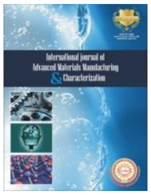

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Past and Current Status of Hybrid Electric Discharge Machining (H-EDM) Processes

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ABSTRACT

Electric discharge machining (EDM) process is one of the highly used advanced machining process. The material removal mechanism is melting and evaporation electric discharge in EDM process. EDM process has its advantages and disadvantages. To overcome the disadvantages, many researchers are trying to hybrid this process with other process. So, that the hybrid EDM process clubs the advantages of both processes which can increase performance and efficiency compared to EDM process alone. This paper reviews the past and current status of various hybrid EDM processes.

Introduction

Hybrid advanced machining process is combination of two or more processes for more efficient way of material removal. This hybrid machining is sub divided into two types

- Assisted hybrid machining processes
- Pure hybrid machining processes

In assisted process, the main material removal takes place from the primary source and the secondary source only assists the materials removal. In pure hybrid process, several material removal mechanisms are present. One of the most hybridized advanced machining process is the EDM process. In the present paper, material removal mechanism, capabilities and limitations of various hybrid EDM processes are discussed.

Electro discharge grinding

This process is hybrid of EDM and grinding. Unlike the grinding process, EDG is not an abrasive related process. This process uses metallic grinding wheel without abrasive particles. Filtered paraffin oils are used as the dielectric. The workpiece is given appropriate feed with a servo control [1]. Usually the grinding wheel is made of graphite so it is electircally conductive. The Fig 1 shows the pictorial representation of the elements of the EDG process. With this process, creep feed grinding can be done by moving the workpiece under the rotating wheel or by plunge cut operatio [2].

Shih et al. [3] used a rotary disk electrode to experiment surface characteristics of EDG, and found that upward discharge gave a better surface finish. Uhlmann et al. [4] found the reason for achieving the better surface roughness as the better flow speed of the dielectric fluid between the electrodes.

With EDG, surface roughness can be improved by increasing pulse frequency [1]. MRR which is usually in the range 0.16 to 2.54 cm^3/min can be increased compromising on surface finish [1]. Recent advancements in EDG shows that, it can be used for machining honey comb ring structures made of superalloy (GH536), which cannot be machined by conventional machining processes [5].

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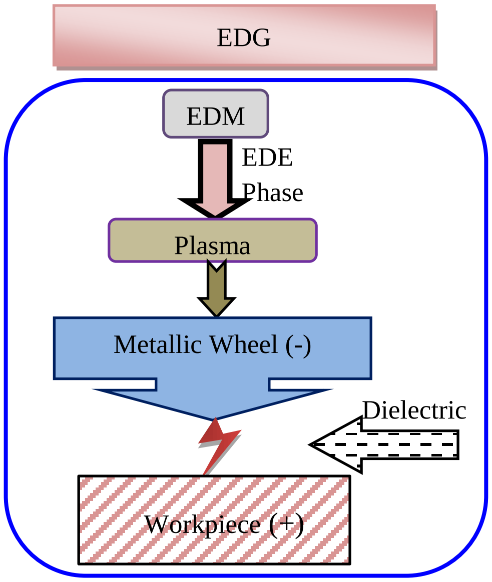

Fig 1 Elements of electric discharge grinding (EDG)

Electrodischarge diamond grinding

Electric discharge diamond grinding (EDDG) is the combination of EDM and fine grinding process where in grinding wheel possess metallic bonding between abrasive particles [6]. Now-a-days other than diamond abrasives also using. So, this process become electro-discharge abrasive grinding (EDAG). This is developed for overcoming the problems of machining harder materials. Thermal softening by EDM and conventional grinding together constitute EDAG. The other name for this process is abrasive electro-discharge grinding (AEDG) (Fig 2).

In this process, the grinding forces are considerably decreased and thus lowers the wheel wear rate (WWR) [1]. Additional benefits are the in-process grinding wheel dressing, because of continuous erosion of material from the wheel metal bonding along with the workpiece due to EDM principle. MRR achieved can be as high as 20 mm³/min at 5A currents and wheel speed of 6 m/s [7]. Specific energy of EDDG (500-3000 J/mm³) has been found to be less than EDM (4000-7000 J/mm³) [8]. MRR of EDAG was found to be 5 times better than EDM and 2 times better than EDG.

There are three configurations of EDDG are being reported by various researchers: EDDSG (Electro-discharge diamond surface grinding), EDDCG (Electro-discharge diamond cut-off grinding), EDDFG (Electro-discharge diamond face grinding) [9]. EDDFG has been researched and optimized using grey relation analysis (GRA) and the results have shown that MRR can be improved by 86.49% and the wheel wear rate (WWR) can be reduced by 21.70%. Optimization parameters were wheel speed, pulse on-time, duty factor and current. When the current increases the EDM becomes more dominant which is as per expectations [8].

Grey relational analysis (GRA) optimization by [9] shown that the average surface roughness (ASR) increased by 14.86%. This difficulty is studied and some methods are suggested. Pulse current, duty ratio and abrasive particle size, when chosen from smaller ranges and the wheel speed from the higher ranges gave a better surface finish [10]. Titanium (Ti6Al4V) grinding in a CNC controlled AEDG process was done [11] and the surface geometrical texture (SGT) was compared with conventional grinding and it was found that rough peaks in the µm level were more for AEDG than a conventional grinding process.

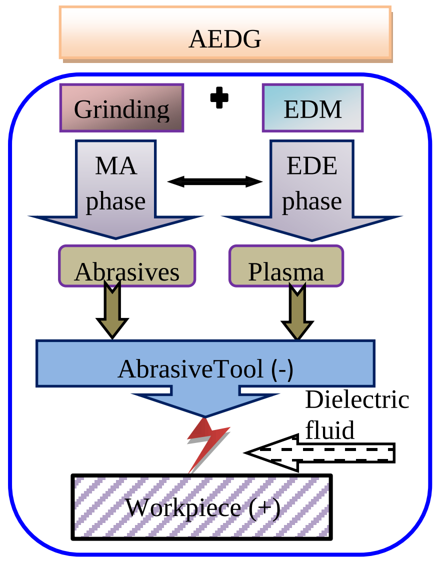

Fig 2 Elements of abrasive electro discharge grinding (AEDG) process [1]

Electrochemical discharge grinding

Electrochemical discharge grinding (ECDG) is a hybrid process of electrochemical machining (ECM) and electrical discharge grinding (EDG). It is used for the machining of electrically conductive materials. This process uses non-abrasive graphite grinding wheel with no abrasive particles and an electrolyte.

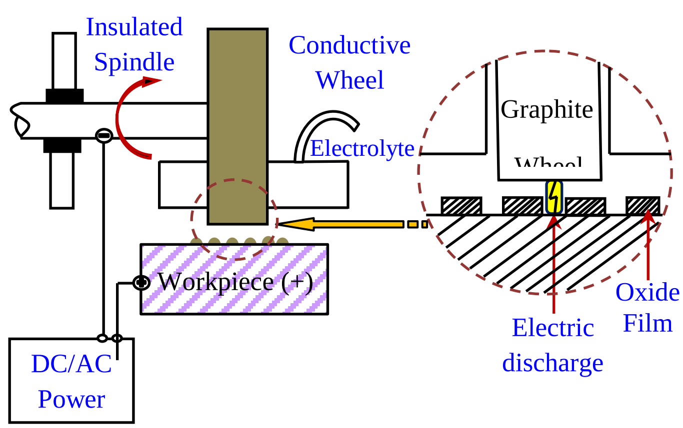

Fig 3 Schematic of electro chemical diamond grinding (ECDG) process

The material removal takes place from the combination of electrochemical dissolution and spark erosion. The spark generation takes place through the insulating oxide film which erodes the anodic films so that the electrolytic action can continue [12]. Fig 3 shows the schematic diagram of the ECDG process.

ECDG can grind brittle and fragile materials having high hardness. The surface finish produced will be around 0.13-0.75 µm and the accuracy obtained can be upto ± 0.0013mm. ECDG produces less force on the workpiece than ECG and produces burr-free and scratch-free surfaces. This process produces no-heat affected zones and the MRR can be five times than that of EDG. There is no loading of grinding wheels. It employs a cheap easily formed graphite wheels [13].

ECDG is employed for the fabrication of honey-comb materials, broaches and grinding form tools. The most famous application is the grinding of carbide cutting tools, which produced a surface finish of 0.38-0.63µm with the removal of 0.25mm depth of material in a single pass.

ECDG requires high current density than EDG. It may also produce corrosive electrolyte, which will corrode the workpiece. There is also a possibility of inter-granular attack. This process requires high preventive maintenance costs. This process cannot be used for cobalt materials because the chemicals of the electrolytic action comes in contact with the cobalt, thus producing residual carbide. This process cause defects in the cobalt workpiece leading to poor surface finish.

Ultrasonic vibration electrical discharge machining

Ultrasonic vibration electrical discharge machining (UEDM) is an unconventional, noncontact material removal process in which heat generated by cyclic electrical discharge between electrode and workpiece in the presence of dielectric fluid. The material is removed by melting due to heat of discharge and the molten material is then flushed of by dielectric fluid that is flowing [14]. In order to avoid environmental pollution through dielectric liquid a process called dry EDM was used which makes use of gas or air as dielectric fluid [15]. Sometimes the dielectric flow gets constricted because of debris pileup which leads to arcing [16].

In UEDM ultrasonic vibration are given to the electrode. The vibration of electrode leads to pumping action which helps in proper movement of dielectric fluid and evacuation of debris. The Working cycle of UEDM is divided into 3 sub-processes, which are electrical discharge machining, ultrasonic machining and washing occurring in succession. Working temperature is in the range of 8000–12,000 °C. The main source of thermal energy to increase the discharge channel temperature and melt both electrodes [17]. The electric supply is then turned off which results in breaking down of plasma channel and hence lowers in temperature leading to solidification of molten material [18].

UEDM can be used for machining deep, small holes in titanium alloy, with low heating conductivity and high tenacity. Holes with 0.2mm diameter and depth/diameter ratio about 15 can be drilled steadily giving improved surface quality, higher MRR and elimination of the recast layer[19].

UEDM can used for machining ceramic material like Si_3N_4 using cylindrical copper tungsten bar, producing twice the conventional MRR [20]. Yuan-Feng Chen et al. machined Al–Zn–Mg alloy with addition of TiC particles into the dielectric [21]. AISIH13 tool is machined using UEDM to get higher material removal rate than traditional EDM [22]. Srivastava et al. machined M2 HSS lowering the electrode wear ratio and surface roughness using cryogenically cooled electrode [23]. In EDM of cemented tungsten carbide workpiece arc pulses were deeper than 180µm whereas there was no sign of arcing in ultrasonic-assisted EDM [24]. UEDM significantly reduces arcing and short circuit pulses [22], [25]. Fatigue resistance can be improved, reducing HAZs [26].

At a high peak current in machining of Al–Zn–Mg alloy, the relative electrode wear rate (REWR) of the combined process was lower than that of conventional EDM. Better precision in machining of Al–Zn–Mg alloy is obtained when TiC particles are added to dielectric fluid in combined process [21]. Ultrasonic assisted EDM of steel significantly reduced inactive pulses [25].

The surface roughness increased when the ultrasonic vibration was applied for machining of insulating ceramic material Si_3N_4.The ultrasonic amplitudes intervened with the generation of a conductive layer, which decreases MRR, and it also increases surface roughness [20]. At a low peak current in machining of Al–Zn–Mg alloy, the relative electrode wear ratio (REWR) of the combined process exceeded that of conventional EDM [21]. In machining of AISIH13 tool steel the surface roughness value of the ultrasonic assisted EDM is slightly higher than EDM [22].

Electro-chemical discharge machining

Electrochemical discharge machining (ECDM) is a hybrid process of ECM and EDM, which is used to machine electrically non-conducting materials. This process is known by several names as used by different researchers: electrochemical arc machining (ECAM) [27],[28], electrochemical spark machining (ECSM) [29],[30] and electro-erosion dissolution machining (EEDM) [31],[32].

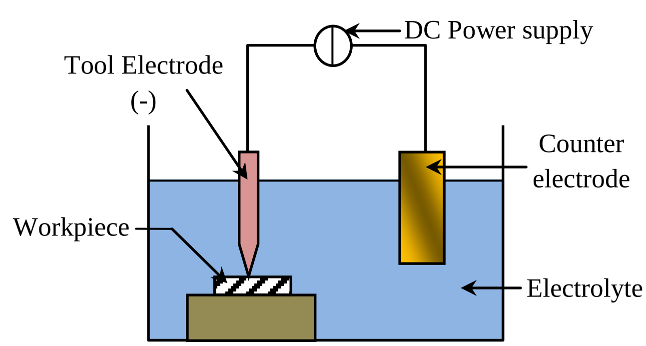

Fig 4 Schematic of electro chemical discharge machining (ECDM) process

The MRR is higher in ECDM as compared to ECM and EDM processes. Kulkarni et al.[33], proposed that hydrogen gas bubbles evolve causing the cathode-electrolyte interface resistance to increase and further causing a single large layer leading to a large resistance as well as zero current. A high electric field of the order of 10 V/μm is responsible for the material removal.

The discharge phenomenon was considered as a switching off due to bubble bridges [34], [35]. Yang, C. T., et al [36] improved the surface quality by adding SiC abrasive particles to the electrolyte. 'Khairy' experimented on die-sinking with the ECDM process and reported a specific material removal rate of 8.17 – 58.84 mm^3/ KC, higher than both unconventional ECM and EDM [32].

Advance materials such as high hardness, brittleness, strength and electrical insulation materials, which are difficult to cut, can be machined through ECDM. Wuthrich. R [37] stated the applications of ECDM in micro-machining and nanotechnologies. Microstructuring of glass can be done with ECDM. Rapid prototyping of microhole and microchannel of brittle and hard materials can be achieved with this process. The cost of machining is low and we can get relatively high aspect ratio and negligible tool wear.

Fine sparks with uniform energy is needed to improve the machining efficiency and the surface quality. Basic problems associated with ECDM are low surface integrity, concentrated sparks at local sites which causes structural damages such as micro cracks and heat affected zones (HAZ). This causes adverse effect on surface roughness and geometric accuracy of the produced product. Materials, which are very brittle, like glass and ceramics easily gets crack under the high spark energy.

Han et al., 2007 [38] improved the surface integrity of ECDM process by the use of conductive particles in the electrolyte. They showed that the HAZ and micro cracks are reduced as well as surface quality is improved.

Laser assisted electric discharge machining

Laser assisted electric discharge machining (LAEDM) is a hybrid process of laser beam machining (LBM) and EDM. Stute et al. [39] studied the interaction between electrical arc and Nd-YAG laser radiation. They have seen that there was an alignment, stabilization and guidance of arc through the interaction with low power laser radiation. The laser provides a channel of increased conductivity. The coincidence of a laser beam and an arc discharge results in stabilization of the arc.

Many researchers have tried to use nanosecond pulsed laser drilling without using EDM but it produces larger recast and heat affected zones. That is the reason to go for hybrid process. EDM alone takes about 30 seconds per hole for micro-drilling process. Hybrid process takes even less time per hole. The drilling efficiency in hybrid process is much higher than individual process.

Li et al. [40] have used LBM and EDM sequentially for micro-drilling of fuel injection nozzles. They initially drilled holes by a nanosecond pulsed laser beam and then finished by EDM drilling. The quality of Laser holes are drilled in steps of 10μm from 10 μm to 120 μm. EDM finishing finally produced the required diameter of 140 μm. They found out that hybrid process has eliminated the recast layer and HAZs which are associated with laser drilling. It is also found that the hybrid process took 70% less time in drilling as compared to EDM drilling. Kuo, C-L., et al. [41] performed the fabrication of 3D metal microstructures by using a hybrid process of micro-EDM and laser assembly. It has enhanced the process applicability, and reduced the assembled component setting, inspection problems, high failure sensitivity and micro-precision requirement can be overcome. Future possibility of fabricating a different range of 3D metal micromoulds was suggested. Huang, et al. [42] have performed the micro-assembly of pin-plate, diameter of 50μm with a thin plate of 200 μm thickness made of SUS304.

Powder mixed electric discharge machining

Powder mixed electric discharge machining (PMEDM) has a hybrid material removal mechanism where the dielectric electrolyte is mixed with some additives. As PMEDM works with powder mixed electrolyte the basic mechanism of material removal is different from conventional EDM process. Wong et al. [43] showed the depending on the required surface finish different powder should be used like graphite, silicon (Si), aluminium (Al), crushed glass, silicon carbide (SiC) and molybdenum sulphide with different grain size.

Powder mixed electrolyte makes the discharge breakdown easier, it enlarges and widens the discharge gap and passage. Finally it forms "large and shadow" shaped evenly distributed etched cavities [44]. The fine powder characteristics such as particle size, type, concentration and conductivity affects the machinability performance [45]. Powder reduces the insulating strength and makes EDM process becomes more stable and improves machining efficiency, Material removal rate and surface finish.

PWEDM produces mirror like surface finish. Yan et al. [46] performed the surface modification of SKD 61 mateial with PMEDM using metal powder. He showed that the corrosion resistance and surface hardness were improved. PWEDM produces near mirror like finish. Yih-fong and Fu-chen [47] investigated the effect of powder on the surface finish of SKD-11 workpiece using chromium (Cr), Aluminum (Al), copper (Cu), and SiC powders. Al with small grain size produced the best surface finish.

Jeswani [48] used graphite as a powder additive and showed that the MRR has been increased by 60%. Various optimization techniques have been used nowadays to improve the MRR. Klocke et al. [49] added Al and Si powder to investigate the thermal influenced zone and found out that these zones were thin in Al and MRR was also high. PWEDM produces thin recast layer and increases MRR.

Chow et al. [50] used PWEDM with the addition of SiC for the micro-slit machining of titanium alloy. Tani et al. [51] reported the machining characteristics of insulating Si3N4 ceramic by the addition of powders to the dielectric fluid. PWEDM has been used by various researchers for the near mirror finish applications. Zhao and Wang [44] studied the application of PWEDM in rough machining.

While PMEDM is very much effective but it is used in industry at very slow speed. This is because of the complexity in context with thermo physical properties of the suspended particles, which needs a thorough investigation. PWEDM consumes high amount of energy. It also requires proper disposal of the fluid. The optimization techniques also need some good advancement.

Abrasive wire electric discharge machining

Abrasive wire electric discharge machining (AWEDM) is a hybrid wire EDM process that has a wire embedded with electrically non-conducting abrasives.

Material removal occurs due to the electrical erosion which is augmented by two-body abrasion. The abrasive action enhances electrical erosion through the removal of the molten/recast workpiece material.

Menzies and Koshy [52] performed AWEDM with diamond abrasives on steel SAE 1018 material and found that the efficiency, material removal rate and surface quality were increased while heat affected zone, recast layer and kerf loss were decreased. Experiments performed the WEDM experiment on nickel 600 alloy and the recast layer generated was continuous with a thickness of ~ 5µm, while AWEDM produced almost no recast layer.

In WEDM alone, only about 10% of the molten material is actually removed from the parent material, due to inefficient ejection forces. The rest of the material forms recast layer and sustains micro cracks.

The problem of diamond abrasives is the graphitization because of which the performance highly decreases. AWEDM is best suited for abrasives like aluminum oxide but this requires significant research effort in wire design and development.

Wire electrical discharge machining (W-EDM) as name suggests is EDM process where wire is used as tool electrode. The machining efficiency of EDM is considered to be low. Many people have studied the effect of ultrasonic vibration in EDM and have found favorable results for MRR, Surface roughness, REWR, etc.

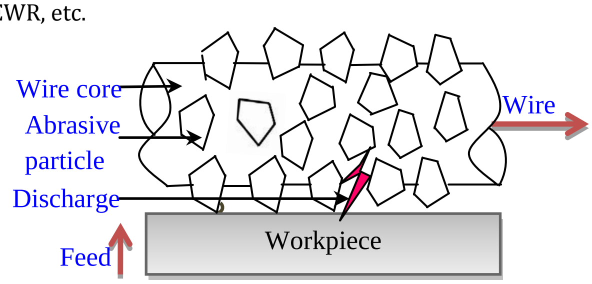

Fig 5Schematic diagram of abrasive WEDM process

Ultrasonic vibrations assisted wire electrical discharge machining

The working principle of ultrasonic vibration assisted wire electrical discharge machining (UWEDM) is same as W-EDM [53]. The wire ultrasonic vibrations helps in evacuation of eroded material, uniform discharge distribution, boosting cutting rates, good machine stability, multi-point discharge leading to better surface finish. Higher frequency of contact helps in favourable polishing action. In UWEDM 30% increase in cutting efficiency was recorded compared to WEDM. The high frequency continuously shifts the discharge location thus reducing wire breakage [54],[55]. Smoother and plainer crater is formed in UWEDM [55]. Reduced surface residual tensile stress is observed in UWEDM [54].

Brush erosion-dissolution mechanical machining

Brush erosion-dissolution mechanical machining (BEDMM) utilizes elastic discrete electrodes made as a brush that rotates in a water-glass solution. This was first introduced by Nowicki et al. [56] for machining complex shapes with large variation of shapes and dimensions in which case EDG or EDM cannot be efficiently used. The advantages are the random nature of the frequency and encounter of electrodes with the workpiece, the periodic contact between the electrode and the workpiece and the current flow through this [56]. Fig 6 shows the various elements of the process.

As for the principle, it involves three phenomena happening simultaneously: electrochemical dissolution, electrodischarge thermal process and the mechanical contact through friction between the brush and the workpiece. The frictional contact performs an important function in this process and in fact, the machining efficiency of this process is zero without it. Due to the electrochemical dissolution, a damaging anodic layer of silicon is formed that if not removed, it leads to etching and mating between the electrodes as well as this is where the frictional contact helps by removing it as soon as it is formed during the process, without any harm to the workpiece.

Due to its nature, BEDMM can be used for finishing of complex surfaces too. When peaks of roughness occur in an ongoing machining process, the current supply can be switched off without stopping rotation and frictional contact quickly polishes and finishes the workpiece while at the same stand and equipment [56]. Spadlo, one of the inventors of this process later did a more elaborate work on the mechanics and kinematics of the mechanism [57]. He derived the relations the radius and the deflection of the filaments, and the force components. A higher packing density is suggested to increase the mutual support between filaments.

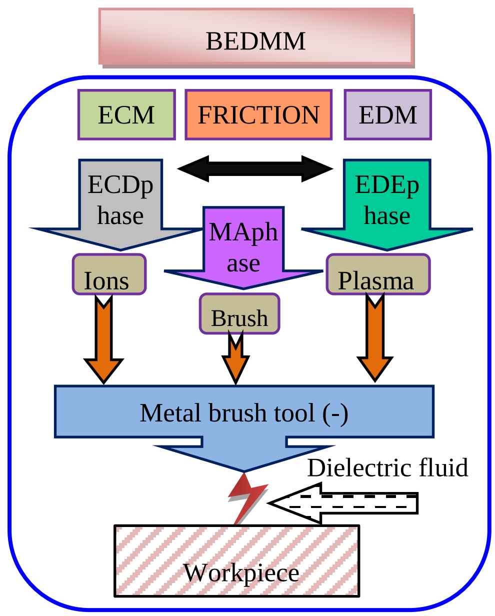

Fig 6 Elements of brush erosion-dissolution mechanical machining (BEDMM*)*

Grinding assisted electrochemical discharge machining

Grinding assisted electrochemical discharge machining (G-ECDM) is a hybrid process of electrochemical dissolution, electric discharge erosion and mechanical abrasion of the grinding process. The grinding wheel is connected to negative terminal and the workpiece is connected to the positive terminal of the pulsed power supply.

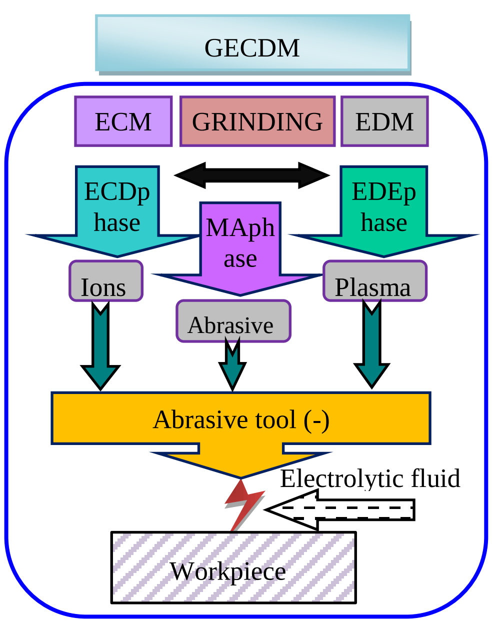

Fig 7 Elements of grinding assisted electro-chemical discharge machining (GECDM)

Liu Jiangwen[58] performed G-ECDM of aluminum metal matrix composite (MMC). He used a tool-electrode, which had a composite coating of hard reinforcement diamond phase particles as an abrasive particle. This can take various forms to suit different shapes. shows the process flowchart.

The material removal takes place from the anodic dissolution, spark erosion and mechanical abrasion of abrasive particles on the grinding wheel. During the process, glazed surface is formed by the action of discharge spark and electrochemical dissolution. This glazed surface is removed by the action of mechanical abrasion.

The problems of ECDM of metal matrix composites are of close dimensional tolerance and poor surface finish. The MRR and molten material throw-out coefficient is higher than that of ECDM. The increase in the feed rate and penetration depth accelerates the discharge. Average surface roughness (R_a) of 0.25µm was obtained with GECDM and R_a of 2.5µm was obtained with ECDM during the machining of MMC. G-ECDM has high machining efficiency and produces god surface integrity. The surface defects and tool wear is less.

The challenging part of this process is the design of tool-electrode for various shapes. If the spindle speed is high then electrical transmission between the spindle and bush creates problems.

Conclusion

Though EDM has been one of the most versatile machining process, it has to be improved to be subject to a wide variety of materials. This paper has reviewed the various hybridizations of EDM process. The applications of the processes are discussed, drawbacks mentioned and methods of overcoming them are also suggested. There is a lot of scope for improving MRR, surface quality and ability to machine a bigger group of materials with these hybrid EDM processes.

References

1 H. El-Hofy, *Advanced machining processes - Nontraditional and hybrid machining processes.* .

2 K. Aspinwall and M. Engineering, “Polycrystalline diamond edge quality and and surface integrity following electrical discharge grinding,” *Materials Processing Technology*, vol. 0136, no. 95, 1996.

3 H. R. Shih and K. M. Shu, “A study of electrical discharge grinding using a rotary disk electrode,” *The International Journal of Advanced Manufacturing Technology*, vol. 38, no. 1–2, pp. 59–67, May 2007.

4 E. Uhlmann, S. Piltz, and S. Jerzembeck, “Micro-machining of cylindrical parts by electrical discharge grinding,” *Journal of Materials Processing Technology*, vol. 160, no. 1, pp. 15–23, Mar. 2005.

5 “Research on Surface Roughness of Superalloy Thin-Walled Parts with Electrical Discharge Grinding Based on Orthogonal Test,” *Applied Mechanics and Materials*, vol. 198–199, pp. 202–206, Oct. 2012.

6 E.Ya.Grodzinskii, “Grinding with electrical activation of the wheel surface,” *Machines and tooling*, vol. 50, no. 12, pp. 10–13, 1979.

7 Koshy.P, V. K. Jain, and Lal.G.K, “Mechanism of material removal in electrical discharge diamond gridning,” vol. 36, no. 10, pp. 1173–1185, 1996.
8 V. K. Jain and R. G. Mote, “On the temperature and specific energy during electrodischarge diamond grinding (EDDG),” *The International Journal of Advanced Manufacturing Technology*, vol. 26, no. 1–2, pp. 56–67, Mar. 2004.
9 G. K. Singh, V. Yadava, and R. Kumar, “Diamond face grinding of WC-Co composite with spark assistance: Experimental study and parameter optimization,” *International Journal of Precision Engineering and Manufacturing*, vol. 11, no. 4, pp. 509–518, Aug. 2010.
10 S. Kumar and S. K. Choudhury, “Prediction of wear and surface roughness in electro-discharge diamond grinding,” *Journal of Materials Processing Technology*, vol. 191, no. 1–3, pp. 206–209, Aug. 2007.
11 R. Święcik, “Experimental investigation of abrasive electrodischarge grinding of Ti6Al4V titanium alloy,” vol. 37, no. 2, pp. 706–711, 2009.
12 M. E. Zohdi, W. E. Biles, and D. B. Webster, “Production processes and equipment for metals,” in *Handbook of materials selection*, 2007, pp. 847–923.
13 G. F. Benedict, *Nontraditional manufacturing processes*. 1987.
14 N. Mohd Abbas, D. G. Solomon, and M. Fuad Bahari, “A review on current research trends in electrical discharge machining (EDM),” *International Journal of Machine Tools and Manufacture*, vol. 47, no. 7–8, pp. 1214–1228, Jun. 2007.
15 G. Skrabalak and J. Kozak, “Study on Dry Electrical Discharge Machining,” vol. III, pp. 2–7, 2010.
16 S. T. Jilani and P. C. Pandey, “- 284 275,” vol. 84, pp. 275–284, 1983.
17 J. Marafona and J. A. G. Chousal, “A finite element model of EDM based on the Joule effect.” .
18 K. . Ho and S. . Newman, “State of the art electrical discharge machining (EDM),” *International Journal of Machine Tools and Manufacture*, vol. 43, no. 13, pp. 1287–1300, Oct. 2003.
19 Z. Wansheng, W. Zhenlong, D. Shichun, C. Guanxin, and W. Hongyu, “Ultrasonic and electric discharge machining to deep and small hole on titanium alloy,” *Journal of Materials Processing Technology*, vol. 120, no. 1–3, pp. 101–106, Jan. 2002.
20 C. Praneetpongrung, Y. Fukuzawa, S. Nagasawa, and K. Yamashita, “Effects of the EDM Combined Ultrasonic Vibration on the Machining Properties of Si3 N4.”
21 Y.-F. Chen and Y.-C. Lin, “Surface modifications of Al–Zn–Mg alloy using combine d EDM with ultrasonic machining and addition of TiC particles into the dielectric.” .
22 M. R. Shabgard, B. Sadizadeh, and H. Kakoulvand, “The Effect of Ultrasonic Vibration of Workpiece in Electrical Discharge Machining of AISIH13 Tool Steel,” pp. 161–165, 2010.
23 V. Srivastava and P. M. Pandey, “Effect of process parameters on the performance of EDM process with ultrasonic assisted cryogenically cooled electrode,” *Journal of Manufacturing Processes*, vol. 14, no. 3, pp. 393–402, Aug. 2012.
24 A. Abdullah, M. R. Shabgard, a. Ivanov, and M. T. Shervanyi-Tabar, “Effect of ultrasonic-assisted EDM on the surface integrity of cemented tungsten carbide (WC-Co),” *The International Journal of Advanced Manufacturing Technology*, vol. 41, no. 3–4, pp. 268–280, May 2008.
25 V. S. R. Murthy and P. K. Pinup, “Pulse train analysis in ultrasonic assisted EDM,” vol. 27, no. 4, 1987.
26 D. Kremer, J. L. Lebrun, B. Hosari, A. Moisan, and E. N. S. A. M. Paris, “Effects of Ultrasonic Vibrations on the Performances in EDM,” vol. 38, no. 1, pp. 199–202, 1989.
27 A. B. Khayry and J. A. McGeough, “Analysis of Electrochemical Arc Machining by Stochastic and Experimental Methods,” *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 412, no. 1843, pp. 403–429, Aug. 1987.
28 J. A. Mcgeough, A. B. M. Khayry, and W. M. S. J. R. Crookal, “Theoretical and Experimental Investigation of the Relative Effects of Spark Erosion and Electrochemical Dissolution in Electrochemical ARC Machining G3,” vol. 32, pp. 113–118, 1983.
29 V. K. Jain, P. M. Dixit, and P. M. Pandey, “On the analysis of the electrochemical spark machining process,” vol. 39, pp. 165–186, 1999.
30 Y.P.Singh, V. K.Jain, P. Kumar, and D.C.Agarwal, “Machining piezoelectric (PZT) ceramics using an electrochemical spark machining (ECSM) process,” 1996.
31 M. Sadegh Amalnik, H. . El-Hofy, and J. . McGeough, “An intelligent knowledge-based system for wire-electro-erosion dissolution in a concurrent engineering environment,” *Journal of Materials Processing Technology*, vol. 79, no. 1–3, pp. 155–162, Jul. 1998.
32 A. B. E. Khairy, “Die sinking by electroerosion dissolution machining,” vol. 3, no. 1, pp. 191–195, 1989.
33 A. Kulkarni, R. Sharan, and G. K. Lal, “An experimental study of discharge mechanism in electrochemical discharge machining,” vol. 42, pp. 1121–1127, 2002.
34 I. Basak, “Mechanism of material removal in electrochemical machining : a theoretical model and experiment verification,” *Journal of Material Processing Technology*, vol. 71, pp. 350–359, 1997.
35 I. Basak and A. Ghosh, “Mechanism of spark generation during electrochemical discharge machining: a theoretical model and experimental verification,” *Journal of Materials Processing Technology*, vol. 62, no. 1–3, pp. 46–53, Nov. 1996.
36 C. T. Yang, S. L. Song, B. H. Yan, and F. Y. Huang, “Improving machining performance of wire electrochemical discharge machining by adding SiC abrasive to electrolyte,” *International Journal of Machine Tools and Manufacture*, vol. 46, no. 15, pp. 2044–2050, Dec. 2006.
37 R. Wuthrich, *Micro-machining using electrochemical discharge phenomenon: fundamentals & applications of Spark assisted chemical engraving (Micro & nanotechnologies).* 2009.
38 M.-S. Han, B.-K. Min, and S. J. Lee, “Improvement of surface integrity of electro-chemical discharge machining process using powder-mixed electrolyte,” *Journal of Materials Processing Technology*, vol. 191, no. 1–3, pp. 224–227, Aug. 2007.

39 U. Stute, R. Kling, and J. Hermsdorf, “Interaction between Electrical Arc and Nd: YAG Laser Radiation,” *CIRP Annals - Manufacturing Technology*, vol. 56, no. 1, pp. 197–200, Jan. 2007.
40 L. Li, C. Diver, J. Atkinson, R. Giedl-Wagner, and H. J. Helml, “Sequential Laser and EDM Micro-drilling for Next Generation Fuel Injection Nozzle Manufacture,” *CIRP Annals - Manufacturing Technology*, vol. 55, no. 1, pp. 179–182, Jan. 2006.
41 C.-L. Kuo, J.-D. Huang, and H.-Y. . Liang, “Fabrication of 3D Metal Microstructures Using a Hybrid Process of Micro-EDM and Laser Assembly,” *The International Journal of Advanced Manufacturing Technology*, vol. 21, no. 10–11, pp. 796–800, Jul. 2003.
42 J.-D. Huang and C.-L. Kuo, “Pin-plate micro assembly by integrating micro-EDM and Nd-YAG laser,” *International Journal of Machine Tools and Manufacture*, vol. 42, no. 13, pp. 1455–1464, Oct. 2002.
43 Y. . Wong, L. . Lim, I. Rahuman, and W. . Tee, “Near-mirror-finish phenomenon in EDM using powder-mixed dielectric,” *Journal of Materials Processing Technology*, vol. 79, no. 1–3, pp. 30–40, Jul. 1998.
44 W. . Zhao, Q. . Meng, and Z. . Wang, “The application of research on powder mixed EDM in rough machining,” *Journal of Materials Processing Technology*, vol. 129, no. 1–3, pp. 30–33, Oct. 2002.
45 P. Pecas and E. Henriques., “Influence of silicon powder-mixed dielectric on conventional electrical discharge machining,” *International Journal of Machine Tools and Manufacture 43.14*, pp. 1465–1471, 2003.
46 B. H. Yan, Y. C. Lin, F. Y. Huang, and C. H. Wang, “Surface modification of SKD 61 during EDM with metal powder in the dielectric,” *Materials transactions-JIM 42.12*, pp. 2597–2604, 2001.
47 T. Yih-fong and C. Fu-chen, “Investigation into some surface characteristics of electrical discharge machined SKD-11 using powder-suspension dielectric oil,” *Journal of Materials Processing Technology*, vol. 170, no. 1–2, pp. 385–391, Dec. 2005.
48 M. L. Jeswani, “Effect of the addition of graphite powder to kerosene used as the dielectric fluid in electrical discharge machining,” *Wear 70.2*, vol. 70, pp. 133–139, 1981.
49 F. Klocke, D. Lung, G. Antonoglou, and D. Thomaidis, “The effects of powder suspended dielectrics on the thermal influenced zone by electrodischarge machining with small discharge energies,” *Journal of materials processing technology*, vol. 149, no. 1, pp. 191–197, 2004.
50 H.-M. Chow, B.-H. Yan, F.-Y. Huang, and J.-C. Hung, “Study of added powder in kerosene for the micro-slit machining of titanium alloy using electro-discharge machining,” *Journal of Materials Processing Technology*, vol. 101, no. 1–3, pp. 95–103, Apr. 2000.
51 T. Tani, “Machining phenomena in EDM of insulating ceramics using powder suspended working oil,” in *12th ISEM Bilbao*, 2001, pp. 388–392.
52 I. Menzies and P. Koshy, “Assessment of abrasion-assisted material removal in wire EDM,” *CIRP Annals - Manufacturing Technology*, vol. 57, no. 1, pp. 195–198, Jan. 2008.
[53] A. B. Puri and B. Bhattacharyya, “Modelling and analysis of the wire-tool vibration in wire-cut EDM,” *Journal of Materials Processing Technology*, vol. 141, no. 3, pp. 295–301, Nov. 2003.
54 Z. N. Guo, T. C. Lee, T. M. Yue, W. S. Lau, H. Hom, and H. Kong, “A Study of Ultrasonic-aided Wire Electrical Discharge Machining,” vol. 0136, no. 96, 1997.
55 Z. N. Guo, T. C. Lee, T. M. Yue, and W. S. Lau, “Study on the machining mechanism of WEDM with ultrasonic vibration of the wire,” vol. 0136, no. 97, 1997.
56 B. Nowicki, R. Pierzynowski, and S. Spadøo, “New possibilities of machining and electrodischarge alloying of free-form surfaces,” vol. 109, pp. 371–376, 2001.
57 S. Spadlo, “The analysis of brushing tool characteristics,” vol. IV, no. 4, 2004.
58 L. J. Wen, “Grinding-Aided Electrochemical Discharge Machining Of Metal Matrix Composites,” 2010.