A Comparative Study on Micro Electro-Discharge Machining for Machining of Ti–6Al–4V Alloy Shape Memory Alloy (NI-TI)

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Abstract

Nowadays, it has become very difficult for the manufacturer to satisfy all its customers with satisfactory products, as they have deferent demands considering the responses. However, hard-to-machine materials are difficult to manufacture. This study explores the application of electro- discharge machining (EDM) of Ti–6Al–4V alloy with pulse duration (Ton), duty factor (Ʈ), peak current (*Ip*) and gap voltage (*Vg*) as the control parameters using pure copper electrode. Machining effects are evaluated by performance characteristics including material removal rate (MRR), tool wear rate (TWR) and surface roughness (SR) by considering the multi-criteria preference of the customers that vary with the preference of responses.

Keywords: EDM; Ti–6Al–4V; utility concept; desirability approach.

1. Introduction

Die-sinking electro-discharge machining (EDM) process has proved its importance in manufacturing industries due to its nontraditional nature. It has both its electrode and work piece submerged in a dielectric liquid which is connected to a source of current that is switched on and automatically depending on the parameters set on the controller. An electric spark is generated between the two metal parts when the current is switched on. This spark jump takes place if the two parts are brought close within a minimum gap. Where it strikes, the metal is heated up so much that it melts. Sinker EDM, also called cavity EDM or volume EDM consists of an insulating liquid such as, oil or, less frequently, other dielectric fluids. Nowadays, advance materials are mostly used due to their remarkable properties. Ti–6Al–4V with its exceptional qualities is widely used in many engineering fields, such as manufacturing of turbines, inkjets of printers as well as in the case of biomedical, automobile and aerospace industries. It has a high strength-to-weight ratio, good temperature stability, and noticeable corrosion resistance. It cannot be machined traditionally with its properties of high melting and low thermal conductivity. Therefore, EDM, as a nontraditional machining process, is most electively used to machine this hard-to-machine alloy. It is a noncontact electro-thermal machining method which does not depend upon the mechanical properties of the machining material and is used to machine hard, high strength and temperature resistance materials. The material is first melted and then gets evaporated by the heat created by the sparks on the work piece where the dielectric is used for effective crushing of the machining debris formed. The vanadium-free titanium materials have greater mechanical and bio-compatible properties owing to their use in artificial hip joints. Hascalik and Caydas elaborated the surface integrity property of Ti–6Al–4V alloy by EDM and abrasive electro-chemical grinding (AECG). The damages occurred by EDM can be reduced by the AECG to achieve the good surface finish. The material is eroded using EDM and then the surface is grounded to achieve a highly polished surface. Including both the processes to manufacture a better element is more expensive. Harcuba *et al.* explored the biocompatibility of Ti–6Al–4V alloy after the machining of the surface by the EDM process. The surface adaptation is considered to be a promising improvement to orthopedic implants and bone tissues. In this framework, the survey is made on responses of machining of Ti-based alloys and the statistical methods used to correlate the experimental study. The effects of the machining parameters in EDM on the machining features of high-speed steel were investigated by Yan-Cherng *et al*. The relationship of material removal rate (MRR) and surface roughness (SR) with pulse-on-time with different peak current was found **[1]**. have studied the distinct influence of the operating factors on Ti–6Al–4V by the laser texturing process which has been deliberate using two experimental approaches: Taguchi methodology and Response Surface Methodology (RSM). Results analysis shows that the laser pulse energy and frequency are the most important operating factors. Bergaley explores the optimization of electrical and nonelectrical factors in EDM for machining die steel using copper electrode by adopting Taguchi technique. The research showed that the peak current has a significant effect on MRR. In separate studies **[2]**. as well as Tsai and Lu established that the most important electrical pulse parameters of EDM are discharge current and pulse duration. These parameters directly influence the machining performance. Several researchers have worked on the statistical and regression analysis using Design of Experiment Methodology to analyze the performance parameters of EDM. Thus, Design of Experiment Methodology is found to be a very useful tool to analyze the performance parameters of EDM. **[3]**. adopted grey relational grade to solve performance characteristics to find optimum levels of parameters with significant contributions by ANOVA. **[4]**. found optimum level of parameters by applying a modified algorithm of particle swarm optimization for experimentation with stainless steel. **[5]**. compared benefits of their augmented approach using two real data sets by com- paring their solutions with those obtained from the desirability approach. Karande *et al.* compared two conceptually simple but strong mathematical techniques, i.e. utility concept and desirability function approaches are proposed to solve four material selection problems. Many researchers have successfully used Taguchi approach to design and analyze EDM process. Peak current and pulse-on-time controls the total amount of energy supplied during machining. Many research works have already been conducted with a motive to increase the MRR and to decrease the tool wear rate (TWR) and SR by obtaining the optimum combination of the input parameters. Though there are various works on conventional Taguchi- based single objective or weight-based multi-response optimization in EDM, the utility- and desirability-based techniques have not been effectively used, especially in EDM for machining of high performance materials like titanium alloys. Thus, the present study investigates the influence of process parameters for machining of Ti–6Al–4V in detail and development of optimum parametric conditions for fullling the demand of multi-users with different priorities.

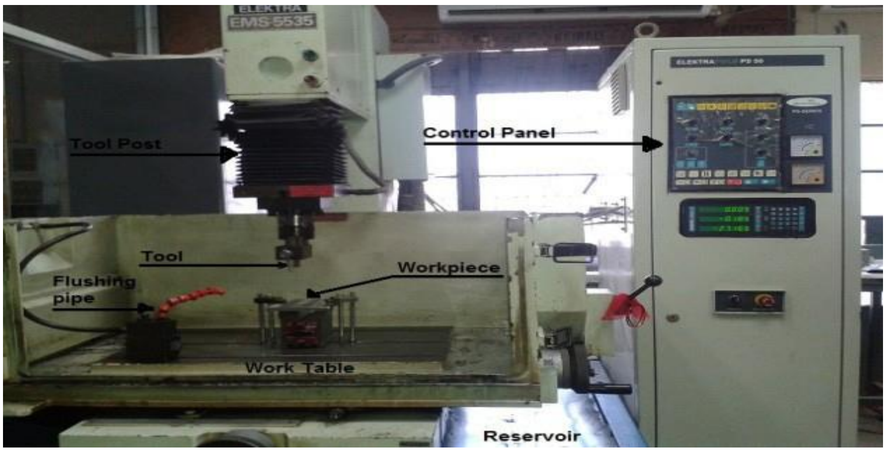

Fig. 1 Schematic Diagram of Electrical Discharge Machine **[1]**

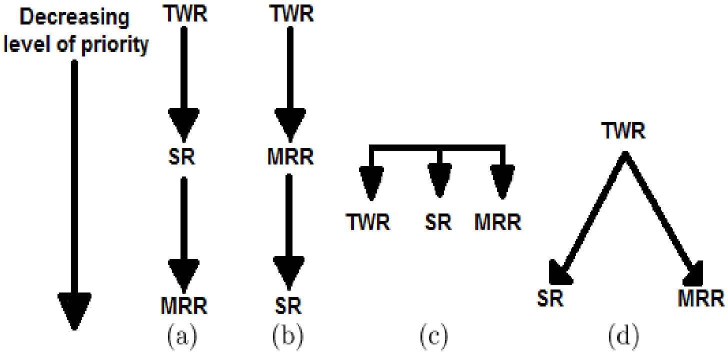

Fig. 2 Representation of the priorities of four different users in graphical form [2]

2. An overview of shape memory alloys

Arne O¨lander first found SMA or ''intelligent alloy'' in 1932, and Vernon first defined the word ''shape memory'' in 1941. the function of shape memory components was not recognized until 1962. Wang and Buehler disclosed about the impact of shape memory in an alloy of nickel-titanium (Ni-Ti), often called nitinol (Drawn from the material structure and the place of discovery, i.e., a mixture of Ni-Ti and Naval ordnance lab). SMAs belongs to a group of metallic alloys, those when exposed to a process of memorization among two stages of transformation depending on temperature or magnetic field, can retain their actual form (size & shape). This phenomenon of transformation is referred to as the shape memory effect (SME) **[6]**. These kinds of materials have two basic phase systems, lower martens tic phase and higher austenitic phase of

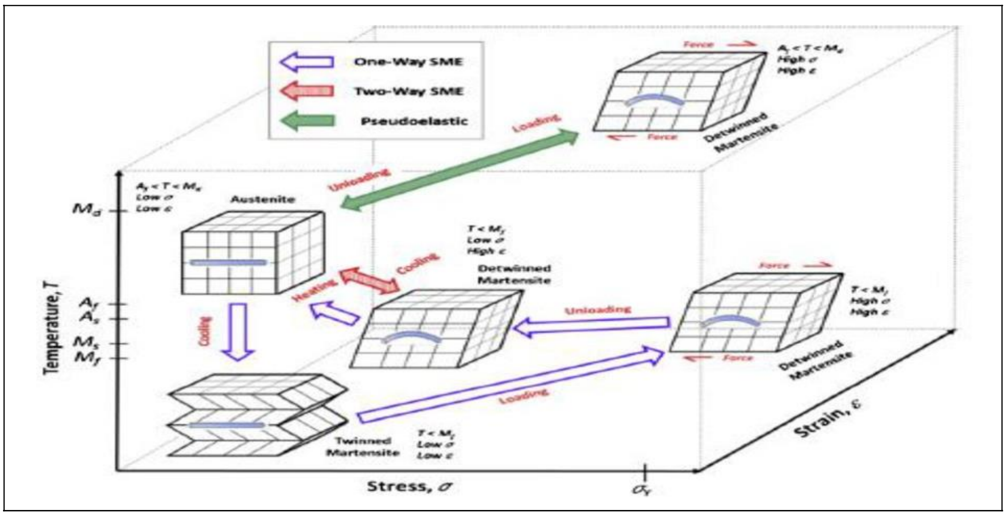

Figure 3 SMA different phase changes and the crystal structure.

Temperature. Evolution in such materials is widely referred to as shape memory transformation in phase schemes. The driving force behind this transition is the difference in Gibbs free energy for the altered phases and can be induced by stress or temperature. The SMAs exist with different structures of crystals and six transformations in two different phases in the two distinct phases with six different transformations and three structures of crystals, as shown in Figure 1. The three separate crystal forms are martensite twined, martensite detwined, and austenite **[7]**. The shape change effect and pseudo elasticity are characterized into three categories, that is, Pseudo elasticity or Super elasticity, one-way shape memory effect (OWSME), and two-way shape memory effect (TWSME). Three main classes of SMA system are; Nickel-Titanium-based (Ni-Ti) SMAs, Copper-based (Cu) SMAs, and Iron-based (Fe) SMAs. Nickel-titanium (Ni-Ti) alloys have initiated the applicability of alloys that exhibit shape retention effects for saleable & industrial purposes. NiTi SMA has high ductility, great corrosion resistance, excellent fatigue, and strain-controlling in diverse environments including fluids.[42] the other explores NiTi variants are Ni-Ti-Cu, Ni-Ti-Nb, Ni-Ti-Fe, Ni-Ti-Co, Ni-Fe-Ga, and Ni-Ti-Pd. Copper-based SMAs are considered as the economical alloys rather than NiTi SMAs because they are easy to manufacture using orthodox powder metallurgy and liquid metallurgy routes **[8]** Alloys based on Cu have extensive transforming temperature range, low hysteresis; Great super elastic effect, and high damping coefficient. All these anticipated properties have expanded Cu's potential to shape memory applications. Cu–Zn & Cu–Al are the main Cu-based alloys, with a third alloy element which has been often added to alter the temperature or microstructure of the transformation. The third SMAs projecting group is Iron-based SMAs subsequently the Ni-Ti, and Copper-based

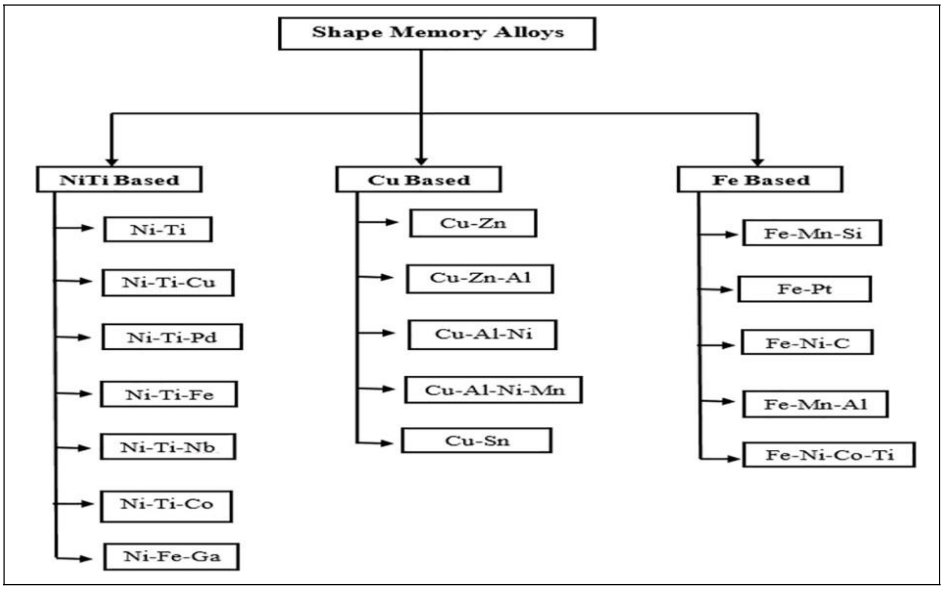

Figure 3. Broad classification of SMAs **[9]**.

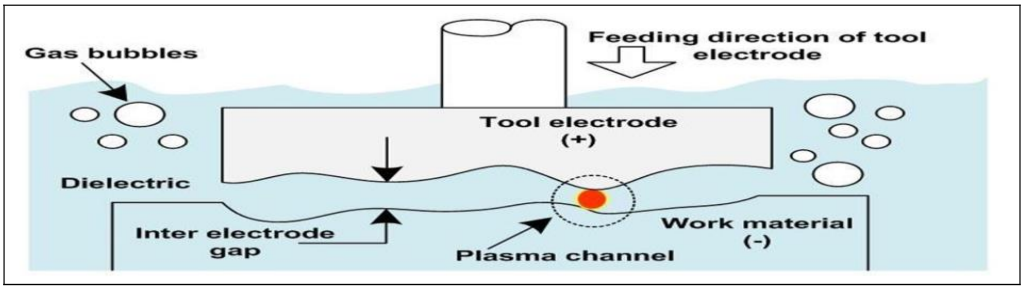

Figure 4. Basic working mechanism of EDM process.

SMAs. Detailed Classification of SMAs is depicting in Figure 2. This SMA class over the NiTi alloy system was economically viable due to its relatively low alloy component & easy manufacturing. Iron-based SMAs are also known as shape memory steel (SMS) and consist of various alloys; that is Fe–Mn–Si, Fe–Pt, Fe–Pd, Fe–Ni–C, Fe–Mn–Al, and Fe–Ni–Co–Ti. For an eco nomically viable process, SMS production rates must be as high as carbon steel (Table 1) **[10]**.

3. Electrical discharge machining and its allied processes

EDM is a thermo-erosive type of process in which spatially and temporally controlled separated pulsed discharges are utilized to machine electrically conductive materials regardless of their mechanical, chemical, and thermo-physical properties. The EDM process was invented in the 1940s. EDM exists as one of the modern machining operations productively used for machining tough to cut materials. This machining method has been utilized in modern industrial sectors for the promotion of machining material with great accuracy, cut complex shapes with optimal surface parameters. One of EDM's major advantages is that there has been no direct interaction amid the tool (electrode) & work material during the machining progression, this further leads to material free from residual stresses after the machining process. EDM is a production process using electric discharge (sparks) to obtain the desired shape. Furthermore, known as; die-sinking, machining method using spark, tool erosion machine **[11]**.

3.1 Working principle of EDM

The overall concept of the EDM process is the use of thermos-electric energy to erode the material from a piece of work with the assistance of periodic electric sparks between the work piece and the uncontested electrode. The work piece and the tool are submerged in a dielectric fluid, as explicated in Figure 3. The common types of liquid dielectrics used in the EDM are kerosene, de-ionized water, EDM oil, etc. In some other cases, dielectrics based on gaseous also used in the EDM process **[12]**.

The work piece is made as anode and tool as a cathode. If the gap voltage is adequately high, then in the form of spark it discharges through the gap. The spark formation results in the formation of electrons and positive ions which results in the formation of a conductive channel. There is a collision between the electrons and ions ensuing in the creation of the plasma channel. Due to the creation of a channel of plasma, a very large thermal energy generated which results in very high temperature. Due to such high-temperature formation in the machining zone, removal of material takes because of instant melting and vaporization of the material. During the machining process, the flushing of dielectric fluid carries away the unwanted debris, residue material, and restores the sparking condition. EDM input and response parameters The different performance parameters guide the electrical discharge process and these are known as peak current, voltage, pulse-off time, discharge gap, pulse-on time, work piece rotation, dielectric fluid flushing, pulse waveform, etc. Spark voltage (V) is the mean voltage while performing machining in the interface amid the work piece and the electrode. Spark gap size regulation and overcut are directly affected by the discharge voltage. The power expended during the discharge process is known as the peak current. The parameters which are directly prejudiced by the peak current are machining accuracy, rate of material removal, and electrode wear **[13]**. The duration of discharge time is known as pulse-on-time. MRR is directly influenced by Ton, which upsurges with larger Ton.50 When there is no discharge applied during the machining process, then that particular time period is known as pulse off time (T_{off}). During the no discharge period, unwanted debris is flushed away with the dielectric from the machining area. The positive or negative charge of the electrodes in the machining process is known as Polarity. The work piece has different polarity as compared to the tool electrode. The tool and work piece interface space is identified as the discharge gap (G).

Table 1. Various characteristics of different SMAs.

Sr. No.	Process characteristics	Fe-based	Cu-based	NiTi
1	SME	Low[45]	Low[46]	High[38]
2	Workability	Good[47]	Low[43]	Moderate[41]
3	Fabrication	Moderate[44]	Good[46]	Low[39]
4	Maximum recoverable strain	Less than 6%[25]	5–6%[26]	8–9%[38]
5	Cost	Low[45]	Low[43]	High[23]

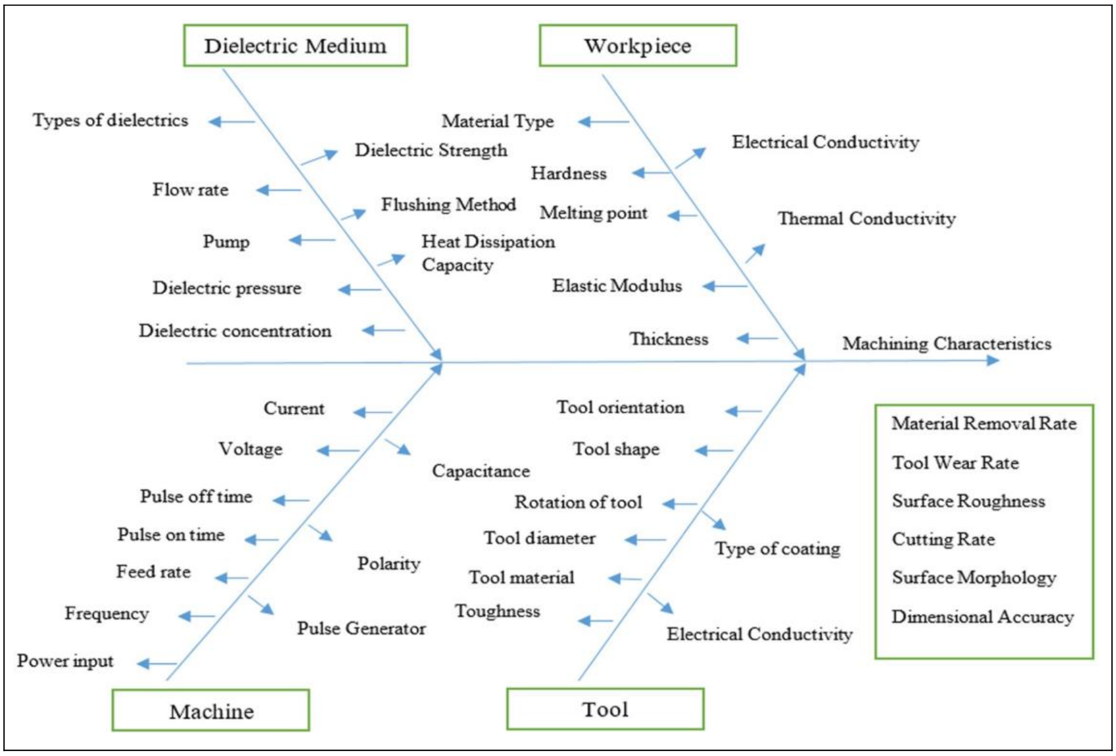

Figure 4. Fishbone representation of various process and machining characteristics in EDM operations.

Lies usually between 0.01 and 0.1 mm. The important non-electrical parameter in EDM is Flushing. It is defined as the flow rate of dielectric onto the machining area in the machining of the product in EDM. Flushing helps to keep the machining area clean with the removal of debris and control of temperature at the machining zone with the proper flow rate of dielectric fluid.

The overall process performance in EDM is measured by the various response parameters. These process characteristics can be articulated as; material removal rate (MRR), surface quality, electrode wear rate (EWR), dimensional deviation, overcut length, surface profile, etc. MRR is known as the amount of removed material from the work piece in a unit time. The main goal of the industries is to increase the MRR by controlling the other parameters. Different techniques and methods are followed for obtaining the optimum response measures. Electrode wear rate (EWR) is defined same as the MRR but in this case, the tool is there instead of the work piece, it is known as the amount of removed material from the tool during the process of machining in a unit time. Figure 4 is exploring various parameters that influence the EDM process. Surface quality is an imperative response factor which governs the surface characterization of the work piece. It includes a heat-affected zone, surface roughness, micro crack density, crack cavity, etc. Based upon the various investigations carried out in the domain of EDM process, this machining method has been studied broadly by attempting into its numerous variants namely; Die-sinking EDM, dry EDM, micro-EDM, wire-EDM, and PM-EDM.

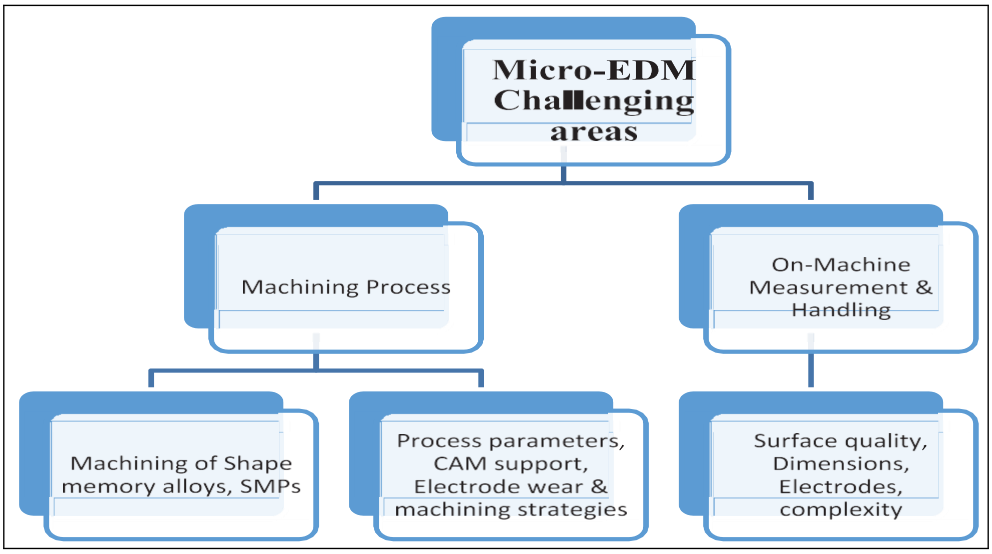

Figure 5. Micro-EDM challenging areas.

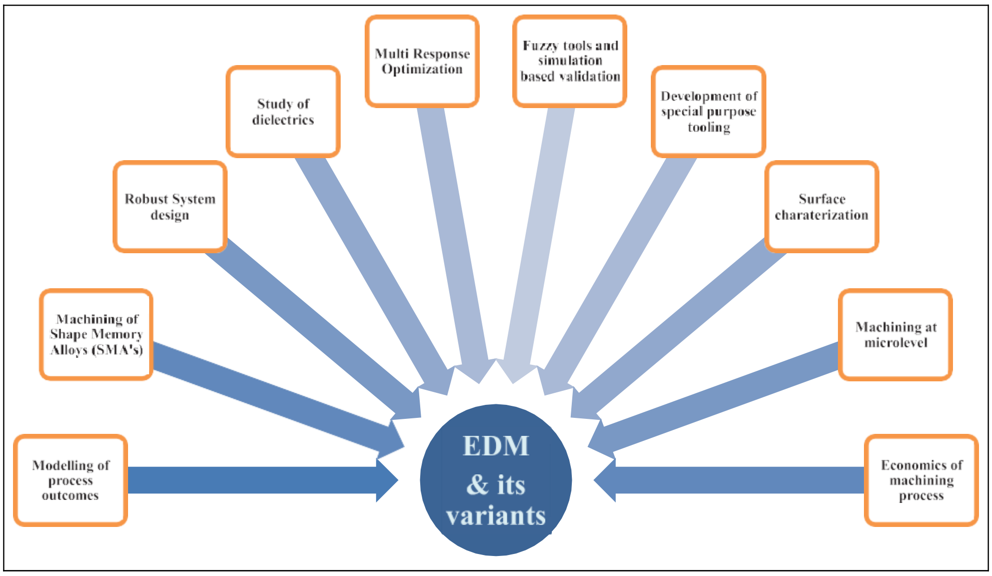

Figure 6. Some other research issues need to be taken care in prospect of work piece, process responses & environment based in EDM & its variant processes.

Conclusion

Micro Electric discharge machining is a thermal-based contemporary processing method which has been widely employed to effectively process the vast range of technically-advanced engineering materials. It has also been used competently to commercially process a broad variety of advanced materials including SMAs. This work targets the working tenet of EDM, material removal mechanism involved, and study of different experimental and modeling techniques, its application, and influence of various process factors on the umpteen process characteristics. The gaps revealed from the previous investigations and opportunities for future attempts in EDM of SMAs have also been deliberated. The following conclusions are drawn as:

- EDM offers better concert in terms of rate of material amputation (MRR), rate of tool wear (TWR), surface roughness (SR), and healthier surface characterization as compared to the conventional machining methods.
- Miniature holes and complex geometries are important machining characteristics of EDM whereas, with the help of conventional machining processes, the complex geometries and intricate shapes cannot be possible due to direct tool interaction with the work piece which further leads to tool failure and causes into more loss of power.

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