International Journal of Scientific Research & Engineering Trends
Volume 8, Issue 2, Mar-Apr-2022, ISSN (Online): 2395-566X

Review Paper on Electrical Discharge Machining

Prof. Kalpesh S. Kamble, Pankaj Rane, Shadab Shaikh, Mahesh Dalvi, Rahul Chavan
Department of Mechanical Engineering,
S.S.P.M's College of Engineering,
Kankavli, India

Abstract- By means of the improvement and growths in new machineries, low weight- high strength, high hardness and temperature resistant materials have been advanced for distinctive applications which include aerospace, medical, automobile and more. In the machining of hard and metal matrix composite materials, outdated manufacturing processes are being more and more changed by more nontraditional machining processes which include Electrical Discharge Machining (EDM). The work piece material designated in this experiment is Inconel 925 taking into interpretation its wide usage in industrial applications. In today's world stainless steel provides to nearly half of the world's production and consumption for industrial determinations. In this experiment the input variable factors are voltage, current and pulse on time. As we know that Taguchi method is functional to produce an L9 orthogonal array of input variables by means of the Design of Experiments (DOE). So, Taguchi method is used to analysis the output data. The consequence of the compliant parameters stated overhead upon machining characteristics such as Material Removal Rate (MRR) and Tool Wear Rate (TWR) is considered and examined. In this we are focused on to analysis minimum TWR and maximum MRR based on control factors and response parameters.

Keywords- EDM, Electric Discharge Machining, Unconventional Manufacturing Process, TWR and MRR.

I. INTRODUCTION

Electrical discharge machining (EDM) EDM is most widely and successfully applied process in machining of hard metals or those that would be very difficult to machine with traditional techniques. The material is removed from the work piece by the thermal erosion process, i.e., by a series of recurring electrical discharges between a cutting tool acting as an electrode and a conductive workpiece in the presence of a dielectric fluid. This discharge occurs in a voltage gap (Vg) between the electrode and work piece. Heat from the discharge vaporizes minute particles of work piece material, which are then washed from the gap by the continuously flushing dielectric fluid. (1)

This technology is increasingly being used in tool, die and mould making industries, for machining of heat treated tool steels and advanced materials (super alloys, ceramics, and metal matrix composites) requiring high precision, complex shapes and high surface finish. Traditional machining technique is often based on the material removal using tool material harder than the work material and is unable to machine them economically. EDM is one of the most popular non-traditional material removals process and has become basic machining method for the manufacturing industries of aerospace, automotive, nuclear and medical.(2)

With the increasing demands of high surface finish and machining of complex shape geometries, conventional machining process are now being replaced by non-traditional machining processes. Electrical discharge machining utilizes rapid, repetitive spark discharges from a pulsating direct current power supply between the workpiece and the tool submerged into a dielectric liquid. (3)

II. LITERATURE SURVEY

In this chapter few search are done on selected research paper related to EDM with effect of metal MRR,TWR, OC, surface roughness (SR) workpiece material, we are broadly classified all the paper into five different category, i.e. paper related to material related workpiece or tool, tubular electrode, tool design, some paper related to Effect of multiple discharge.

Sushil Kumar Chaudhary and Dr. R.S. Jadoun [4] have made a research review on the current advancement of EDM machine. They stated that Electrical discharge machining (EDM) is a process for shaping hard metals and forming deep complex shaped holes by arc erosion in all kinds of electro conductive materials. The erosion of Materials occurs due to pulse of Current. Researchers have explored a number of ways to improve EDM Process parameters such as Electrical parameters, Non-Electrical Parameters, tool Electrode based parameters & Powder based parameters. This Paper gives research work done on to the development of die-sinking EDM, Water in EDM, dry EDM, and Powder mixed electric Discharge Machining. In this review paper, Researcher works on enhancement of Material removal rate (MRR), reduction of tool wear rate (TWR), improve Surface Quality (SQ) by experimental investigation is expressed. Various approaches like Vibration, rotary and Vibro-rotary mechanism based on EDM, water based EDM has been employed for increase of EDM efficiency, Dry EDM use of gas instead of oil electrolyte, PM-dielectric Electric Discharge Machining .

Sandeep Kumar [5] has published research paper status of recent development in EDM machine. He stated that it is based on the thermoelectric power between the work piece and tool. The process includes controlled erosion of electrically conductive work piece by introduce of the rapid and repetitive spark discharge between the tool and work piece by the use of dielectric medium. He also give the various application in EDM machine in automobile, nuclear, surgical industry and thin and fragile parts. He concluded that EDM can be used as viable machining operations for producing complex parts, EDM is independent of the mechanical properties of the workpiece and in order to remain competitive as a micromanufacturing technology, EDM process should use computer numerically controlled.

C. Bhaskar Reddy et al [6] has made research on the growth of EDM machine and its various application. Experiments with wire EDM on reciprocating dry sliding pin on plate revealed that the Zro2-WC composite exhibits better tribological characteristics over Zro2-TiCN and Zro2-TiN. The recent observation is being the application of the Wire-EDM in Granite Mining, operations to avoid the heavy manual involvement. The technique starting from a simple means of making tools and dies has reached the stage as the best alternative of producing micro scale parts. He concluded that EDM are flexible enough to meet the requirements in the global metal cutting industries. Thus, the ultimate goal of Wire EDM process is to achieve an accurate and efficient machining operation combined with quality with at most best machining performance by the various factors affecting the process and identifying the optimal machining condition from number of combinations.

Manpreet Singh et al [7] conducted research on recent development in wire EDM machine. They stated that EDM is used to manufacture geometrically intricate shapes with great accuracy and good surface finish that are difficult to machine with the help of conventional machining processes. They also considered the various affecting parameters on EDM machine. They concluded that wires with greater tensile strength can be made but they face adverse effects in terms of increase in resistance to breakage. Some work is also done on cryogenics treatment on various pieces of materials. Thus, WEDM can serve the purpose of high speed machining with good quality products in short time period and at reduced costs. D.T. Pham et al [8] published research papers on Micro-EDM and its development. As MRR is in micro and due to the high precision and good surface quality that it can give, EDM is potentially an important process for the fabrication of micro tools, micro-components and parts with micro-features. Researches are conducted of micro EDM on wire, drilling, milling and die-sinking. The focuses are laid on the planning of the EDM process and the electrode wear problem. Special influences are made to achieve high accuracy, including positioning approaches during EDM and electrode grinding.

They concluded that while assigning process tolerances for micro EDM all aspects of the process, such as type of electrode grinding, type of positioning and duration of the operation, should be considered, overall machining efficiency based on empirical methods and in order to remain competitive as a micro-manufacturing technology, micro-EDM processes should use reliable algorithms and strategies with repeatable results.

EdreesAbd Ali Khudhair and Mustafa MohsinKhuder [11] have published research paper on effect of current on EDM machine. They stated that electric spark is used in this thesis to generate high electrical discharge at high currents. Electric current was passed (DC pulse type) from the power supply to the capacitor then to the electrode and work piece, the electric discharge machining process are created bubbles within the small gap between the work piece and electrode. Electric current was passed (DC pulse type) from the power supply to the capacitor then to the electrode and work piece, the electric discharge machining process are created bubbles within the small gap between the work piece and electrode. They concluded that MRR in this method are about (0.74581 - 1.53663 mm3/min), wear of electrode between (0.006567 - 0.131354) and the material removal and electrode wear increases in current.

Khushmeet Kumar and Sushma Singh [9] has conducted experimental study of Al-Sic (30%) composite on EDM machine. Engineering Composite Materials are gradually becoming very important material for their scope due to their high fatigue strength, thermal shock resistance, high strength to weight ratio etc. Hence, it is essential for searching an advanced machining method by which machining of composite can be performed with ease and accuracy. For effective machining of AL6061/ Sic (30%) composite, an electrochemical discharge machining (EDM) has been developed.

The developed EDM has been utilized to machine holes on AL6061/Sic (30%). Material removal rate and tool wear rate were obtained experimentally for Brass and Copper tool. Materials with different tool diameter and different levels of current. They concluded that Based on the experimental results it may be concluded that MRR and TWR are directly proportional to the current. They saw that MRR for 8mm tool diameter at 5 amp current is 2.22mg/min for brass tool where as it is 2.38 mg/min for copper tool which is 0.16mg/min (7.21%) more than that of brass tool. Also the corresponding tool wear rate (TWR) was observed as 1.43mg/min for brass tool and for copper tool it is 1.57mg/min which indicates the TWR of copper tool is more by 9.79% as that of brass tool.

Kuldeep Ojha et al [10] has published review papers MRR improvement in sinking Electrical Discharge machine. They published that Material removal rate (MRR) is an important performance measure in EDM process. Despite a range of different approaches, all the research work in this area shares the same objectives of achieving more efficient material removal coupled with a reduction in tool wear and improved surface quality. Apart from all these, various parameters, dielectric and ultrasonic performance are also considered.

They concluded that found that the basis of controlling and improving MRR mostly relies on empirical methods. This is largely due to stochastic nature of the sparking phenomenon involving both electrical and non-electrical process parameters along with their complicated interrelationship. Being an important performance measure, the MRR has been getting overwhelming research potential since the invention of EDM process, and requires more Study /experimentation/modeling in future

III. TYPES OF ELECTRO DISCHARGE MACHINING (EDM)

Some of the variations of EDM process that can be altered for micro fabrication applications are micro-EDM,wire EDM (WEDM), dry EDM [12-14].

1. Wire EDM (WEDM):

Wire electrical discharge machining (WEDM) wasintroduced because it hasthe ability to cut intricate shapes and extremely tapered geometries with high performance especially in precision, efficiency, and stability WEDM operation has a very similar material removal mechanism as EDM process except WEDM uses winding wire as an electrode. Micro-WEDM operation uses a very small diameter wire (Ø 20-50 µm) as the electrode to cut a narrow width of cut in the workpiece.

The wire is pulled through the workpiece from a supply spool onto a take-up mechanism. Discharge occurs between the wire electrode and the workpiece in the presence of a flood of dielectric fluid. The most important control parameters for this process are discharge current, discharge capacitance, pulse duration, pulse frequency, wire speed, wire tension, voltage, and dielectric flushing condition [15-21].

2. Micro-EDM:

EDM operation has already been developed in micro scale industries, asdelicatemicro tools can machine workpiece surface without any deviation or breakage. Micro-EDM follows the similar principle of conventional EDM technology. However, there are some differences between these two machining in terms of circuitry. EDM uses resistance capacitance relaxation (RC-relaxation) circuit while micro-EDM uses RC-pulse circuit.

In RC-relaxation circuit, current and voltage are usually assumed as constant in modellingprocess. However, in reality, for RC-relaxation circuit, current andvoltage are controlled at a predefined levelthroughout the pulse on-time. In contrast, based on the modelling process and parametric analysis, RC-pulse generator for a single dischargeshows that the current and voltage are not maintained to any predefined level.

Still, the RC-pulse generator depends on capacitor charge state at any instant.The RC-pulse circuit type is known to have low material removal rate (MRR) since it can produce very small amount of discharge energy. Micro-EDM is particularlydeveloped to manufacture component of sized between 1 and 999 µm. Hence, in order to produce high precision and high accuracy micro geometries products, micro-EDM is a suitable type of machining[22,23].

3. EDM of Non-Conductive Materials:

Materials that are able to provide a minimum electrical conductivity of 0.1 Scm-1can be processed using EDM. Thus, materials like metals and conductive ceramics are capable to undergo this process. Researchers are applying EDM and micro-EDM to machine ceramics since they are difficult to machine using conventional cutting techniques. But, in order to make the machining process to be continuous, the ceramics need to be conductive. So, one of the solutions is to create a composite with dopants such as titanium nitride (TiN) or tungsten carbide (WC) onto the ceramic.

Other alternative is to create a conductive compound by embedding the ceramic particles in a metal matrix. Another approach is by using the ultrasonic assisted spark erosion. The ultrasonic energy can assist in creating spark erosion and lead to crack formation that causes spalling. Non-conductive ceramics also have been successfully machined by EDM using the assisting electrode method (AEM) (Figure 3) with some modifications done in the process which is one of the commonly method used.

In AEM, a conductive layer is applied on top of the non-conductive ceramic in order to generate spark between the workpiece and the tool electrode. High temperature around the dielectric fluid will degenerate the polymer chains and creates carbon elements from cracked polymer chains. The carbon elements, together with the conductive debris cover the ceramic surface to sustain the conductivity [24-37].

International Journal of Scientific Research & Engineering Trends
Volume 8, Issue 2, Mar-Apr-2022, ISSN (Online): 2395-566X

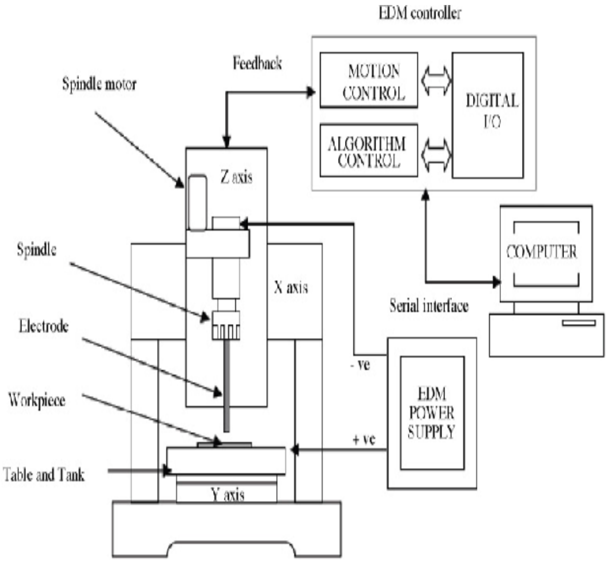

Fig 1. Schematic diagram of micro-EDM.

4. Dry EDM

In EDM process, dielectric fluid plays an important role in order to flush away the debris from the machining gap. In addition, the dielectric fluid also helps to improve theefficiencyof the machining operation as well as improving the quality and economy of the machined parts. The commonly used dielectric fluids are mineral oil-based liquid or hydrocarbon oils which causefire hazard and environmental problems. This is because dielectric wastes generated during the machining operation are very toxic and non-recyclable.

Besides that, during the machining operation, toxic fumes (CO and CH4) are produced because of the high temperature chemical breakdown of mineral oils. The toxicfumes also pose a health hazard to the machining operators [20, 38-42]. In order to avoid these problems, researchers introduce dry EDMwhich includes dry WEDM, dry micro-EDM,and dry micro-WEDM [4, 5, 20,43, 44].

Dry EDM (Figure 4) is a green machining method where the electrode used is in a pipe form and gas or air flows through the pipe instead of the liquid as a dielectric fluid which removes the debris from the gap and cools the machining surface [45-49]. As for dry WEDM, also known as the WEDM using dry dielectric fluid is a modification of the oil WEDM operation where gas is used as dielectric fluid instead of liquid. The flow of gas with high pressure helps to remove the debris and also avoids unnecessary heating of thewire and workpiece at the discharge gap.

Lower tool wear, better surface quality, lower residual stresses, thinner white layer, and higher precision in machining are the prime outcome of this dry technique [1, 20, 50-53]. This dry technique can be applicable for almost all micro level machining operation [49, 54].

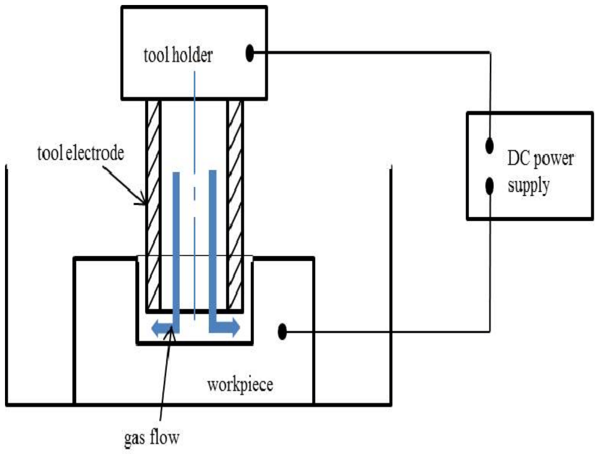

Fig 2. Schematic diagram of dry EDM.

There are researchers who do not agreed with the idea of using the gas instead of the liquid as the dielectric fluid. It is because when the sparks happened in the air, the erosion effect would be very small since the electrical discharge loses its energy.Moreover, the bubble of vapour expands which resulted from the spark into the dielectric fluid and causes the dynamic plasma pressure to rise. It is due to the surrounding dielectric fluid restricts the plasma growth.

The bubble collapses and removes the molten metal out of the crater when the temperature decreases during the off time. Even though there are some disagreements among the researchers, the dry EDM was first introduced and reported by NASA in 1985 [55]. The commonly used gases as the dielectricfluid are atmospheric air, compressed air, liquid nitrogen, oxygen, and argon and helium gas [48, 53, and 56]. Some research shows that material removal rate (MRR) improves when oxygen is used as the dielectric fluid [57, 58]. It is because the oxidation reactionoccurs with the supply of the oxygen gas which increases the work removal volume during one discharge cycle. In addition, there is no corrosion on the machining surface but it may suffer fromrusting due to the oxidation [58].

Compared to conventional WEDM, the vibration of the wire electrode, narrower gap distance, and very negligible process reaction force in dry micro-WEDM assists this process to enable high accuracy in finishing of cut. Higher machining speed and lower electrode wear ratio are achieved in dry EDM milling. Three dimensional (3D) machining of cemented carbide can be done by using dry EDM milling [50, 58]. Higher material removal rate (MRR) can also be achieved in dry EDM when the workpiece is added with the ultrasonic vibration. This is because the ultrasonic vibration helps to flush of the molten metal from the craters [13]. Polarity is a one of the important factor in machining dry EDM. When the polarity of the tool electrode is negative, the tool wear ratio is smaller and the material removal rate is higher

International Journal of Scientific Research & Engineering Trends
Volume 8, Issue 2, Mar-Apr-2022, ISSN (Online): 2395-566X

compared to the positive polarity [59, 53].The machining operation stability is maintained when the tool is in rotation or planetary motion [60]. Low electrode wear ratio in dry EDM is due to the small physical damage of the tool electrode caused by the reactive force. It is because the dry EDM is free from the vaporization of liquid dielectric fluid when the discharge occurs. Besides that, adhesion of machining debris on the electrode helps to reduce electrode wear [58]

IV. WORKING PRINCIPLE OF EDM

The working principle of EDM process is based on the thermoelectric energy. This energy is created between a workpiece and an electrode submerged in a dielectric fluid with the passage of electric current. The workpiece and the electrode are separated by a specific small gap called spark gap.[61-63] Pulsed arc discharges occur in this gap filled with an insulating medium, preferably a dielectric liquid like hydrocarbon oil or de-ionized (de-mineralized) water. Schumacher described the technique of material erosion employed in EDM as still arguable. [64]

This is because ignition of electrical discharges in a dirty, liquid filled gap, when applying EDM, is mostly interpreted as ion action identical as found by physical research of discharges in air or in vacuum as well as with investigations on the breakthrough strength of insulating hydrocarbon liquids. The working principle of EDM is shown in Fig. 1.

This technique has been developed in the late 1940s [65]. The electrode moves toward the workpiece reducing the spark gap so that the applied voltage is high enough to ionize the dielectric fluid [66]. Short duration discharges [67] are generated in a liquid dielectric gap, which separates electrode and workpiece. The material is removed from tool and workpiece with the erosive effect of the electrical discharges. The dielectric fluid serves the purpose to concentrate the discharge energy into a channel of very small cross sectional areas. It also cools the two electrodes, and flushes away the products of machining from the gap. The electrical resistance of the dielectric influences the discharge energy and the time of spark initiation [68].

Low resistance results in early discharge. If resistance is large, the capacitor will attain a higher charge value before initiation of discharge. A servo system is employed which compares the gap voltage with a reference value and to ensure that the electrode moves at a proper rate to maintain the right sparkgap, and also to retract the electrode if short-circuiting occurs. When the measured average gap voltage is higher than that of the servo reference voltage, preset by the operator, the feed speed increases. On the contrary, the feed speed decreases or the electrode is retracted when the average gap voltage is lower than the reference voltage, which is the case for smaller gap widths resulting in a smaller ignition delay. Thus short circuits caused by debris particles and humps of discharge a crater are avoided.

Also quick changes in the working surface area, when tool shapes are complicated, does not result in hazardous machining. In some cases, the average ignition delay time is used in place of the average gap voltage to monitor the gap width [69]. The RC circuit employed in EDM did not give good material removal rate, and higher material removal rate was possible only by sacrificing surface finish. A major portion of the time of machining was spent on charging the capacitors as shown

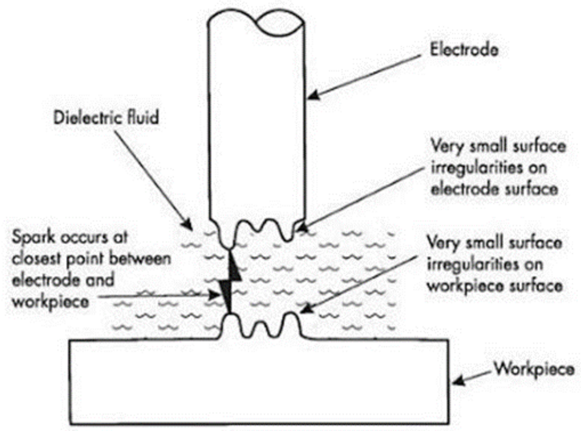

Fig 3. Working principle of EDM.

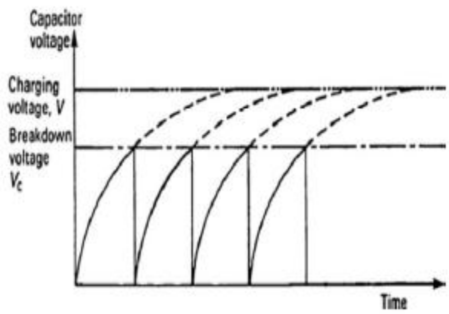

Fig 4. Variation of Capacitor voltage.

V. PROBLEM FORMULATION

Electric Discharge Machining (EDM) is a Traditional Machining technique of metal removal process consisting of erosion of material from the work piece due to series of discrete sparks between work piece and electrode separated by a thin film of dielectric fluid medium. In the Electro-discharge machining (EDM) process electric current is to be converted into heat. The surface of the electrode material is heated in the area of the discharge channel at a very high intensity.

After that current is interrupted, due to which the discharge channel collapses immediately, as a result of that the molten metal on the surface of the work piece and the electrode both evaporates at a very high intensity and send liquid material into the dielectric.

The process removes metal via electrical and thermal energy, having no mechanical contact with the workpiece. Its unique feature of using thermal energy is to machine electrically conductive parts regardless of their hardness; its distinctive advantage is in the manufacture of mold, die, automotive, aerospace and other applications.

The system moves in different axes and movement is control manually by computer system. With the increase in industrialization and globalization, there is a great need and demand in the manufacturing process. The customers demand are increasing rapidly, as a result the need of advanced manufacturing process arises. Most of the industries spread worldwide, due to this advancement competition are increasing at a great scale. Thus, the need of highly efficient products, high surface finish, improved mechanical properties, reliability, life, durability various strength. Performance of water based dielectric is yet to be investigated for machining materials like composites and carbides.

Copper electrode has frequently been used as electrode material in ultrasonic vibration assisted EDM. Other electrode materials need to be investigated thoroughly.

Some portion of the material is conductive and some portion is non-conductive. But EDM requires conductive workpiece. So the composite properties of the workpiece may also lead to some observations. Researcher works on enhancement of material removal rate (MRR), reduction of tool wear rate (TWR), improve Surface Quality (SQ) by experimental investigation.

- Studying the effect of cutting other materials like Al and steel.
- Using other dielectric solution such as oil.
- Using other tool electrode materials such as steel and carbon.
- Studying the surface roughness in the current of EDM.

It is not possible to achieve high surface finish by other machines, as result lots of research is presently being carried out.

There are very less materials on which the researches are done like aluminum and some composite, so we decided to compare and optimize the following material.

- Brass
- Copper
- Aluminum composites
- Brass composites

VI. CONCLUSION

The introduction of EDM to the metal cutting has been a viable machining option of producing highly complex parts, independent of the mechanical properties of work piece material. This is by virtue of the capability of EDM to economically machine parts, which are difficult to be carried out by conventional material removal processes. With continuous improvement in the metal removal efficiency and the incorporation of numerical control, the viability of the EDM process in terms of the type of applications can be considerably extended.

The basis of controlling the EDM process mostly relies on empirical methods largely due to the stochastic nature of the sparking phenomenon involving both electrical and nonelectrical process parameters. The complicated interrelationship between the different optimized process parameters is therefore a major factor contributing to the overall machining efficiency.

However, several means of improving the machining performance commonly measured in terms of MRR, TWR and SR have been made with an overwhelming research interest being paid to the metallurgical properties of EDMed part. Thus, the EDM process needs to be constantly revitalized to remain competitive in providing an essential and valuable role in the tool room manufacturing of part with difficult to-machine materials and geometries.

REFERENCES

[1] P. Srinivasa Rao, J. Suresh Kumar, K. Vijaya Kumar Reddy, B. Sidda Reddy “Parametric Study Of Electrical discharge Machining Of Aisi 304stainless Steel” .
[2] Singh Jaspreet, Singh Mukhtiar and Singh Harpreet” Optimization of machining parameters of Electric Discharge Machining for 202 stainless steel” International Journal of Modern Engineering Research, Vol. 3, Issue. 4, Jul - Aug. 2013 pp-2166-2169.
[3] Munmun Bhaumik, Kali PadaMaity “Study the Effect of Tungsten Carbide Electrode on Stainless Steel (AISI 304) Material in Die Sinking EDM” Journal of Material Science and Mechanical Engineering Volume 1, Number 1; October, pp. 1-6, 2014. Pradeep Kumar P. “Investigation of Material Removal Rate in.
[4] Sushil Kumar Chaudhary (2012) ‘Current Advanced Research Development of Electric Discharge Machining (EDM): A Review’, International Journal of Research in Advent Technology, Vol.2, No.3, March 2014, E-ISSN: 2321-9637
[5] Sandeep Kumar (2014) ‘Status of recent developments and research Issues of electrical discharge machining (EDM)’, International Journal

of Research in Advent Technology, Vol.2, No.3, March 2014, E-ISSN: 2321-9637

[6] C. Bhaskar Reddy, G. Jayachandra Reddy, and C. Eswara Reddy (November 2012) 'Growth of Electrical Discharge Machining and Its Applications – A Review', International Journal of Engineering Research and Development, volume 4 e-ISSN: 2278-067X, p-ISSN: 2278-800X, PP. 13-22.

[7] Manpreet Singh, HarvinderLal, Ramandeep Singh (May - Oct 2013), 'Recent Developments in Wire EDM: A Review, CTIEMT, Jalandhar, Punjab, India, e-ISSN: 2249- 5762, p-ISSN: 2249-5770.

[8] D.T. Pham, S.S. Dimov, S. Bigot, A. Ivanov, K. Popov (June 2004), 'Micro-EDM recent developments and research issues', Journal of Materials Processing Technology, UK.

[9] Khushmeet Kumar, Sushma Singh (October 2014), 'An Experimental Study on Machining of Al-Sic (30%) Composite by EDM Process, Baddi University, Baddi, HP, India, and e-ISSN: 2249-5762, p- ISSN: 2249-57.

[10] KuldeepOjha, R. K. Garg, K. K. Singh, 'MRR Improvement in Sinking Electrical Discharge Machining: A Review', Journal of Minerals & Materials Characterization & Engineering, USA Vol. 9, No.8, pp.709-739.

[11] .Nipanikar, 'parameter optimization of electro discharge Machining of aisi d3 steel material by using taguchi method, Journal of Engineering Research and Studies, Maharashtra, India, e-ISSN0976.

[12] Hoang, K. T. & Yang, S. H. (2013). A study on the effect of different vibration-assisted methods in micro-WEDM. Journal of Materials Processing Technology, 213, 1616-1622.

[13] Chakraborty, S., Dey, V., & Ghosh, S. K. (2015). A review on the use of dielectric fluids and their effects in electrical discharge machining characteristics. Precision Engineering, 40, 1-6.

[14] Ali, M. Y., Karim, A. N. M, Adesta, E. Y. T., Ismail, A. F., Abdullah, A. A., &Idris, M. N. (2010). Comparative study of conventional and micro WEDM based on machining of meso/micro sized spur gear. International Journal of Precision Engineering and Manufacturing, 11 (5), 779-784.

[15] Hoang, K. T. & Yang, S. H. (2015). A new approach for micro-WEDM control based on real-time estimation of material removal rate. International Journal of Precision Engineering and Manufacturing, 16 (2), 241-246.

[16] Debroy, A. & Chakraborty, S. (2013). Non-conventional optimization techniques in optimizing non-traditional machining processes: a review. Management Science Letters, 3(1), 23-38.

[17] Di, S., Chu, X., Wei, D., Wang, Z., Chi, G., & Liu, Y. (2009). Analysis of kerf width in micro-WEDM. International Journal of Machine Tools and Manufacture, 49(10), 788-792.

[18] Chen, Z., Huang, Y., Huang, H., Zhang, Z., & Zhang, G. (2015). Three-dimensional characteristics analysis of the wire-tool vibration considering spatial temperature field and electromagnetic field in WEDM. International Journal of Machine Tools and Manufacture, 92, 85-96.

[19] Patil, P. A. &Waghmare, C. A. (2014). A review on advances in wire electrical discharge machining. In Proceedings of the International Conference on Research and Innovation in Mechanical Engineering (pp. 179-189). Springer India.

[20] Azhiri, R. B., Teimouri, R., Baboly, M. G., & Laseman, Z. (2014). Application of Taguchi, ANFIS and grey relational analysis for studying, modelling and optimization of wire EDM process while using gaseous media. International Journal of Advanced Manufacturing Technology, 71 (1), 279-295

[21] Tosun, N. &Cogun, C. (2003). An investigation on wire wears in WEDM. Journal of Materials Processing Technology, 134, 273-278

[22] . Schubert, A., Ziedler, H., Wolf, N., &Hackert, M. (2011). Micro electro discharge machining of electrically nonconductive ceramics. AIP Conference Proceedings, 1353, (1) 1303-1308.

[23] Pecas, P. &Henriques, E. (2008). Electrical discharge machining using simple and powder-mixed dielectric: the effect of the electrode area in the surface roughness and topography. Journal of Materials Processing Technology, 200, 250-258.

[24] Asfana, A., Ali, M. Y., Mohamed, A. R., & Hung, W. N. P. (2015). Material removal rate of zirconia in electro discharge micromachining. Advanced Materials Research, 1115, 20-23.

[25] Hosel, T., Muller, C., & Reinecke, H. (2011a). Spark erosive structuring of electrically nonconductive zirconia with an assisting electrode. CIRP Journal of Manufacturing Science and Technology, 4, 357-361

[26] Schubert, A. & Zeidler, H. (2009). Machining of non conductive ZrO2 ceramics with micro-EDM. In: Van Brussel, H.; Brinksmeier, E.; Spaan, H. (ed): Proceedings of the 9th International Conference of the European Society for Precision Engineering and Nanotechnology, ISBN: 978-0-9553082-6-0, S. 6-9 (Bd.2).

[27] Muttamara, A., Janmanee, P., & Fukuzawa, Y. (2010). A Study of Micro-EDM on Silicon Nitride Using Electrode Materials. International Transaction Journal of Engineering, Management, & Applied Science & Technologies, 1 (1), 001-007.

[28] Asfana, A., Ali, M. Y., Mohamed, A. R., & Hung, W. N. P. (2015). Material removal rate of zirconia in electro discharge micromachining. Advanced Materials Research, 1115, 20-23. 31.

[29] Hosel, T., Cvancara, T., Ganz, T., Muller, C., & Reinecke, H. (2011). Characterization of high aspect ratio nonconductive ceramic microstructures made by spark erosion. Microsystem Technologies, 17, 313–318. 32.

[30] Hosel, T., Muller, C., & Reinecke, H. (2011a). Spark erosive structuring of electrically nonconductive zirconia with an assisting electrode. CIRP Journal of Manufacturing Science and Technology, 4, 357-361. 33.
[31] Schubert, A. & Zeidler, H. (2009). Machining of nonconductive ZrO2 ceramics with micro-EDM. In: Van Brussel, H.; Brinksmeier, E.; Spaan, H. (ed): Proceedings of the 9th International Conference of the European Society for Precision Engineering and Nanotechnology, ISBN: 978-0-9553082-6-0, S. 6-9 (Bd.2). 34.
[32] Muttamara, A., Janmanee, P., &Fukuzawa, Y. (2010). A Study of Micro-EDM on Silicon Nitride Using Electrode Materials. International Transaction Journal of Engineering, Management, & Applied Science & Technologies, 1 (1), 001-007.
[33] Mohamed, A. R., Asfana, B., & Ali, M. Y. (2014). Investigation of recast layer of non-conductive ceramic due to micro-EDM. Advanced Materials Research, 845, 857-861. 36
[34] Muttamara, A., Fukuzawa, Y., Mohri, N., & Tani, T. (2009). Effect of electrode material on electrical discharge machining of alumina. Journal of Materials Processing Technology, 209, 2545-2552. 37.
[35] Chen, Y. F., Lin, Y. C., Chen, S. L., & Hsu, L. R. (2009). Optimization of electrodischarge machining parameters on ZrO2 ceramic using the Taguchi method. Journal of Engineering Manufacture, 224, 195-205. 38.
[36] Banu, A., Ali, M. Y., & Rahman, M. A. (2014). Micro-electro discharge machining of non-conductive zirconia ceramic: investigation of MRR and recast layer hardness. International Journal of Advanced Manufacturing Technology, 75, 257-267.
[37] .Fukuzawa, Y., Mohri, N., Tani, T., & Muttamara, A. (2004). Electrical discharge machining properties of noble crystals. Journal of Materials Processing Technology, 149, 393-397.
[38] Pandey, A. & Singh, S. (2010). Current research trends in variants of electrical discharge machining: a review. International Journal of Engineering Science and Technology, 2 (6), 2172-2191. 42.
[39] Kunieda, M. & Furudate, C. (2001). High precision finish cutting by dry WEDM. CIRP Annals – Manufacturing Technology, 50 (1), 121-124. 43.
[40] Pradeep, G. M. & Dani, M. S. H. (2015). A review on the use of pollution free dielectric fluids in wire electrical discharge machining process. Journal of Chemical and Pharmaceutical Sciences, (7), 312-315.
[41] Dhakar, K & Dvivedi, A. (2016). Parametric evaluation on near-dry electric discharge machining. Materials and Manufacturing Processes, 31, 413-421.
[42] Zhang, Q. H., Zhang, J. H., Ren, S. F., Deng, J. X., & Ai, X. (2004). Study on technology of ultrasonic vibration aided electrical discharge machining in gas. Journal of Materials Processing Technology, 149, 640-644.
[43] Khatri, B. C., Rathod, P., & Valaki, J. B. (2015). Ultrasonic vibration-assisted electric discharge machining: a research review. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 1-12. DOI: 10.1177/ 0954405415573061
[44] Wang, T., Xie, S. Q., Xu, X. C., Chen, Q., Lu, X. C., & Zhou, S. H. (2012). Application of uniform design in experiments of WEDM in gas. Advanced Materials Research, 426, 11-14.
[45] Mahendran, S. & Ramasamy, D. (2010). Micro-EDM: overview and recent developments. In National Conference in Mechanical Engineering Research and Postgraduate Students (1st NCMER 2010), 26-27 May 2010, Pahang, Malaysia, 480-494. 49.
[46] Fujiki, M., Ni, J., & Shih, A. J. (2011). Tool path planning for near-dry EDM milling with lead angle on curved surfaces. Journal of Manufacturing Science and Engineering, 133(5), 051005. 50
[47] Besliu, I., Schulze, H. P., Coteata, M., &Amarandei, D. (2010). Study on the dry electrical discharge machining. International Journal of Material Forming, 3(1), 1107-1110. 51.
[48] Paul, G., Roy, S., Sarkar, S., Hanumaiah, N., &Mitra, S. (2013). Investigations on influence of process variables on crater dimensions in micro-EDM of titanium aluminide alloy in dry and oil dielectric media. International Journal of Advanced Manufacturing Technology, 65, 1009-1017. 52.
[49] Skrabalak, G. &Kozak, J. (2010). Study on dry electrical discharge machining. Wear, 5, 7.
[50] Wang, T. &Kunieda, M. (2004). Dry WEDM for finish cut. Key Engineering Materials, 259-260, 562-566. 54
[51] Kunieda, M., Lauwers, B., Rajurkar, K. P., & Schumacher, B. M. (2005). Advancing EDM through fundamental insight into the process. CIRP Annals-Manufacturing Technology, 54(2), 64-87. 55.
[52] Liqing, L. & Yingjie, S. (2013). Study of dry EDM with oxygen-mixed and cryogenic cooling approaches. Procedia CIRP, 6, 344-350. 56.
[53] Singh, P., Chaudhary, A. K., Singh, T., &Rana, A. K. (2015). Comparison of outputs for dry EDM and EDM with oil: a review. International Journal for Research in Emerging Science and Technology, 2(6), 45-49.
[54] Yu, Z. B., Takahashi, J., Nakajima, N., Sano, S., &Kunieda, M. (2005). Feasibility of 3-D surface machining by dry EDM. International Journal of Electrical Machining, 10, 15-20.
[55] Leao, F. N. &Pashby, I. R. (2004). A review on the use of environmentally-friendly dielectric fluids in electrical discharge machining. Journal of Materials Processing Technology, 149, 341-346. 59
[56] Besliu, I. &Coteata, M. (2009). Characteristics of the dry electrical discharge machining. Nonconventioal Technologies, 2, 5-8.

[57] Teimouri, R. &Baseri, H. (2013). Experimental study of rotary magnetic field-assisted dry EDM with ultrasonic vibration of workpiece. International Journal of Advanced Manufacturing Technology, 67(5-8), 1371-1384. 61.
[58] Jahan, M. P., Rahman, M., & Wong, Y. S. (2011). A review on the conventional and micro-electrodischarge machining of tungsten carbide. International Journal of Machine Tools and Manufacture, 51, 837-858.
[59] Abbas, M. N., Solomon, D. G., &FuadBahari, M. (2007). A review on current research trends in electrical discharge machining (EDM). International Journal of Machine Tools and Manufacture, 47(7), 1214-1228
[60] Chandra, B., Singh, H., &Garg, J. (2011). A review on emerging areas of interest in electrical discharge machining. International Journal of Advanced Engineering Technology, 2(3), 1-9
[61]] Rudorff, D.W., 1961 "Spark machining and its development", Metal Treatment and Drop Forging, 28 (186), 120–124.
[62]] Pandey, P.C.; Shan, H.S. Modern Machining Process. Tata McGraw- Hill Publishing Company Ltd 1999, 84-113. [9]
[63] Smith, G.V., 1961, "Spark machining – fundamental and techniques. J Br Inst Radio Eng, 22, 409. [10]
[64] Luis, C.J., Puertas, I., Villa, G., 2005 "Material removal rate and electrode wear study on the EDM of silicon carbide", Journal of Materials Processing Technology, 164–165, 889– Vol.9, No.8 MRR Improvement in Sinking Electrical Discharge Machining 733 896. [11]
[65] Schumacher, B.M., 2004 "After 60 years of EDM, the discharge process remains still disputed. Journal of Materials Processing Technology", 149, 376–381. [12]
[66] Singh, S., Maheshwari, S., Pandey, P.C., 2004 "Some investigations into the electric discharge machining of hardened tool steel using different electrode materials", Journal of Materials Processing Technology, 149, 272–277. [13]
[67] Bojorquez, B., Marloth, R.T., Es-Said, O.S., 2002 "Formation of a crater in the workpiece on an electrical discharge machine", Engineering Failure Analysis, 9, 93– 97. [14]
[68] Marafona, J.; Chousal, A.G., 2006 "A finite element model of EDM based on the Joule effect", Int. J. Mach. Tools Manuf., 46 (6), 595-602. [15]
[69] Kuneida, M., Lauwers, B., Rajurkar, K.P., Schumacher, B.M., 2005 "Advancing EDM through fundamental insight into the process", Annals of CIRP, 54 (2), 599–622