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Examination of accuracy aspect in machining of $ZrSiO_{4p}$/6063 aluminium MMC using CNC Wire Electrical Discharge Machining

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A R T I C L E I N F O

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A B S T R A C T

Wire Electrical Discharge Machining (WEDM) is a deep-rooted non-contact modern machining technique used to manufacture geometrically intricate shapes in hard materials which are difficult to machine using conventional methods. To achieve close dimensional accuracy in WEDM, the output parameter dimensional deviation is an essential response to be controlled during machining. Determination of dimensional deviation for a particular process parameter combination assists the manufacturing planners in setting a wire offset so that the actual (cut) work piece dimensions match the part geometry.This study investigates the dimensional deviation induced by WEDM of $ZrSiO_{4p}$/6063 Aluminium metal matrix composite (MMC) by using response surface methodology (RSM). The key WEDM input process parameters namely, pulse-on time, pulse-off time, servo voltage and peak current were varied in order to examine their influence on dimensional deviation. Significant process parameters affecting the process are identified by carrying out analysis of variance (ANOVA) technique. To aid in selecting the best combination of input parameters during WEDM of $ZrSiO_{4p}$/6063 Aluminium MMC the concept of desirability is utilized. Confirmation experiments have been conducted to verify the optimal parameter combinations.

1. Introduction

There is a great need for materials with special properties with emergence of new stringent requirements posed by manufacturing industries. Traditional engineering materials are unable to meet these requirements of special properties like high strength, low weight, hot hardness, temperature resistance for various industries like aerospace, automotive etc. Composite materials emerged as a new class of engineering materials to cater the needs of these aforesaid industries. Composites are a unique class of materials formed by combining two or more distinct materials to form stronger, tougher and more durable material than each would have been separately. The extreme environment in space a typical spacecraft encounter with high temperature while entering the earth's atmosphere, naturally occurring phenomena such as vacuum, thermal and ionizing radiation, along with factors such as micro or macro meteoroids and debris therefore, demand lightweight space structures with high strength and dimensional accuracy. Nevertheless, such materials are difficult to be machined by traditional machining methods. The presence of high strength reinforcements in the MMC leads to the rapid wear and tear of cutting tools during machining by conventional or traditional methods [1]. This leads to low cutting rate and subsequent increase in production cost. Therefore, there is a need to enhance the machining performance for these materials. Hence, non-traditional machining methods including abrasive jet machining (AJM), laser beam machining (LBM), water jet machining (WJM), electrical discharging machine (EDM) etc. are applied to machine such difficult-to-cut materials. Techniques like EDM and WEDM are quite successful for machining of high strength MMC's. EDM can be used only for drilling purpose, while WEDM conforms to easy control and can machine intricate and complex shapes as a result of which WEDM technique is highly recommended for machining of MMC's [2]. WEDM is a specialized machining technique which uses electro-thermal mechanism to produce complicated cut-outs through electrically conductive and difficult-to-machine materials. Generally, WEDM is perceived to be an accurate non-traditional process.

Aluminium based MMC's also known as aluminium matrix composites (AMC's) have demonstrated improved mechanical properties compared to properties of pure or non-reinforced Al alloys. Because of their attractive properties, relative ease in fabrication technology and their potential to be available at low cost, Aluminium-matrix composites (AMCs) are being widely used by various industries [3]. AMCs reinforced with hard ceramic particles have emerged as a potential

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material especially for wear-resistant and weight critical applications such as brake drums, cylinder liners, pistons, cylinder blocks, connecting rods, and so on [13]. Past studies have indicated that efficient and economical WEDM processing of these materials has opened new areas of applications for MMC's, but there is a lack of efforts made to investigate machining of MMC's through WEDM process and particularly of Al-based MMC's. Literature surveys indicate that most of the reported research is concentrated on machining of conventional materials like steel, brass, titanium etc. than on aluminium based materials [4–11].

1.1. Fabrication of $ZrSiO_{4p}$/6063 al metal matrix composite

The fabrication methodology of a MMC can be clustered under solid state, liquid state and powder metallurgy, based on the physical state of the matrix i.e., solid phase and liquid phase.

$ZrSiO_{4p}$/6063 Al MMC's can be widely used materials in many engineering applications due to their improved properties but none of the research effort is made to investigate the potential of WEDM in machining of $ZrSiO_{4p}$/6063 Al MMC. $ZrSiO_{4p}$/6063 Al MMC offers a wide variety of applications including wear-resistant components, punches, engine parts, high temperature applications, medical and biomedical purposes etc. Zirconium silicate or zircon ($ZrSiO_4$) reinforced particles of average particle size 5μm, is used for casting of Al 6063 MMC by stir-casting technique. Table 1 represents the chemical composition of Al 6063 alloy used as a base metal for fabrication of MMC. In this study, commercially available Al 6063 in the form of cylindrical rods is used as matrix reinforced with $ZrSiO_4$ particles. The melting of measured quantity of (3 kg) pickled Al 6063 is carried out in a clay-graphite crucible (Fig. 1a) placed inside the muffle furnace. Fig. 1b shows the muffle furnace and the developed stirring setup for melting and mixing of Al 6063 and $ZrSiO_4$ particles. Prior heating of required quantity of zirconium silicate ($ZrSiO_{4p}$) particulates 150gm (5 wt %) to around 500 °C for 1 hour was carried out in a separate furnace. Preheating of $ZrSiO_4$ particles before mixing it with molten metal was purposely done to eliminate the water vapours present within the particles and also to improve the wettability by removing the absorbed hydroxide and other gases. The furnace temperature is first raised above 1000 °C (50° above the melting point of Al 6063) for proper liquidification of Al 6063. At this stage, the pre-heated $ZrSiO_4$ particles are added to the molten metal and mixed mechanically using stirrer. While adding the zircon particles to the molten aluminium alloy, to avoid atmospheric contamination nitrogen gas (Fig. 1c) is used as the shield of the mixer. The composite slurry is then reheated to a fully liquid state and mechanical mixing was carried out for 5 min at 100 rpm average stirring speed. Stirring is carried out to ensure even temperature distribution as well as particulate distribution. The mixer of reinforced particulate and the molten metal is then poured to a prepared sand mould. After pouring is over, the melt is allowed to cool and solidify in the mould under the shield of N_2. After solidification, the casting is taken from the mould and is cut to the required shape and size (110mm x 80mm x 11mm) for subsequent WEDM.

The improved properties of $ZrSiO_{4p}$/6063 Al MMC and the conventional properties of base metal Al 6063 are shown in Table 1. It reveals that the important mechanical properties are improved to a good extent by addition of 5% $ZrSiO_{4p}$ to base metal Al 6063 and it can effectively replace conventional Al 6063 material in automobile and aerospace applications owing to its improved properties.

Table 1
Mechanical properties of $ZrSiO_{4p}$/6063 Al MMC and base metal Al 6063.

Specimen	Tensile strength (KN/mm^2)	% elongation	Hardness
Aluminium 6063	0.117	14 to 19	68
$ZrSiO_{4(p)}$/6063 Al MMC	0.152	15	74.8

One of the main purposes of the present study is to investigate the effects of key input process parameters such as, pulse on time, pulse off time, servo voltage and peak current on the output response namely dimensional deviation (DD) and to obtain optimal parameter combinations using desirability approach. This study also aims to establish an empirical relationship between various input process parameters and output response using ANOVA for machining of MMC using Box Behnken Designs (BBD). BBD are one class of the experimental designs for response surface methodology. They are rotatable or nearly rotatable based on three-level incomplete factorial designs. Rotatable means that the model would possess a reasonably stable distribution of scaled prediction variance throughout the experimental design region. BBD allows calculations of the response function at intermediate levels and enables estimation of the system performance at any experimental point within the range studied through careful design and analysis of experiments [12]. For three factors BBD, its graphical representation can be seen as a cube that consists of the central point and the middle points of the edges as shown in Fig. 2 [13].

2. Design of experiments and experimentation

Various input process parameters viz. Pulse on time (T_{ON}), Pulse off time (T_{OFF}), Peak Current (IP) and Servo Voltage (SV) are varied to investigate their effects on DD during machining of $ZrSiO_{4p}$/6063 Al MMC. The ranges of input parameters were selected on the basis of literature survey, machining capability of the machine and pilot study conducted by using one variable at a time approach [14]. The range of selected process parameters for further analysis is presented in Table 2. Table 2 also lists the parameters and there levels which were kept fixed in the study.

The experiments were performed on a four axis Electronica Sprintcut 734 CNC Wire Cut Machine. Diffused brass wire of 0.25mm diameter was used as tool material and deionized water is used as dielectric. A plate of rectangular shape (110 mm × 80 mm × 11 mm) having 5% $ZrSiO_4$ particles (by weight) as reinforcement is fixed on the machine table. An 8 mm × 8 mm rectangular cut is taken on the work piece as shown in Fig. 3a. Fig. 3(b,c) represents the selected machine tool and the rectangular pieces cut from the plate respectively in each run. Experiments are performed according to the run order as shown in Table 3. The experimental results are collected for DD on 4-axis Sprintcut 734 CNC wire cut machine. Table 3 summarizes the data related to dimensional deviation obtained for 29 experiments by following the design plan of BBD.

The output response in the present study is DD in μm. 'Dimensional Deviation' is defined as the difference in the actual profile traced by the wire with the job profile required. DD of a square punch is equal to the half the width of cut. DD is measured using the digital micrometer, with a least count of 0.01mm. It is measured at two random places on sides AB, BC and CD and the average of these six values represents the dimensional deviation used in the present article. DD is calculated as [15]:

$$DD = 0.5 \times (W_d - W_a) \quad (1)$$

where

$(W_d$-$W_a)$ = width of the cut.
W_d = desired size of work piece = 8 mm.
W_a = actual size of workpiece obtained after machining.

3. Results and discussion

Quadratic model is recommended by design expert software (6.0.8) for dimensional deviation after performing three tests namely sum of square test, lack of fit test and model summary statics on the sets of observation data. ANOVA is applied to identify the significance of process parameters towards dimensional deviation.