction
Non-conductive ceramics, because of their exceptional mechanical, thermal, and physicochemical characteristics are likely to encounter a wide spectrum of uses in a variety of industries. They are likely to find a wide range of applications in a variety of industries. Aluminum oxide (Al₂O₃) and zirconium oxide (ZrO₂) are the most commonly used ceramics in machinery for purposes like grinding wheels grinding wheel, bearing, gas sensor, automobile part and medical tools. The biggest issue with ceramics is that they are very onerous to machine. The most prevalent method for machining ceramics is diamond grinding [1, 2], although this method is somewhat expensive and inefficient. Ceramics' greater hardness causes a higher grinding force, which causes diamond cutting edges to wear out quickly. Ceramics' strength is degraded during diamond grinding because of surface and subsurface fractures [3]. They are difficult to operate due to their machining characteristics, which include high cutting force, elevated heat, poor surface integrity, and poor tool life. In recent years, Electrical Discharge Machining (EDM) of advanced engineering ceramics has gotten a lot of attention. EDM provides for the flexible and precise machining of complicated shaped hard-conductive objects. Electrode discharge machining has the potential to be a cost-effective and efficient method for producing tools and parts from conducting ceramic blanks [4]. In 1943, B. R. Lazarenko and N. I. Lazarenko, two Russian scientists, were charged with figuring out how to keep tungsten electrical contacts from corroding due to sparking. They failed at this goal, but discovered that if the electrodes were submerged in a dielectric fluid, the erosion could be more precisely regulated. This led to the development of the EDM system, which could be used to process materials that are hard to machine, such as tungsten, super alloys, and composites [5].

The Lazarenko’s machine is known as an R-C- type machine. It was also used to finish surgeries equipment, as well as aeronautical and automotive. To remove material from a component of this phase,
In the presence of a dielectric fluid, a series of successive electrical discharges between an electrode and the workpiece are utilized. The electrodes are brought closer to the workpiece until there is a tiny enough distance between them for sparking to occur and an impression to be created. The electrode is placed closer to the work-piece until the distance between them is small enough for sparking to be happened & the impression to be created. The material is removed by the erosive effect of the electrical discharges from the tool-electrode and work-piece. During machining, EDM reduces mechanical tension chatter and vibration problems by avoiding direct interaction between the electrode and the work-piece. Any material can be cut regardless of its hardness as long as it can conduct electricity [6, 7]. Advanced ceramics may be machined by EDM if their electrical conductivity reaches a certain threshold value of the order of 0.01 S/cm (or resistivity less than 100 cm) [8, 9]. When machining advanced ceramics with EDM, the thermal spalling mechanisms used to extract the material [3]. EDM is proving to be a promising and appealing technology for machining ceramics, as long as the materials have a high adequate electrical conductivity. On improve processing parameters, an electrically conductive film must be added to non-conductive ceramics having Alumina, Silicon-Nitride, or Zirconia matrix [10].

2. EDM of Non-Conductive Ceramics

Metallic and non-metallic constituents make up non-conductive ceramics. Ceramics are significantly stronger than metals because of these types of bonds. Non-conductive ceramics have been used as electrical insulators and high-temperature resistance in vehicle spark plugs for many years. Ceramics are now widely regarded as the ideal material for diverse angles and perspectives manufacture of home, industrial, and building products, as well as aesthetic artefacts. Machining tools, self-sustainable bearings, engine components, diesel engines, heat exchangers, bulletproof shield, automotive brakes, diesel particulate filters, and a range of prosthetic implants are just a few categories [11]. Engineering ceramic micro-parts are applied in the biomedical industry to make femoral heads and acetabular cups for total hip replacement, dentures and remodels, bone fillers, and tissue engineering scaffolds [12].

Fig. 1 A line diagram of the EDM process variables for ceramics
Based on the input parameters provided in Fig. 1, the machining of advanced-ceramics has been analyzed. Surface roughness number and material removal rate are used to demonstrate the EDM process' performance. The performance of conductive and non-conductive ceramics depends mainly on machining parameters like current, voltage, work-piece property like electric resistivity, conductivity, assisting electrode properties, etc. These parameters are found to be affecting the performance of the process in various degrees. Electrical conductive workpiece is required for machining by EDM, researchers used a conductive layer between the workpiece and electrode as an assisting electrode. The pictorial view of the arrangement of assisting electrode is given in Fig. 2. Here a conductive material like copper or copper alloy is made to pass between workpiece and the tool electrode.

The pulse generator's positive and negative sides are connected to the tool electrode and the auxiliary electrode, respectively. A steel wheel is mounted on a rotary spindle that is powered by an A.C. motor. A numerically controlled (NC) table provides the workpiece, which is an insulating ceramic blank. A thin coating of conductive material serves as an auxiliary electrode in this case. The tool electrode rotates at a high speed during machining, and the auxiliary electrode is fed along the surface of the insulating ceramic work towards the tool electrode.

The conductive layer allows for sparking, which contributes to material removal as the spark energy triggers a crack in the workpiece [12, 13]. This spark leads to the dissociation of the dielectric. On the machined surface, dissociated carbon and tool electrode particles rebuild a conductive layer. As a result, another EDM spark occurs. EDM comes in a variety of forms, the most common of which are wire EDM and die-sink EDM. A thin conductive material wire serves as the electrode in wire EDM, and the workpiece is placed on a CNC-controlled worktable. By controlling the movement in X-Y direction, the setup is able to cut complex 2-dimensional shapes. While die sink EDM, a three-dimensional form conductive material tool is employed to machine a conductive material immersed in a dielectric tank. An electrical spark is produced for a very short time when a regulated voltage is applied between the electrode and the workpiece, and the material on the workpiece melts and evaporates locally. The appropriate cavity in the workpiece is formed by a series of successive sparks. In comparison, much less material is extracted from the tool material, allowing the tool to wear out over time.
Melting, vaporization, and disintegration, as well as fracture-related spalling, are key phenomena that occur during EDM owing to spark erosion of ceramic materials, depending on the mechanical characteristics and EDM settings. Material removal mechanisms during EDM of ceramic composites have been carefully examined [13]. To acquire an insight into the mechanism, most researchers looked at microscopic scans of the machined part. The researchers found various models of the mechanism of material removal [14]. It is said the main mechanism of material removal is melting, evaporation, dissociation, and micro-cracking. The various mechanisms observed by different researchers are shown in Fig. 3.

![Theoretical models available in literature for mechanism of material removal](image)

**Fig. 3 Theoretical models available in literature for mechanism of material removal**

### Progress so far in the machining of insulated ceramics by EDM

Diamond grinding has typically been used to process exceptionally hard and challenging materials, however the problem with diamond grinding is that it is inefficient and expensive. Because EDM can process the material despite its hardness, it is thought to be a very viable technology for machining ceramics. EDM can be used to efficiently machine conductive ceramics. Patel et al. [15] explored whether melting, evaporation, and dissociation, or fracture-related spalling, are the predominant material removal mechanisms during electrical discharge machining of conductive Al2O3 composites. D.Hanaoka et al. [16] experimentally investigated that Insulating Si3N4 ceramics, and Si3N4/CNT and Si3N4/GNP can be efficiently machined. They also explain that surface roughness, wear rate properties are better for conductive ceramics and MRR obtained in insulated ceramic is better than conductive ceramics.

Y.H. Liu et al. [17] have explained that using the copper sheet as an assisting electrode, the non-conductive ceramic can be easily machined in EDM milling. They also explained the importance of using water-based emulsion as dielectric medium. Abdus Sabur et al. [14] has experimentally shown that by using copper sheet around the insulated ceramics help to machine it by EDM machine. Apiwat Muttamara et al. [18] has shown experimentally that copper layer and carbon powder painted work well as an assisting electrode while micro-machining of non-conductive Si3N4 ceramics is done. They also shown that the pipe electrode is better than the solid type of electrode. A. Schubert et al. [19] have used silver varnish as assisting electrode for micro-milling of non-conductive ZrO2 ceramics. The table given below shows the various non-conductive ceramics machined with the assisting electrode method and the process parameters with the outcomes of the processes. A classification based on various materials that have machined by EDM, parameters used during machining and the outcomes of their research is given in Table 1.
### Table 1 Classification based on various materials that have been machined by EDM

| Sn | JOURNAL NAME | CERAMICS TO BE MACHINE | ASSISTING ELECTRODE TYPE | PROCESS PARAMETER | OUTCOMES |
|----|---------------|------------------------|--------------------------|-------------------|----------|
| 1  | Procedia CIRP 6 (2013) 95 – 100 | Si3N4 ceramics (SN) | Pyrolytic carbon | Machining conditions | 1: The insulating materials generated higher MRRs than the conductive materials.  
2: Conductive materials have better EDM properties than insulating materials in terms of tool wear ratio and surface quality.  
3: The aiding electrode method produced a better edge contour than the standard approach on a GNP composite with lower thermal conductivity. |
| 1  | SN            |                        | Electrode Cu (Φ8mm)    | Open circuit voltage (V) | 100 |
| 2  | SN/0.9 CNT    |                        | Setting Current (A)     | 5.0                  |
| 3  | SN/5.3CNT     |                        | Discharge duration (μs) | 1.0                  |
| 2  | SN/11.3CNT    |                        |                        | Electrode Polarity     | negative |
| 4  | Al2O3         | Thin copper sheet      | -                       |                      |
| 2  | SN/20.6CNT    |                        |                        |                      |
| 3  | International Journal of Machine Tools & Manufacture 48 (2008) 1030-1035 | Si3N4 | Copper sheet | Machining conditions | 1: There is no hazardous gas produced when a water-based emulsion is used as the machining fluid and the machinery is not corroded.  
2: The material is extracted predominantly by spalling non-conductive ZrO2 ceramics in an EDM process.  
2: A small amount of material is removed via melting and evaporating. |
| 3  | Tool electrode | Copper                 | Input power (KVA)       | 1.1, 1.2, 1.3, 1.4 |
| 3  | Tool polarity | ve                     |                        |                      |
| 4  | Journal of Materials Processing Technology 140 (2003) 243-247 | Si3N4 | Copper sheet | - |
| Procedia CIRP | 6 (2013) 297–302 | Zirconia ceramics | Silver varnish with 45% silver | Machining conditions | 1: Micro EDM-milling of non-conductive ZrO2 ceramics could successfully be done. |
|--------------|-----------------|-------------------|-------------------------------|---------------------|--------------------------------------------------------------------------------|
| Open Circuit Voltage | 100V | Discharge energy level | (CT) 100 104 | |
| Discharge current | 3A to 8.5A | Discharge duration | 100ns to 180ns | |
| Recharge frequency | (nominal) 150kHz | |

| Applied Surface Science | 276 (2013) 731–743 | Reaction-bonded silicon carbide | Additives in dielectric fluid | Machining condition | 1: Micro EDM of RB-SiC is employed to machine local material migration phenomenon between tool electrode and work piece material. |
|------------------------|-------------------|-------------------------------|-----------------|---------------------|--------------------------------------------------------------------------------|
| Work piece material | RB-SiC | Electrode | Tungsten | |
| Voltage | 60–110V | Additive(μm) | CNF(diameter 0.15 , length 6–8) | |
| Concentration(g/L) | 0.06–0.28 | Machining time | 3min | |
Procedia CIRP 6 (2013) 135 – 139

| 7[20] | Procedia CIRP 6 (2013) 135 – 139 | Machining conditions | 1: Negative polarity is advantageous for SiC foil EDM with higher machining speeds and lower tool wear proportions when the pulse duration is short.

2: By raising the discharge current and employing thinner foil electrodes, the cutting speed of SiC foil EDM can be enhanced.

| Machining conditions | Assisting Electrode | Copper foil |
|----------------------|---------------------|-------------|
| Width/Thickness      | 10mm/50,80,100,200  |
| Open voltage         | 120V                |
| Servo voltage        | 90V                 |
| Discharge duration   | 3μs                 |
| Discharge interval   | 30μs                |
| Dielectric fluid     | EDM oil             |

| 8[22] | Journal Of Materials Processing Technology 208 (2008) 245–250 | Machining conditions | 1: When we utilize a water-based emulsion as the working fluid, no hazardous gases are produced and the equipment is not rusted during ED milling.

| Machining conditions | Pulse duration | 50-500 μs |
|----------------------|----------------|-----------|
| Pulse interval       | 350 μs         |
| Peak current         | 25A            |
| Dielectric          | water-based emulsion |
4. Conclusions

Wear resistance, high compressive strength, chemical resistance, and abrasion resistance are among the mechanical features of advanced engineering ceramics. Modern industry might get benefit from improved engineered ceramics. EDM is a viable machining procedure if the ceramics, composites have a low electrical resistivity and are adequately conductive to induce sparking. EDM is used to machine hardened materials that are conductive in nature that’s why conductive ceramics can be easily machined by this method. For non-conductive ceramics, a conductive layer, as an assisting electrode has to use in the form of a conductive material layer on the ceramics. Thus if any how it is possible to generate a spark between tool and workpiece for carrying-out EDM, very hard materials such as Advanced ceramic, Insulated ceramics, ceramic-composite could be machined. By reviewing previous various works it can also be said that:

1. When EDM is used to machine conductive ceramics, the major material removal mechanism is melting, evaporation. Thermal fracture or thermal cracking are used to remove non-conductive ceramics.

2. While milling non-conductive materials with the EDM process and an auxiliary electrode, thermal spalling or thermal cracking is observed to be the predominant material removal mechanism. Thermal spalling is not seen in materials with a higher toughness.

3. The rate of material removal increases as the input power increases and decreases when the material’s hardness increases.

4. When machining conductive materials, surface roughness was better than when machining insulating materials. The MRRs on the insulating materials significantly higher than those on the conducting materials.

5. When a water-based emulsion is employed as the machining fluid, no hazardous gas is produced, and the equipment is not corroded during ED milling.

6. Due to the lower viscosity of water, EDM in de-ionized water produces a thinner recast layer.

References

1. Baghel, R., Mali, H.S. & Biswas, S.K. Parametric optimization and surface analysis of diamond grinding-assisted EDM of TiN-Al2O3 ceramic composite; The International Journal of Advanced Manufacturing Technology (2018), Vol. 100, Issue 5-8, pp. 1183-1192, IF 2.601.

2. Baghel, R., Mali, H.S. & Biswas, S.K.; Micro hole fabrication in TiN-Al2O3 ceramic composite by SiC powder assisted micro-EDM; Engineering Research Express 2 (2020), 015028.

3. Lok, YK; and Lee, TC. “Processing of Advanced Ceramics Using the Wire-Cut EDM Process” Journal of Materials Processing Technology 63 (1997) 839-843

4. Baghel, R., Mali, H.S. & Biswas, S.K.; An Experimental study on the fabrication of microchannels in Titanium Nitride Alumina Composite Using electro-discharge Milling; International Journal of Modern Manufacturing Technologies (2018), vol. 10, Issue 10, pp. 24-29. ISSN 2067-3604

5. Ji, Renjie; Liu, Yonghong; Zhang, Yanzhen and Wang Fei “Machining performance of silicon carbide ceramic in end electric discharge milling” Int. Journal of Refractory Metals and Hard Materials 29 (2011) 117–122

6. Norlina Mohd Abbas, Darius G. Solomon, Md. Fuad Bahari, “A review on current research trends in electrical discharge machining (EDM)” International Journal of Machine Tools & Manufacture 47 (2007) 1214–1228

7. Baghel, R., Mali, H.S.; The Scope of Machining of Advanced Ceramics by Electro-Discharge Machining and Its Hybrid Variants, International journal of advanced materials manufacturing and characterization (2018), vol. 8, Issue 2, pp. 88-101

8. Baghel, R., Mali, H.S. & Biswas, S.K Study of Vibration Assisted Micro Electro-Discharge Milling Of Titanium Nitride- Aluminium Oxide Composite, All India Manufacturing Technology, Design, and Research conference (AIMTDR) 16-18 Dec. 2016
9. Luis, C.J.; Puertas, I.; Villa, G. “Material removal rate and electrode wear study on the EDM of silicon carbide”. Journal of Materials Processing Technology 164–165 (2005) 889–896
10. Lauwers, B.; Kruth, J.P.; Liu, W.; Eeckaerts, W.; Schacht, B.; Bleys, P. “Investigation of material removal mechanisms in EDM of composite ceramic materials”, Journal of Materials Processing Technology 149 (2004) 347–352
11. Mitra, Souren; Sarkar, Soumya; Paul, Goutam; Bhaduri, D.; Biswas, Sampad “Pareto Optimization Of Electro Discharge Machining Of Titanium Nitride-Aluminium Oxide Composite Material Using Genetic Algorithm”, Advanced Materials Research Vols. 264-265 (2011) pp 985-990
12. Zhang, Chengmao “Effect of wire electrical discharge machining (WEDM) parameters on surface integrity of nano-composite ceramics”. Ceramics International 40(2014)9657–9662
13. Sabur, Abdus; Yeakub Ali, Mohammad; Maleque, Md. Abdul; Khan : Ahsan Ali “Investigation of material removal characteristics in EDM of nonconductive ZrO2 ceramic” Procedia Engineering 56 (2013) 696 – 701
14. Mali, H.S., Baghel, R., Unune, Deepak R.; Experimental Investigation on Hybrid Micro-Electro Discharge Machining of Inconel 718 and ceramics materials, International Journal of Conceptions on Mechanical and Civil Engineering (2017), Vol. 5, Issue. 1, pp. 1–6
15. Baghel R., Mali H.S., Baghela V. (2019) Micro-tool Fabrication and Micro-ED Milling of Titanium Nitride Alumina Ceramic–Composite. In: Shunmugam M., Kanthababu M. (eds) Advances in Micro and Nano Manufacturing and Surface Engineering. Lecture Notes on Multidisciplinary Industrial Engineering. Springer, Singapore.
16. Liu, Y.H.; Ji, R.J.; Li, X.P.; Yu, L.L.; Zhang, H.F.; Li, Q.Y. “Effect of machining fluid on the process performance of electric discharge milling of insulating Al2O3 ceramic”. International Journal of Machine Tools & Manufacture 48 (2008) 1030–1035
17. Muttamara, Apiwat; Fukazawa Yasushi; Mohri, Naotake; Tani, Takayuki “Probability of precision micro-machining of insulating Si3N4 ceramics by EDM”. Journal of Materials Processing Technology 140 (2003) 243–247
18. Schubert, H.; Zeidler, M.; Hahna, M.; Hackert-Oschatzchen, J. Schneider “Micro- EDM milling of electrically nonconducting zirconia ceramics”. Procedia CIRP 6 (2013) 297–302
19. Zhao, Y.; Kaniwa, M.; Abe K. “Experimental investigations into EDM behaviors of single crystal silicon carbide” Procedia CIRP 6 (2013) 135 – 139
20. Liew, Pay Jun; Yan, Jiawang; Kuriyagawa, Tsumimoto “Experimental investigation on material migration phenomena in micro-EDM of reaction-bonded silicon carbide” Applied Surface Science 276 (2013) 731–743
21. Liu, Y.H.; Li, X.P.; Ji, R.J.; Yu, L.L.; Zhang, H.F.; Li, Q.Y. “Effect of technological parameter on the process performance for electric discharge milling of insulating Al2O3 ceramic”. Journal of materials processing technology 208 (2008) 245–250
22. Hu, C.F.; Zhou, Y.C.; Bao, Y.W. “Material removal and surface damage in EDM of TiSiC2 ceramic” Ceramics International 34 (2008) 537–541