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Multi-objective optimization of micro-electrical discharge machining of nickel-titanium-based shape memory alloy using MOGA-II

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ABSTRACT

Shape memory alloys (SMAs) have received significant attention especially in biomedical and aerospace industries owing to their unique properties. However, they are difficult-to-machine materials. Electrical discharge machining (EDM) can be used to machine difficult to cut materials with good accuracy. However, several challenges and issues related with the process at micro-level continue to exist. One of the aforementioned issues is that the micro-EDM (μEDM) process is extremely slow when compared to other non-conventional processes, such as laser machining, although it offers several other benefits. The study considers the analysis and optimization of μEDM by using a multi-objective genetic algorithm (MOGA-II). Drilling of micro-holes is performed by using a tabletop electrical discharge machine. Nickel-Titanium (Ni-Ti) based SMA (a difficult to cut advance material) is used as a specimen. The objective involves determining optimal machining parameters to obtain better material removal rate with good surface finish. The results of the study indicate that MOGA-II is an efficient tool to optimize input parameters. Optimum results are obtained with tungsten electrode at low to moderate capacitance values and low discharge voltage. Conversely, brass electrode yields high MRR at the expense of tool wear and micro-holes quality.

1. Introduction

Various difficult-to-machine materials are available in the market owing to advancements in the field of material science and engineering. Non-conventional processes, such as electrical discharge machining (EDM), laser machining, and ultrasonic vibrations, are widely used to process these materials [1–3]. Specifically, EDM is widely used because it provides good surface finish and accuracy without undesirable results such as a heat affected zone [4,5]. Furthermore, there is a significant demand for miniaturization given developments in the field of automotive, aerospace, and biomedical industries. Therefore, a precise and accurate machining process is required to fulfill the industrial demand. Micro-EDM (μEDM) offers a solution by providing an accurate process to machine difficult to cut materials even at the micro-level [6,7].

The conventional machining processes are incompetent in terms of machining advanced materials within an acceptable tolerance limit [8]. Especially, in the case of micro-holes drilling, the drill bits are easily broken when the conventional drills are used, and chip evacuation is also an issue [9]. The μEDM process results in no mechanical stresses and machining vibrations because there is no direct contact between the tool and the workpiece [10]. A further advantage of the process is that it can machine materials irrespective of their hardness. However, the workpiece material should be electrically conductive. Workpiece hardness plays a significant role in the case of conventional machining processes. In the EDM process, there is no direct contact between tool and workpiece, and electrical sparks are used for material removal, and thus, the hardness of workpiece does not come into effect.

Murali and Yeo explained EDM as a process in which a cathode and an anode (two electrodes (i.e., workpiece and tool) that are separated by a dielectric medium come close to each other and make the dielectric conductive by breaking it down [11]. Hence, a spark is generated between cathode and anode, and thermal energy released by the phenomenon is used for material removal by melting and vaporization. If the amount of energy released is reduced to a lower value, then micromachining is possible [11]. Furthermore, EDM is also known as spark machining and removes material without any physical contact between the workpiece and tool electrode. It removes material by using repetitive pulse discharges obtained from an electric pulse generator with dielectric fluid flowing in between the workpiece and tool electrode. Each generated spark melts and vaporizes material from both the

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workpiece and tool electrode, and this leads to material removal. The discharge current causes the heating of the dielectric, workpiece, and tool electrode. The dielectric forms a plasma channel of partially ionized gas. The channel provides a heat source and heats up the workpiece beyond its melting temperature, and the material is removed and solidified with the dielectric cooling effect. The μEDM method is a subset of EDM that operates at the miniature level [12].

The characteristic that differentiates μEDM from macro-EDM is the size of tool electrode and discharge energy. The plasma size exceeds in the macro-EDM and axes movement resolutions by several orders of magnitude, which are at micron levels in case of μEDM [13]. μEDM can be used to machine almost burr free micro-holes ranging from a few hundred microns to 5 μm, and complex 3D cavities [14]. The μEDM method is mainly selected owing to its high efficiency and accuracy for the micro-machining of difficult-to-machine material irrespective of their hardness, such as metals, metallic alloys, graphite, and a few selected ceramics [15]. Hence, μEDM is considered as an efficacious process to drill any types of holes including blind, small, or deep holes. Extant studies successfully drilled holes ranging from a diameter of 5 μm to few hundred μm by using the process [6,9].

Shape Memory Alloys (SMAs) are special type of advanced engineering materials that exhibit the ability to remember their shape or the pseudo-plasticity. Shape memory phenomenon was observed in Ni-Ti alloys in 1963 [16]. Specifically, SMAs exhibit several exceptional properties including high mechanical strength, wear resistance, hardness, high efficiency in converting thermal into mechanical energy, and excellent biocompatibility [17,18]. Otsuka and Kakeshita indicated that Ni-Ti-based SMA is widely used in industrial applications (such as in the aerospace industry), in MEMS, and as sensors, actuators, and couplings [19,20]. Additionally, SMAs are used in a broad range of applications in various fields including dentistry [21]; thin film coatings [22]; advanced actuators [23]; safety of civil structures [24]; bone tissue engineering [25]; and biomedical engineering [26]. Hsieh et al. examined the machining characteristics of TiNiX SMA by using wire electro-discharge machining (WEDM). They examined the thickness of the recast layer that is an issue in the EDM process and concluded that the thickness of the recast layer varies with the pulse duration[27].

Several studies are underway to increase the efficiency of the process. Specifically, μEDM is the key process for drilling micro-holes (with diameters less than 200 μm) in diesel and gasoline injection nozzles and in turbine blades for cooling effect [28]. The μEDM method is a competent technique to create simple and complex shapes, cavities, and 3D micro-contours. Furthermore, μEDM is used to produce inkjet nozzles [29]. Sato et al. used the μEDM process to drill holes on inkjet nozzles for the first time [30]. Jeong et al. proposed an algorithm to predict the shape of tool and holes drilled by μEDM [31]. Yeo et al. investigated the μEDM input parameters (discharge energy and electrode material) to machine zirconium-based bulk metallic glass. The output parameters that were considered included surface roughness, tool wear, and burr width. It was reported that the lower discharge energy mitigates the surface roughness and tool wear. Additionally, it was concluded that tube electrodes performed better than rod electrodes in terms of tool wear [32]. The effect of the process parameters of μEDM on plastic and mold steel workpiece was investigated in an extant study [33]. The blind micro-holes were analyzed for their shape and dimensional accuracy. The μEDM of titanium alloy Ti–6Al–4V was modeled by using response surface methodology and an artificial neural network (ANN). Process parameters that were considered included peak current, pulse on time, and dielectric flushing pressure. The output responses were material removal rate (MRR), tool wear rate (TWR), and overcut. The set of optimal process parameters obtained were the pulse-on-time of 14.2093 ms, peak current of 0.8363 A, and flushing pressure of 0.10 kg/cm^2. The obtained values were successfully validated by experiments [34]. Prihandana et al. suggested a novel method of vibrating the dielectric and the mix MoS_2 powder in it to increase the MRR and obtained an improved surface finish in the μEDM process [35]. Somashekhar et al., optimized the gap voltage, capacitance, federate, and speed in μEDM process for drilling holes in a 1-mm thick aluminium plate. The tool material corresponded to tungsten carbide with a diameter of 500 μm. Moreover, ANN and genetic algorithm (GA) was used to model and optimize the process. The results revealed that a combination of ANN and GA was effective in modeling and optimizing the μEDM process [36].

Multi-objective optimization of μEDM process using GA was performed. Responses that were considered included TWR and overcut. Pulse-on time, peak current, and flushing pressure were the input variables. A set of Pareto optimal non dominated points were presented [37]. Output responses of micro electrical discharge milling were optimized by using GA. Responses that were considered included MRR and TWR. Input parameters were voltage, capacitance, electrode rotation speed, and feedrate. In an extant study, multi-objective optimization was performed while machining Ti-6Al-4V specimen. Optimized values of MRR, and TWR were obtained at a parameter setting of 150 V, 0.01 μF, 734.24 rpm, and 18 mm/min [38]. A study was conducted to drill accurate micro-holes with least electrode depletion by using μEDM. The Grey based Taguchi approach was applied to optimize the input parameters (gap voltage, capacitance, pulse-on-time, aspect ratio, and electrode rotation) for output responses (overcut at the top and bottom and taper angle). Aluminum sheets were used as the workpiece material, and a tungsten rod was used as an electrode. Validating tests performed at optimal machining parameters to yield good results [39]. Grey relational analysis technique was implemented to optimize the μEDM drilling process of Inconel 718 nickel-based super alloy. Experiments were performed by using full factorial design. Pulse duration and discharge current were input variables that were considered, and taper ratio and hole dilation were measured as the output response. The findings indicated that the discharge current affects the outputs more than the pulse duration [6].

Manjaiah et al. examined the WEDM of SMA by using the Taguchi orthogonal array. The results revealed that pulse duration affects the MRR and surface roughness substantially [40]. The μWEDM process of titanium alloy (Ti-6Al-4V) was examined by using the response surface methodology (RSM). The input variables included voltage, capacitance, and feed rate. The examined responses included MRR, kerf width, and surface roughness. Additionally, GA was used to implement multi-objective optimization [41]. The μWEDM process was modeled, and multi-objective optimization was conducted for the micro-machining of Inconel-718. An L18 mixed orthogonal array design was used in the experiments. Grey relational analysis was implemented for multi-objective optimization. The examined process parameters included voltage, capacitance, feed rate, wire tension and wire feed velocity. The output responses included MRR and surface roughness [42]. Furthermore, RSM and GA were used to optimize the input parameters (discharge current, pulse-on time and pulse-off time) while investigating their effect on output responses (MRR and TWR) during the μEDM of SS 316L by using a brass electrode. The results indicated that the resulting optimal input parameters improved the selected objectives substantially [43].

The μEDM input parameters (discharge current, pulse duration, pulse off, and jump distance) were optimized by using grey relational analysis for machining high-speed steel alloy (SKH59) using a tungsten-carbide (WC) electrode. Furthermore, a comparative study was performed between coated electrodes to achieve better MRR, surface finish, and lower TWR. The results indicated that WC-coated Cu electrodes achieved highest MRR, WC-coated Ag produced a better surface finish while the WC electrodes exhibited the least wear rate [44]. The μED milling was investigated to optimize its parameters (voltage, capacitance, electrode rotational speed, and feed rate) while machining Ti-6Al-4V. The responses under study were MRR and TWR. Box-Behnken design of RSM was used to conduct the experiments. It was revealed that capacitance and feed rate were the most significant parameters that were affect the responses [45]. Jahan et al. investigated the effect of different functional parameters on the μEDM behavior of