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Modeling and multi-objective optimization of powder mixed electric discharge machining process of aluminum/alumina metal matrix composite

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ABSTRACT

Low material removal rate (MRR) and high surface roughness values hinder large-scale application of electro discharge machining (EDM) in the fields like automobile, aerospace and medical industry. In recent years, however, EDM has gained more significance in these industries as the usage of difficult-to-machine materials including metal matrix composites (MMCs) increased. In the present work, an attempt has been made to fabricate and machine aluminum/alumina MMC using EDM by adding aluminum powder in kerosene dielectric. Results showed an increase in MRR and decrease in surface roughness (R_a) compared to those for conventional EDM. Semi empirical models for MRR and R_a based on machining parameters and important thermo physical properties were established using a hybrid approach of dimensional and regression analysis. A multi response optimization was also performed using principal component analysis-based grey technique (Grey-PCA) to determine optimum settings of process parameters for maximum MRR and minimum R_a within the experimental range. The recommended setting of process parameters for the proposed process has been found to be powder concentration (C_p) = 4 g/l, peak current (I_p) = 3 A, pulse on time (T_{on}) = 150 μs and duty cycle (T_{au}) = 85%.

1. Introduction

Electro discharge machining (EDM), one of the most popular non-conventional machining processes, is an electro-thermal process in which work piece is usually submerged in a liquid dielectric medium and shaped through the action of a succession of high frequency discrete electrical discharges (sparks) produced by a DC pulse generator. Every spark locally erodes (melts and vaporizes) tiny amount of the material surface, the overall effect being a cavity as the complementary shape of tool electrode geometry over the work surface. Besides tool and die making, in the recent years, EDM has found many applications in the fields of automobile, aerospace, surgical instruments making and military industry. The major problem to use EDM for large scale production is its low machining rate and poor surface finish. Many advances have come in the field of EDM to overcome these difficulties. One of those advancements is powder mixed EDM (PMEDM). Even though, the principle of PMEDM is not completely understood, the results of the experiments done by many researchers have shown significant improvement in material removal rate (MRR) and surface quality. Among the powder materials, aluminum produced better MRR and good surface finish compared to other materials like Cr, Cu and SiC [1,2]. This was attributed to the increased spark gap due to aluminum's high electrical conductivity and low density. Kerosene or some commercial EDM oil was widely used as the dielectric medium in PMEDM [1,2,4–16]. However, Yan et al. [3] established the feasibility of urea suspended water as a dielectric medium by achieving a smooth machined surface. MRR and surface quality can be further enhanced by providing ultrasonic vibration to the tool [4–6]. Apart from expelling the debris from the machine zone, the vibration provides the abrasive action on work-piece surface. Tzeng and Lee [2] investigated the effect of thermo-physical properties of work-piece material and various additives (Al, Cu, Cr, SiC) on the efficiency of EDM. Multi-objective optimization of PMEDM process was performed by Kansal et al. [7] used Taguchi technique to optimize

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the process parameters during machining of AISI D2 die steel using silicon suspended dielectric. Singh and Yeh [8] employed grey relational analysis (GRA) for the multi-objective optimization of high MRR and low R_a, for PMEDM of 6061 Al/Al_2O_3 aluminum matrix composite (MMC) using SiC particles suspended dielectric. Kumar and Davim [9] studied the role of silicon powder suspended dielectric on the material removal mechanism during PMEDM of Al10%SiC_P MMC. Garg et al. [10], in their review on the EDM of MMCs, discussed the effectiveness of PMEDM for the machining of MMCs. Tsai and Wang [11] developed a semi empirical model for the surface finish for the conventional EDM process with the help of non-linear optimization technique. Patil and Brahmankar [12] developed a semi-empirical model for MRR using the thermo-physical properties of the MMC and compared it with the model generated using response surface methodology (RSM).

Very little research work has been found in the area of PMEDM of MMCs fabricated using stir casting method [8,9]. Owing to more homogeneous distribution of reinforcement in the matrix material along with minimum possibility of oxidation of MMCs, the current research work attempted to fabricate aluminum/alumina MMC using powder metallurgy technique. The machining characteristics of the fabricated MMCs were further investigated during PMEDM process. Models for MRR and R_a were developed using dimensional analysis in which thermo-physical properties of work-piece material were considered along with machining parameters. Furthermore, determination of optimal combination of process parameters was achieved through multi-objective optimization using PCA based grey relational analysis.

2. Experimental details

2.1. Fabrication of MMC

Powders of aluminum and alumina of sizes about 15 μm and 90 μm were taken in the weight ratio of 80:20 and were thoroughly milled in a high energy ball mill for 2 h at 300 rpm. Images of different powder particles captured using scanning electron microscopy (SEM) before and after ball milling operation are shown in Fig. 1. Liquid toluene was used as process control agent. Ball to powder ratio was kept to 10:1. MMC samples were fabricated using conventional compaction and sintering technique. Compaction was performed at pressure of 250 MPa. Acetone was used as the lubricant to prevent the agglomeration of the particles. The green compacted specimens were sintered in argon atmosphere at a temperature of 500 °C and allowed to cool to room temperature for 24 h. The sintered specimens were heated to 400 °C and quenched in iced water. They were further heated to 200 °C and allowed to cool in the muffle furnace for 8 h to avoid natural aging.

2.2. Machining of MMC

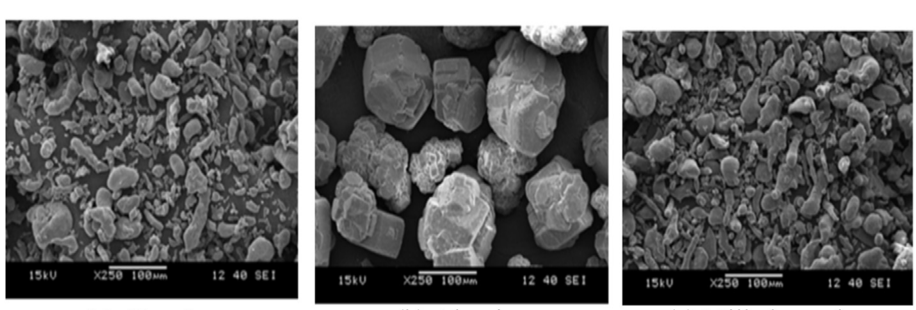
All experiments were performed using a die sinking EDM set up (Model: LEADER-1ZNC, ELECTRONICA). A special arrangement has been made to the EDM set up for proper circulation and mixing of additive particles in the dielectric. Aluminum powder particles (with an average size of 15 μm) were suspended in kerosene which was used as dielectric. Experiments were performed using Taguchi L18 orthogonal array. Copper electrode of diameter 12 mm was used to machine the Al/Al_2O_3 MMC to a depth of 2 mm. The effect of powder concentration (C_p), peak current (I_p), pulse on time (T_{on}) and duty cycle (T_{au}) on responses MRR and R_a was studied. Fig. 2 shows photographic view of the MMC specimens fabricated using the powders shown in Fig. 1, along with shallow blind holes made using powder-mixed EDM process.

2.3. Measurement of responses

Density of the MMC specimens was found to be 2.5 g/cc. Weight of each specimen before and after machining was measured using a high precision balance (Model: VIBRA, SANSUI Electronics). Machining time was recorded using a stop watch. Surface roughness in the form of R_a (center line average) was measured at three randomly chosen locations on each machined surface using a portable stylus type profilometer (Model: Talysurf, Surtronic 3+, Taylor Hobson) and the mean value was calculated.

3. Modeling using dimensional analysis

Dimensional analysis is a method of dimensions and a mathematical technique which deals with the physical quantities involved in the experiments to formulate a model for the response in terms of control parameters as well as some physical properties of the materials. This is based on the hypothesis that the solution of the problem is expressible by means of a dimensionally homogeneous equation. By using the hybrid approach of regression and dimensional analysis, authors tried to incorporate the material properties into the model equations which may not be possible using evolutionary optimization techniques. Buckingham π theorem states that it is possible to assemble all variables appearing in a problem into a number of dimensionless π terms [17,18]. The thermal properties, physical properties along with machining parameters might determine the performance of PMEDM process of MMCs. In the present model, the thermo-physical properties like thermal conductivity, density and coefficient of thermal expansion were considered along with the machining parameters such as peak current, pulse on time, powder concentration, duty cycle and average gap voltage. The dimensions of these variables as well as their values are mentioned in Table 1.



(a) Aluminum (b) Alumina (c) Milled powder

Fig. 1. SEM images of powder particles.