Sustainable Engineering Approaches Used in Electrical Discharge Machining Processes: A Review

Ranjit Singh, Ravi Pratap Singh, and Rajeev Trehan

Abstract Sustainable engineering is the approach in which the process is designed in such a way that there is a balance between the use of energy and resources so that it will not affect the environment and can be conserved for fulfilling the needs of future generations. Sustainable engineering in manufacturing focuses on the enhancement of productivity by controlling process parameters. So, it has become a hot topic in almost every field of manufacturing, aiming to achieve more economical and efficient processes. The key methods of sustainable production mainly include the optimization of energy usage and the innovation of machining techniques, etc. Nowadays, many relevant investigations have been conducted. In this paper, the main study is focused on the sustainable engineering approaches used in the electrical discharge machining processes, various optimization techniques used for better productivity in EDM processes. Effect of different process parameters like pulse-on, pulse-off, peak current, spark gap voltage, tool feed, flushing pressure, electrode polarity, dielectric fluid, etc., in machining operations has been discussed. For better machining time and less energy consumption, the optimization of process parameters, the problem of wire rupture in case of wire electrical discharge machining (WEDM), and the use of different electrode materials in EDM machining operations have been reviewed in this study. Efforts have been made to enhance EDM operations by sustainable engineering approaches with a systematic review of different research articles, industrial catalogs, technical fundamentals, etc. Various conclusions are drawn based on a thorough review of research articles and a list of gaps or future scopes have been provided in this paper.

Keywords EDM · WEDM · PMEDM · MRR · UCM · SEM · TWR · Ra

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1 Introduction to Sustainable Engineering

Sustainable engineering is the method of utilizing resources in such a manner that it would not affect the surrounding environment and resources are conserved for future generations. For practicing sustainable engineering in a complete way, it needs an interdisciplinary approach in every phase of engineering and it should not be designated as the sole responsibility of environmental engineering. All engineering fields should incorporate sustainability into their practice to enhance the quality of life for all. Sustainable development is broadly defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [1]. Within this field, sustainable manufacturing is termed as the "Creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" [2].

2 Concept of Sustainability in Manufacturing Environment

In today's scenario, the manufacturing sector is playing quite an essential role in the country's economy. In 2012, the manufacturing area generated a turnover of €7000 billion and engaged over 30 million people directly in employment. The European industry is a world leader in a number of manufacturing sectors with mechanical engineering area having a global market share of 37% [3]. The use of men, machines, and material in a sustainable manner is very much required in the upliftment of this sector and also for conserving our environment and existing resources. The conventional machining processes involve direct contact between the tool and workpiece, which results in a number of losses in terms of energy, power, tool material, workpiece material, etc. The limitation of these processes is machining of hard and fragile components, complex and intricate shape formation. As compare to the conventional machining operations, advanced machining operations overcome these limitations. In non-conventional machining operations, there is no direct contact of tool with the workpiece, which helps in preventing from wear of tool and workpiece. One of the important operations among these is electrical discharge machining (EDM), in which a series of electrical discharge is used in the presence of dielectric fluid for machining of the workpiece. EDM is used for machining of hard and fragile materials with complex shapes without any barrier to their hardness. Still, this process needs some improvement for saving the loss of energy, power, wear of tool and workpiece. The advanced machining operation like EDM is crucial in the manufacturing processes, and sustainable engineering approaches in these machining operations lead to better productivity in terms of energy, material, and process optimization in manufacturing processes.

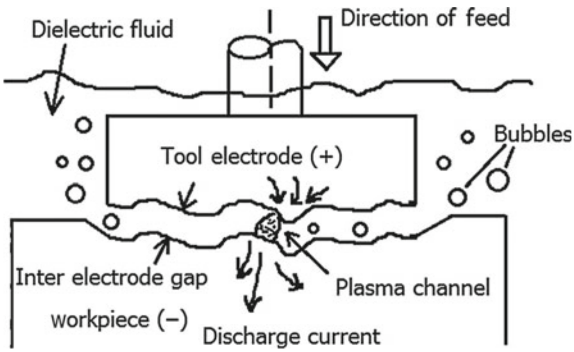

Fig. 1 Schematic view of the concept of EDM process [4]

3 Principle of Electrical Discharge Machining (EDM) Process

EDM is a type of thermo-erosive process in which spatially and temporally controlled separated pulsed discharges are utilized to machine electrically conductive materials irrespective of their chemical, mechanical, and thermophysical properties [4]. The tool used for spark erosion as an electrode is a negative replica of the contour, which the investigators want to produce on the workpiece. Figure 1 shows the schematic view of the EDM process.

Discrete sparks are produced in series between the workpiece and shaped tool electrode, and a complete arrangement is submerged in the dielectric fluid. Dielectric fluids, namely deionized water, EDM oil, kerosene, and paraffin oil among others are used in the EDM process. A very small inter-electrode gap between the workpiece surface and tool electrode must be kept via which the dielectric fluid is passed [5].

4 Review of Literature

EDM is a significant non-conventional machining operation used for the machining of hard and fragile components irrespective of their hardness and depth. The machining of small and microcomponents is a unique application of EDM process as compared to other conventional processes. Complex and intricate shapes with fine accuracy, precision, and surface properties are added advantages of EDM process, which are very hard to obtain with the other conventional machining operations (Fig. 2).

Sustainability in the EDM processes is a need of today's concern, as there are certain losses that can be cured with the application of sustainable approaches. Wear of tool, workpiece, more loss of power, optimization of electrical and non-electrical process parameters, and responses are of important concern in obtaining a sustainable and quality product. The review of literature on sustainable approaches on EDM process has been discussed below.

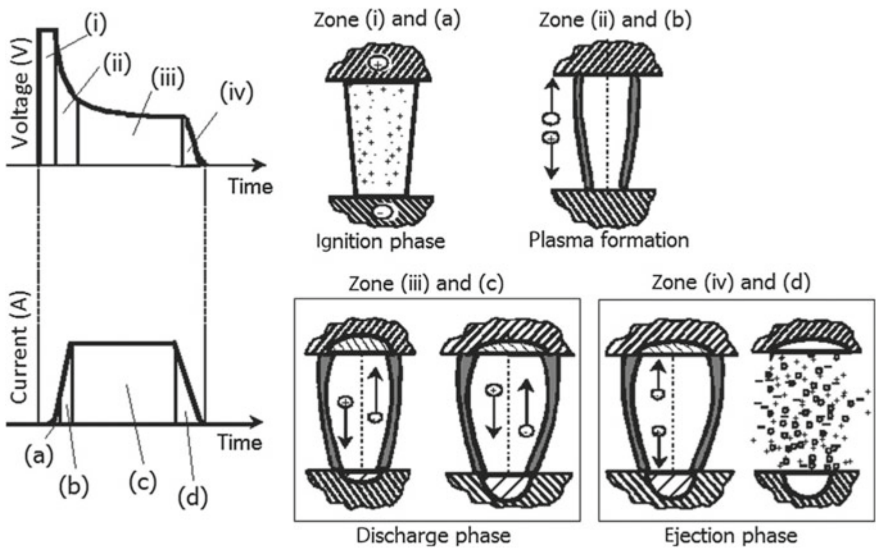

Fig. 2 Schematic view of voltage and current trends of pulse along with the phases of an electrical discharge [4]

Gamage et al. [6] investigated the sustainability of non-conventional machining processes and the evaluation of research needs for optimizing the process. For machining complex, intricate and difficult to cut materials, the unconventional machining practices play a major role in the manufacturing of such products. The product with high precision and fine accuracy can be achieved with the use of non-conventional machines (Fig. 3).

The objective of the present study is to determine the existing state of the art in sustainability evaluation of unconventional machining practices and spot out different gaps in research. An environmental assessment study on EDM revealed a data collection effort to calculate the total environmental impact of three EDM techniques, namely die-sinking EDM, micro-EDM, and WEDM.

This study has revealed that during 1 h of EDM roughing process, the electrical energy for EDM process and the hydrocarbon oil, which is utilized as a dielectric fluid in the process, are the main factors that contribute for the total impact amounting to 47.3% and 23.1%, respectively. It has been observed from the current study that dielectric fluid and energy cause similar amount of burdens on the environment during EDM operation. The operator's health and safety hazards may be reduced with the utilization of non-hydrocarbon-based dielectrics. A thorough review of the utilization of dielectric fluids, which are environmentally friendly in EDM reveals that water-based dielectrics, a substitute to hydrocarbon oil, can be used for die-sinking EDM.

Xiang et al. [7] researched on the sustainable production of micro-gears combining EDM and precise forging of micro-reciprocated wire. This paper presents a hybrid

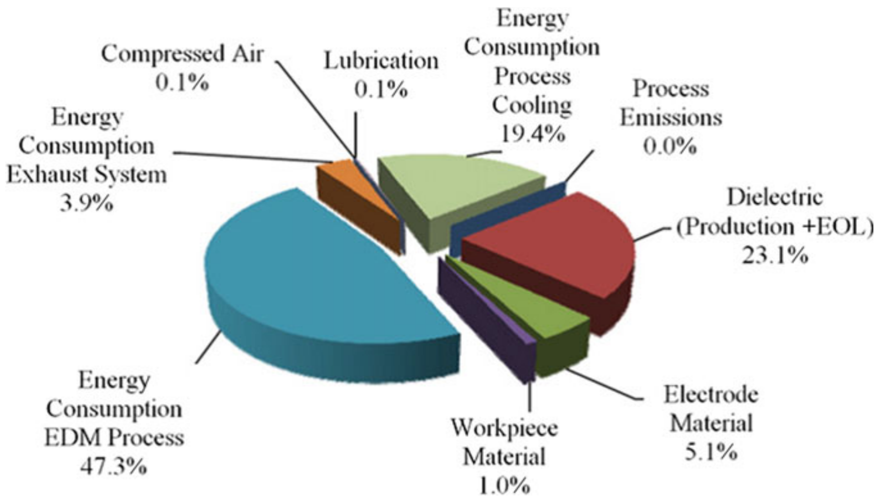

Fig. 3 Distribution of the environmental impact during one hour of EDM roughing operation [6]

process that combines micro-reciprocated wire EDM, which uses reciprocated traveling wire with a diameter of 50 μm as an electrode tool, with accurate forging, achieving economical and efficient sustainable production of micro-gears. The economical and high-precision manufacture of SKD11 micro-gear mold is first carried out by micro-reciprocated wire EDM.

Pramanik et al. [8] investigated the sustainability in machining of titanium alloys in WEDM. The study aims at understanding the wire rupture. The uninterrupted machining is necessary for reducing energy and machining time for making the process sustainable. Understanding the mechanism and factors that will result in wire electrode rupture is important for reducing machining time to preserve resources and improve sustainability of the process. The study aims at studying the wire rupture mechanism while doing machining of Ti–6Al–4V in EDM. To aid the analysis of pulse-on time, wire tension, and electrolyte flushing pressure was varied to understand the effects of these parameters on wire rupture. The occurrence of wire rupture occurs at high wire tension and lower flushing pressure. The effect of pulse-on time on wire rupture depends on the interaction of flushing pressure and wire tension (Fig. 4).

The wire gets deformed in three stages before fracture. At the initial point, the round section of wire converts into oval shape following a gradual decrease in overall cross section, and finally, necking takes place. Chakraborty et al. [9] aim at the study of different dielectric fluids and their effect on EDM. In EDM, material removal occurs in the presence of dielectric fluid; so, this working fluid plays an important role in the material removal phenomenon in EDM (Fig. 5).

The dielectric fluid plays the role of a medium for the production of electrical discharge in EDM, flushes away the debris produced during machining, works as quenching medium to solidify and cool gaseous debris in EDM, and works as a heat

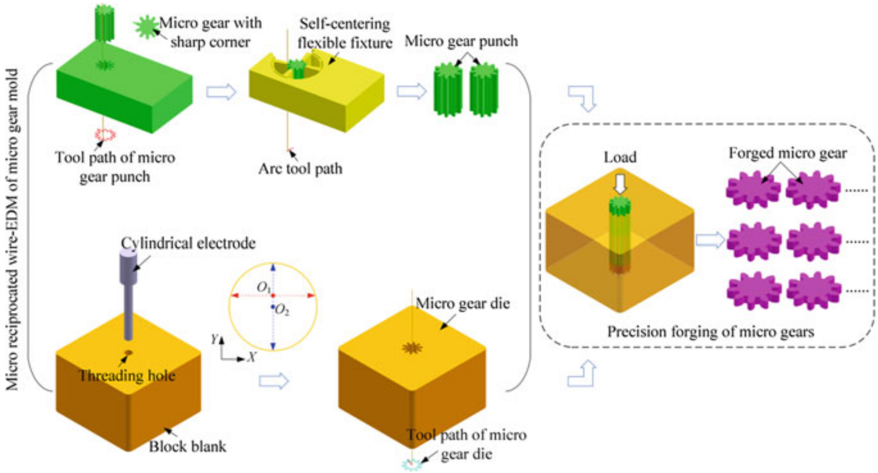

Fig. 4 Machining process of micro-gears combining micro-reciprocated wire EDM and precision forging [7]

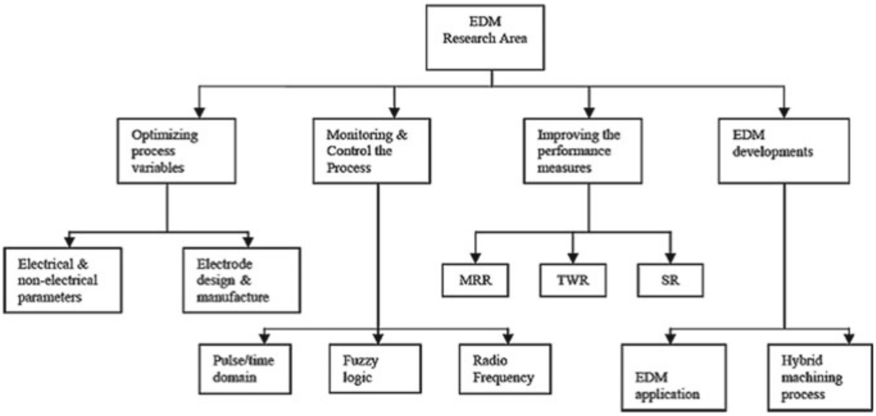

Fig. 5 Classification of major EDM research areas [10]

transfer medium for transferring the heat produced by electrical discharges from both the workpiece and electrode [11]. The dielectric fluids are of different types: mineral oils, kerosene, mineral seal, transformer oil, etc. Water-based dielectric plays an important role in EDM. The use of water as a dielectric fluid is an alternative to the hydrocarbon oil. The approach behind using water as a dielectric is to promote a safe environment and better health while working on EDM. The hydrocarbon oils like kerosene get decomposed and harmful vapors are released, i.e. CO and CH_4 [12]. Powder additives are also one of the new and less explored areas of research in EDM in which fine abrasive powder is mixed with the dielectric fluid. The EDM operation with powder mixed in the dielectric is known as powder-mixed EDM (PMEDM) [13]. The powder reduces the dielectric insulating strength and results in an increase in spark gap between tool and workpiece. With the use of powder in dielectric, the EDM process becomes more stable, and machining efficiency, material removal rate (MRR), and surface quality get improved. Kou et al. [14] investigated the sustainable manufacturing of titanium alloys by using high-speed electrical discharge milling operation with moving electric arcs while using water-based dielectric. For solving the problem of environmental pollution and low machining efficiency of the conventional EDM process, sustainable manufacturing, a new method of EDM milling, along with water as the dielectric medium has been proposed. The moving electric arc is provided better output energy in case of high-speed EDM milling as compare to the spark in the conventional EDM process. More MRR achieved while machining with high-speed EDM milling operations up to five times of conventional EDM. Urso et al. [15] investigated the sustainability of micro-EDM drilling process by studying the effects of workpiece and electrode materials in EDM process. The three different workpiece materials, i.e., tungsten carbide, stainless steel, and aluminum machined with two electrode materials, brass and tungsten carbide. The machining accuracy is also taken into account for calculating the sustainability index. Tool wear has the maximum impact on the sustainability of the process. From the electrode point of view, the brass electrode is more sustainable than that of the tungsten carbide in terms of electrode wear and energy consumption.

Sarkar et al. [16] investigated the optimization and modeling of WEDM of γ-TiAl in the trim cutting operation. A second-order mathematical model, in prerequisites of machining parameters, was advanced for cutting speed, surface roughness (SR), and dimensional deviation using response surface methodology (RSM). Manjaiah et al. [17] investigated the effect of process parameters on the responses such as MRR and SR of Ti50Ni40Cu10 SMA machined by WEDM using the Taguchi techniques to acquire optimum machining process parameters. Experimental results exhibit that peak current, pulse-on time, and servo voltages are major significant factors affecting the MRR and surface finish during machining. Pulse-off time and wire feed had no significance on the responses (Fig. 6).

Rao et al. [18] studied the effect of WEDM parameters on aluminum alloys as the application of Al is rising in various industries. In this present investigation, the parametric examination of WEDM parameters was performed by using Taguchi techniques on SR and MRR. The rising discharge energy usually increases surface irregularities due to a large amount of melting and resolidification of materials. So, the minimum surface roughness is obtained at lower values of peak current and pulse-on time. Prasad and Krishna [19] presented a model for MRR and SR in terms of input variables using RSM. A non-dominated sorting algorithm was then applied to obtain the pareto-optimal solutions for optimization purposes.

Pilligrin et al. [20] investigated the effects of electrode material and its impact on the performance measures in electrical discharge micro-machining. Miniaturization is one of the important concepts in which commercial products are reduced in their size without affecting their functionality. This results in sustainability in the machining processes, where the components are micro-machined, which in turn

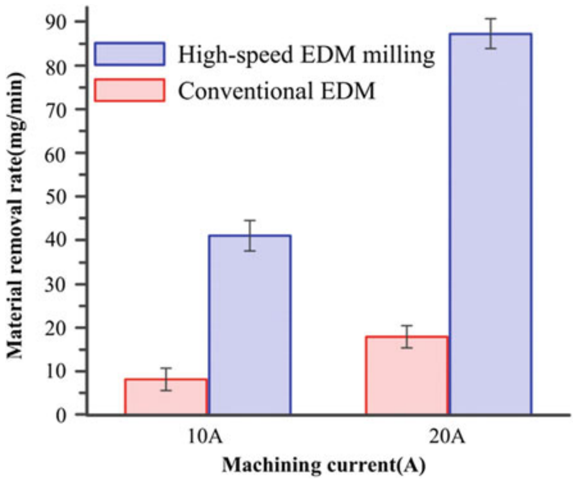

Fig. 6 Comparison of MRR between conventional EDM and high-speed EDM milling [15]

results in the reduction in machining time and conservation of resources. The effect of performance parameters, discharge energy, spindle speed, tools material (Cu, Cu–W, W), and their impact on the response parameters MRR, TWR, Overcut, Taper angle, surface roughness, has been studied. It is found that TWR is low when the thermal conductivity, boiling, and melting point of the electrode is high. It is found from the experimental investigations that TWR and overcut are in the order of Cu>Cu–W>W. This is due to the variations in the thermal properties of electrode material. The surface roughness is found to be low at low spindle speed and low discharge energies. This is due to proper flushing and stable machining conditions. The different sustainable engineering approaches used in EDM processes found from the literature survery are: parametric optimization, heat treatment of electrodes, coating of electrodes and workpieces, use of different tool electrodes at different angles and geometries, heat treatment of workpieces, use of hybrid dielectric fluids, tool feed mechanism, work table movement, surface characterization.

5 Future Scopes

A very less work has been reported on the use of water-based dielectric with an organic compound in the EDM processes. This is a new approach toward sustainability of the EDM process. Compared with the different hydrocarbon oil-based dielectrics, water-based dielectrics are more environmentally friendly and clean. The generation of harmful and airborne particles in the case of water-based dielectrics is quite less as compared to the hydrocarbon oil-based dielectrics. The processing parameters related to the highest material removal rate efficiency have not yet been studied up to a sufficient extent. Very less work has been reported on the optimization of parameters for preventing tool wear in EDM process. In future work, artificial intelligence (AI) techniques should be considered for optimizing different process parameters in EDM process.

6 Conclusion

The following conclusions can be made by studying and investigating different sustainable approaches applied in EDM processes:

1. The micro-EDM process is highly versatile and therefore has an enormous potential for the manufacture of various microstructures and microsystems and devices in a wide range of hard to machine materials.
2. A straight-through micro-hole can be produced by controlling the important process parameters such as pulse-on time, peak current, and flushing pressure properly. In order to increase the yield of micro-manufacturing, innovative hybrid micro-machining processes can also be developed for micro-EDM to machine alloys like Ti–6Al–4V.
3. The sustainable fabrication of micro-gears with high accuracy, productivity, and low cost is achieved by combining EDM and precise forging with micro-reciprocated wire.
4. The precise forging of micro-gears on ultra-fine grained copper is carried out using the machined micro-gear mold, which achieves the sustainable production of micro-gears with high precision and productivity.
5. The pulse-on time influence depends on the interaction between wire tension and flushing pressure in the wire rupture mechanism. The wire break occurs at an instantaneous high temperature due to the creation of unnecessary arcs when the EDM debris/wastes are not properly flushed away.
6. EDM's energy consumption rate depends on the machine tool and machining variables in which chillers/water coolers and pumps consumed the highest energy consumption.
7. In roughing operations, PMEDM can also improve processing efficiency. Electrically conductive powder reduces the dielectric fluid's insulating strength and thus increases the gap between the tool and the workpiece. The EDM process is stabilized and also improves MRR and SQ.
8. Lower viscosity dielectric oils can increase efficiency during micro-EDM. The dielectric oil of low viscosity has a greater influence on the machining cycle than the hydrocarbon oils.
9. The high-speed EDM milling can achieve a higher MRR on titanium alloy with a moving electric arc. Comparative experiments show that the high-speed EDM milling MRR is nearly five times the conventional EDM.

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