Investigations into electrical discharge machining of fabricated AA 6061/10% Al_2O_3 aluminium-based metal matrix composite using OFAT approach

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Abstract: Electrical discharge machining (EDM) process is one of the most commonly used non-traditional machining processes for difficult to cut materials like composites and in die making industries. The work piece material was AA 6061/10% Al_2O_3-based metal matrix composite which was fabricated with newly developed stir casting setup. After fabrication scanning electron microscopy, mechanical testing was carried out to test properties of composite material. In EDM process, the selected EDM input parameters were pulsed current (I), pulse on time (T_{ON}). One parameter at a time was studied to observe the responses with the variation in the selected input parameters. The metal removal rate (MRR) and gap size were observed as output responses in this experimental work. Experimental investigations showed that for higher MRR, there was high pulse current, high pulse on time. Similar effects were also observed for the gap size.

Keywords: AA 6061/Al_2O_3; aluminium-based metal matrix composite; AMMC; discharge current; EDM; electrical discharge machining; gap size; metal removal rate; MRR; pulse on-time; scanning electron microscopy; SEM; stir casting.

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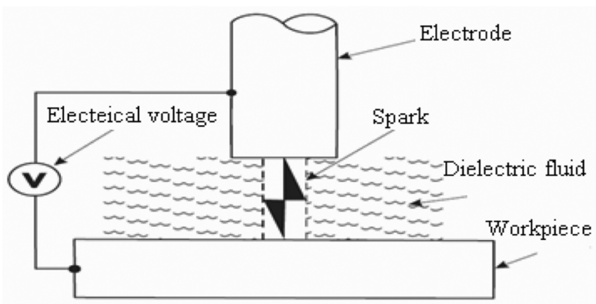
1 Introduction

Electrical discharge machining (EDM) process is a newly developed process for the materials that are difficult to cut. EDM provides an effective manufacturing technique that enables the production of parts made of special materials with complicated geometry which is difficult to produce by conventional machining processes. Controlling the process parameters to achieve the required dimensional accuracy and finishing placed this machining operation in a prominent position. For that reason, EDM has found broad applications in industry. The absorbing interest for electric discharge machines has resulted in great improvements in EDM technology. Nowadays, sophisticated electric discharge machines are available for most of the machine shop applications. The working principle of EDM process as shown in Figure 1 is based on the thermoelectric energy. This energy is created between a workpiece and an electrode submerged in a dielectric fluid with the passage of electric current. The workpiece and the electrode are separated by a specific small gap called spark gap. Pulsed arc discharges occur in this gap filled with an insulating medium, preferably a dielectric liquid like hydrocarbon oil or de-ionised water.

Figure 1 Schematic diagram of EDM process



Source: Jameson (2001)

2 Literature review

The existing manufacturing industries (Vishwakarma, Parashar and Khare, 2012) are fronting challenges from these advanced nascent materials viz., nanomaterial, ceramics, super alloys, and metal matrix composites (MMCs), which are hard and difficult to machine, requiring high accuracy, surface quality excellence which affects and increases machining cost. EDM, a unconventional process, has an extensive applications in automotive, defence, aerospace and micro-systems industries and plays an outstanding role in the development of least cost products with more consistent quality assurance. Die sinking EDM, wire electrical discharge machining (WEDM), dry EDM and rotary disk electrode EDM are some of the alternative methods of EDM. The results of EDM of aluminium matrix composites (Cichosz and Karolczak, 2008) with particular attention given to thickness of the defected layer after machining were discussed. Influence of various machining parameters on the behaviour of saffil fibres and matrix material in the affected zone was presented. Saffil fibres contain 95–97% alumina which is produced by a novel solution spinning process from the highest purity raw materials and an aqueous medium. These fibres have outstanding chemical stability and resistance to degradation in a variety of demanding conditions including reducing atmospheres, vacuum at high temperatures and metal oxide contaminated furnace atmospheres. Scanning micrographs and roughness measurements are used to analyse the surface finish following machining. The investigation showed that EDM process parameters affect the condition of surface layer in machined AMMC. Low current parameters resulted in a thin layer with a recast structure of increased hardness. Reinforcing fibres were generally left undamaged, and some of them are protruding from the surface. There is a need for working out optimised patterns of current density and frequency of sparks that would eliminate or reduce the extent of finishing operations necessary for removing the recast layer (RCL). The additive mixed electrical discharge machining (AEDM) is a novel innovation (Kumar et al., 2010) for enhancing the capabilities of EDM process in this direction. Despite the promising results, AEDM process is used in the industry at very slow pace. Fundamental issues of this new development, including machining mechanism, are still not well understood. These issues require further investigations before this process is well accepted by the industry. Mixing of additive powder in the dielectric medium of EDM plays a significant role in enhancing the process capabilities of EDM. Adding powder causes gap contamination. This gap contamination lowers dielectric strength and initiates the ignition process, which increases the gap distance and increases the stability of the process. Additive powder characteristics (type, shape, size, concentrations, number of particles and thermal properties) significantly affect the process efficiency and surface characteristics of machined surfaces. There is a need to independently study the effect of various powder characteristics with important input process parameter on the phenomenon of surface modification and process capabilities.

Aluminium based metal matrix composites (AMC) are hard (Dhar et al., 2007) to machine due to the presence of hard and brittle ceramic reinforcements. Additionally, researchers are turning to particulate-reinforced aluminium-metal matrix composites (AMCs) because of their relatively low cost and isotropic properties especially in those applications not requiring extreme loading or thermal conditions (e.g. automotive components). They evaluated the effect of current, pulse on-time and air gap voltage on metal removal rate (MRR), tool wear rate (TWR), radial over cut (ROC) on machining of AMMC with 20% SiC reinforcement. A quadratic mathematical model has also been developed for the same relating output and input quantities, respectively. The MRR is found to increase in an almost linear fashion with increase in current for constant gap voltage and pulse on-time. MRR is also found to increase slightly with increase in pulse duration clearly. And in agreement with the literature reported in TWR is also found to increase with increase in current as high current results in higher thermal loading on both electrodes (tool and workpiece) leading to higher amount of material being removed from either. It is found to first decrease and then increase with pulse duration. A similar trend is noticed with gap voltage. It is evident that an increase in current increases the over cut. An increase in pulse duration also increases the over cut due to the prolonged presence of sparks. An uncommon behaviour is observed in the case of voltage gap. The influence of the most relevant parameters of EDM over metal removal rate, electrode wear and machined surface quality (Iosub, Axinte and Negoescu, 2010) of a hybrid MMC material (Al/SiC) has been carried out. They found that the hybrid SiC/Al composite material which contains 7% SiC and 3.5% graphite can be machined by EDM and a good surface quality can be obtained by controlling the machining conditions. Regarding the MRR output parameter, the most influential factors were current intensity, followed by its quadratic effect and pulse off-time. The metal removal rate increases significantly when current intensity increases. The same tendency was observed when pulse off-time increases. They proposed an empirical model in order to optimise the processes. They found that in electrode wear parameter, the most influential factor is the current, followed by its quadratic effect and pulse on-time. For a low electrode wear, low values for intensity and for pulse on-time should be used. It was found (Singh et al., 2004) that the use of unconventional machining techniques in shaping aluminium metal matrix composites (AMMC) has generated considerable interest as the manufacturing of complicated die contours in these hard materials to a high degree of accuracy and surface finish is difficult. The objective of their work was to investigate the effect of current (*C*), pulse on-time (*P*) and flushing pressure (*F*) on metal removal rate (MRR), TWR, taper (*T*), ROC and surface roughness (SR) on machining as-cast AMMC with 10% SiC reinforcement. They found that MRR was found to be higher for larger current and pulse on-time settings at the expense of tapercity, ROC and surface finish. TWR was found to be higher, larger than MRR, for larger current settings but it affects the dimensional accuracy also. Flushing pressure of the dielectric has considerable effect on the MRR and TWR.

They investigated (Satishkumar et al., 2011) the effect of WEDM parameters such as pulse on-time (T_{ON}), pulse off-time (T_{OFF}), gap voltage (V) and wire feed (F) on metal removal rate (MRR) and SR (R_a) in MMCs consisting of aluminium alloy (Al6063) and silicon carbide particles (SiCp) where aluminium alloy Al6063 was reinforced with SiCp in the form of particles with 5, 10 and 15% volume fractions. The experiments were carried out as per design of experiments approach using L9 orthogonal array. The results were analysed using analysis of variance (ANOVA) and response graphs. The results are also compared with the results obtained for unreinforced Al6063. It was found that the increase in volume percentage of SiC resulted in decreased MRR and increased R_a. This may be due to the presence of harder SiCp in the MMCs. The SiCp will enhance the thermal characteristics of aluminium, with consequent reduction in MRR. But MRR is found to increase with increase in pulse on-time because of higher intensity of the spark in WEDM process. The results from this study will be useful for manufacturing engineers to select appropriate WEDM process parameters to machine MMCs of Al6063 reinforced with SiCp at various proportions. They used the EDM process (Hung, Yang and Leong,

1994) for machining of cast AMMC which were reinforced with SiCp. It was found that the SiCp shield and protect the aluminium matrix from being vaporised, thus reducing the metal removal rate. The un-melted SiCp drops out from the MMC together with surrounding molten aluminium droplets. Although some aluminium droplets are flushed away by the dielectric, others trap the loosened SiCp and then re-solidify onto the surface to form a RCL. No crack was found in the RCL and the softened heat-affected zone, which is below the RCL. The input power controls the metal removal rate and the RCL depth, but the current alone dominates the surface finish of surface in EDM process. The EDM has been proven (Patel, Pandey and Rao, 2009) as an alternate process for machining complex and intricate shapes from the conductive ceramic composites. The performance and reliability of EDM ceramic composite components are influenced by strength degradation due to EDM-induced damage. This paper presents a detailed investigation of machining characteristics, surface integrity and material removal mechanisms of advanced ceramic composite Al_2O_3-SiCw-TiC with EDM. The surface and subsurface damages have also been assessed and characterised using scanning electron microscopy (SEM). The results provide valuable insight into the dependence of damage and the mechanisms of material removal on EDM conditions. They fabricated (Talla et al., 2015) aluminium/alumina MMC and machined using EDM by adding aluminium powder in kerosene dielectric. They found that the there is an increase in MRR and decrease in SR (R_a) compared to those for conventional EDM. The principal component analysis based grey technique (Grey-PCA) was used for optimisation of process parameters for maximum MRR and minimum R_a within the experimental range. They fabricated (Singh, Kumar and Kumar, 2015) aluminium 6061 alloy reinforced with 10% SiCp (AA 6061/10% SiCp composite) and then investigated the TWR in powder-mixed electrical discharge machining (PMEDM). The characterisation was done using SEM and energy dispersive spectroscopy. They used the tungsten powder with concentration of 4 g/L that is mixed in the dielectric fluid. The comparison was done using experiments performed with basic EDM and PMEDM process. Experiments were designed as per central composite rotatable design using response surface methodology (RSM) approach. It was found that PMEDM approach provided 51.12% reduction in TWR for machining of AA 6061/10% SiCp composite.

Electric discharge drill machine (EDDM) is a spark erosion process (Khanna et al., 2015) to produce micro-holes in conductive materials. They used the brass rod 2 mm diameter as a tool electrode and used the Taguchi approach for better TWR in drilling of Al-7075. In experimental work, they used the L27 Taguchi design method and ANOVA analysis shows the percentage contribution of the control factor in the machining of Al-7075 in EDDM. It was found that the combination of maximum pulse on-time and minimum pulse off-time resulted in maximum MRR. They (Nataraj and Ramesh, 2016) used the Al-based MMC reinforced with 5% wt of Al_2O_3, 3% wt of SiC and 2% wt of E-glass short fibre as work material and the copper material as an electrode. The optimal conditions of input parameters were found using Box-Benhken design of experiments of RSM. A detailed review (Sidhu, Batish and Kumar, 2015) on EDM of MMCs was done in this paper. They found that processability of MMC depends upon the appropriately chosen elements, their properties, distributions and interface between them. It was found that the ductile property of matrix embedded with ceramics-reinforced particles reduced the coefficient of thermal expansion and increase strength and modulus. The cost of tool in traditional machining was very high which limited the application of these materials in advance technologies, so EDM was widely used in machining these materials to produce complex geometry shapes. The grey relational analysis was used (Kumar et al., 2014) for optimisation of parameters of the EDM parameters of aluminium alloy (Al 6351) matrix reinforced with 5 wt% SiC and 10 wt% boron carbide (B_4C) particles fabricated through the stir casting route. The objective was to minimise the machining characteristics, namely electrode wear ratio, SR and power consumption. The contributions of each machining parameter to the responses were calculated using ANOVA and found that the pulse current contributed more (83.94%) to affect the combined output responses.

They investigated (Radhika, Sudhamshu and Chandran, 2014) the influence of peak current, flushing pressure and pulse on-time on EDM of AlSi10Mg alloy reinforced with 3% graphite and 9% alumina hybrid MMCs. Taguchi's design of ANOVA and signal-to-noise ratio were used to determine the influence of input process parameters on the SR, metal removal rate and TWR. It was found that the peak current was the most influential parameter on SR followed by pulse on-time and flushing pressure. For metal removal rate, the major parameter was flushing pressure followed by peak current and pulse on-time. The most significant parameter of TWR was pulse on-time followed by peak current and flushing pressure. The properties of ceramic-reinforced aluminium matrix composites (Dipti Kanta et al., 2014) were discussed in this paper. The properties discussed include micro-structural, optical, physical and mechanical behaviour of ceramic-reinforced aluminium matrix composites and effects of reinforcement fraction, particle size, heat treatment and extrusion process on these properties. They found that the results obtained by many researchers indicated the uniform distribution of reinforced particles with localised agglomeration at some places, when the MMC was processed through stir casting method. They found that the properties such as density, hardness, compressive strength and toughness increased with increasing reinforcement fraction; however, these properties may reduce in the presence of porosity in the composite material. It was found that the tensile strength and flexural strength were observed to be increased up to a certain reinforcement fraction in the composites, beyond which these were reduced.

The experimental investigation (Milan Kumar et al., 2014) was done to optimise the machining parameters of WEDM for multiple performance characteristics on EN 31 tool steel using weighted principal component analysis. The experiments were conducted based on Taguchi's L27 orthogonal array with combinations of four machining parameters viz., discharge current, voltage, pulse on-time and pulse off-time. They found the optimal setting of process parameters for maximisation of MRR and minimisation of roughness parameters.

3 Experimental details

3.1 Fabrication of aluminium metal matrix composite

The electrode used in the present study was copper with diameter of 10 mm. The aluminium alloy 6061 was used as matrix phase in this composite material which is used in various structural applications and defence applications. Aluminium oxide was used as reinforcement. It is widely used in ceramic production of aluminium-based MMC material other than SiC, B_4C, etc. In this experimental work, 10% of reinforcement particles of aluminium oxide (Al_2O_3) were used with aluminium alloy 6061 to fabricate

AMMC using stir casting process as per the limitation of developed stir casting set up. These limitations are the size of crucible and stirring system. According to these limitations, the maximum 10% reinforcement can be added for proper mixing and wetting during stirring process of manufacturing of MMCs using stir casting process. The fabricated samples of aluminium metal matrix composite AMMC were shown in Figure 2.

Figure 2 Al/Al_2O_3 cast from stir casting process (see online version for colours)

3.1.1 Liquid state fabrication of metal matrix composites

It involves the incorporation of dispersed phase into a molten matrix metal, followed by its solidification. In order to provide high level of mechanical properties of the composite, good interfacial bonding (wetting) between the dispersed phase and the liquid matrix should be obtained. Wetting improvement may be achieved by coating the dispersed phase particles (fibres). Proper coating not only reduces the interfacial energy, but also prevents chemical interaction between the dispersed phase and the matrix.

The methods of liquid state fabrication (Kandpal, Kumar and Singh, 2014) of MMCs are as follows: stir casting, infiltration like gas pressure infiltration, squeeze casting infiltration or pressure die infiltration.

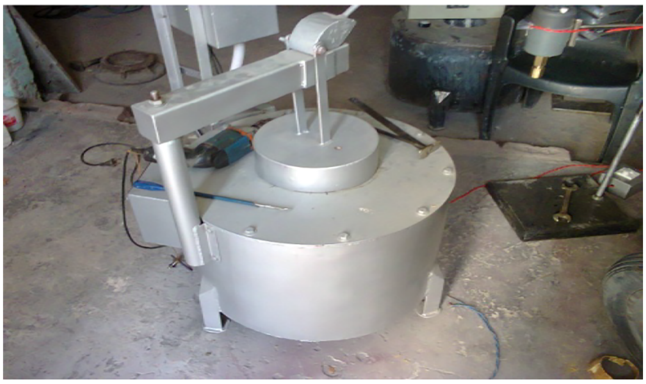
- Stir casting: It is a liquid state method of composite materials fabrication, in which a dispersed phase (ceramic particles, short fibres) is mixed with a molten matrix metal by means of mechanical stirring. The liquid composite material is then cast by conventional casting methods and may also be processed by conventional technologies.
- Infiltration: It is a liquid state method of composite materials fabrication, in which a preformed dispersed phase (ceramic particles, fibres, woven) is soaked in a molten matrix metal, which fills the space between the dispersed phase inclusions. These are of two types as discussed below.
- Gas pressure infiltration: It is a forced infiltration method of liquid phase fabrication of MMCs, using a pressurised gas for applying pressure on the molten metal and forcing it to penetrate into a preformed dispersed phase.
- Squeeze casting infiltration or pressure die infiltration: It is a forced infiltration method of liquid phase fabrication of MMCs, using a movable mould part (ram) for applying pressure on the molten metal and forcing it to penetrate into a preformed

dispersed phase, placed into the lower fixed moulded part. The method is used for manufacturing simple small parts like automotive engine pistons.

Infiltration temperature and infiltration atmosphere are the key parameters distinctly affecting on infiltration processes. The composite Al-Mg/ZrO_2 (Foroughi et al., 2014) was produced at atmospheric pressure by infiltrating 2–10 wt% magnesium content Al-Mg alloys into 25% dense ZrO_2 foams with highly interconnected porosity. Moreover, the increasing in Mg content (2–10 wt%) resulted in an increased amount of infiltration. They found that infiltration was faster at higher temperatures and nitrogen partial pressures. The use of ZrO_2 preform with low cell size in composite resulted in the increase in hardness of Al-Mg/ZrO_2 composite. Composites (Bader et al., 1985) have been produced by infiltrating a porous preform of semi-random short alumina fibres with liquid aluminium alloys, using squeeze casting techniques. Full infiltration was observed to take place very rapidly when moderate pressures were applied. The composites produced have been shown to possess enhanced stiffness which is maintained at useful levels at temperatures approaching 400°C; at ambient temperature they were brittle, but at elevated temperatures the strength was significantly enhanced. High pressure squeeze casting (Sample, Bhagat and Amateau, 1989) has been developed to fabricate unidirectional fibre-reinforced MMCs having a wide range of fibre volume fraction. The process development required innovative die design to minimise the direct contact of molten metal with the metallic die, to prevent liquid metal escape from the die, to ensure fast infiltration and rapid solidification under high pressure. However, the application of high pressure causes certain difficulties, such as maintaining all fibres aligned in one direction and ensuring their uniform distribution in any cross section of the composites. Optical and SEM analysis of polished and fracture surfaces provides details of fibre/matrix interface characteristics and fracture mechanisms of the composites. Squeeze forming process (Vijayaram et al., 2006) is a special casting technique that combines the advantages of traditional high pressure die casting, gravity permanent mould die casting and common forging technology. The major advantages of this technology are elimination of porosity and shrinkage, 100% casting yield, attainment of greater part details, good surface finish, good dimensional accuracy, and high strength to weight ratio, improved wear resistance, higher corrosion resistance, higher hardness, high temperature resistance, improved fatigue and better creep strength. The components manufactured by this casting method require lesser post-machining operation and they have improved mechanical properties such as higher strength and ductility. In squeeze casting process, the liquid metal is pressurised while they solidify and hence near net shapes can be produced with sound and dense quality. This process is simple, economical and it can be automated easily. The process generates the highest mechanical properties attainable in a cast product. So this process has been adopted to make composite castings at an affordable cost. In recent years, there has been an increasing demand from automotive, space and aeronautical industries for materials possessing high specific strength, better wear resistance and stability at high temperatures (Seshan et al., 1995). The process of improving the properties of conventional engineering materials has led to the technique of reinforcing polymers, ceramics and metals with particles, fibres and whiskers, thus leading to the production of composites. They discussed about various techniques such as stir casting, squeeze casting, etc., for processing composites. They discussed about the principle and application of squeeze casting for manufacturing aluminium-based MMCs (Dhanashekar and Kumar, 2014). They found that squeeze casting is the combination of the casting and forging processes that can be done with the help of high pressure when it is applied during melt solidification. Applying pressure on the solidification of molten metal could change the melting point of alloys which enhances the solidification rate. They found that it refines the micro- and macro-structure; it is helpful to minimise the gas and shrinkage porosities of the castings. They discussed about various parameters of squeeze casting such as squeeze pressure, casting (melt)/preform preheat/die temperature, etc.

Aluminium-based MMC was produced by an indigenously developed stir casting process as shown in Figure 3. This process helps to minimise the production-related problems associated with the conventional stir casting process. Stir casting is the simplest and the most cost-effective method of liquid state fabrication. The liquid composite material is then cast by conventional casting methods and may also be processed by conventional technologies. The stir casting process is one of the cheapest processes for manufacturing MMCs. The stir casting set up was first fabricated as per the requirement of process and previously developed stir casting set up. As we know, the shape of stirrer played an important role in the stir casting process. The suitable design of stirrer was selected as per the literature review for proper stirring action during stirring process. In preparing MMCs by the stir casting method, there are several factors that need considerable attention, including the following

Figure 3 Stir casting process set up (see online version for colours)

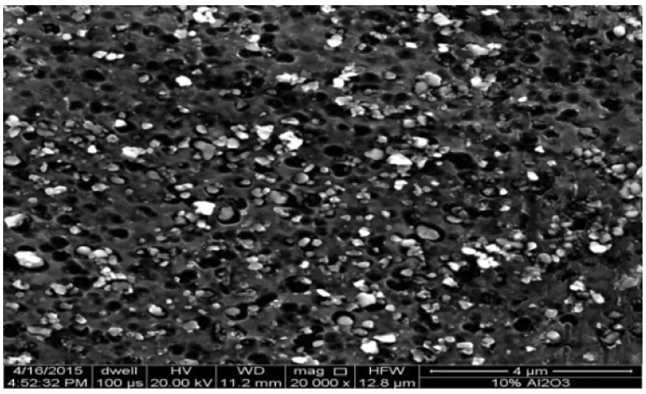


1. the difficulty of achieving a uniform distribution of the reinforcement material
2. wettability between the two main substances
3. porosity in the cast MMCs
4. chemical reactions between the reinforcement material and the matrix alloy.

3.1.2 Characterisation and mechanical testing

It is evident from SEM photographs as shown in Figure 4 that the distribution of Al_2O_3 particles in the aluminium matrix is fairly homogeneous. In AMMC, the distribution of ceramic particles should be intra-granular to obtain higher mechanical and tribological properties. The mechanical testing was done to evaluate the mechanical properties of composite material.

Figure 4 SEM photograph AA 6061/10% wt Al_2O_3



The tensile test specimen was prepared per ASTM: E8/E8 M - standard as shown in Figure 5. It was found that both ultimate tensile strength and hardness were improved as the percentage of reinforcement increased from 5 to 20%. But the percentage of elongation was decreased. The increase in Al_2O_3 content shifted the fracture mode from ductile to brittle.

Figure 5 Tensile test specimen (see online version for colours)

3.2 Experimental details

Machining of AA 6061/10% wt Al_2O_3 composite material is performed in an ECO 200 EDM of Ecoline Company. The experimental set up is shown in Figure 6 and the workpiece which was machined in EDM is shown in Figure 7. In EDM, a large number of factors are affecting the machining performance. Out of which only three process parameters are the primary factors contributing towards the heat input and subsequently have a significant influence on MRR. These three highly influencing parameters are as follows: supply current (*I*), T_{ON} (pulse on-duration) and duty factor. Some of the parameters of EDM process are discussed here.

- Pulse duration (T_{ON}): It is the duration of time measured in micro-seconds. During this time period, the current is allowed through the electrode towards the work material within a short gap known as spark gap. Pulse duration is also known as pulse on-time and the sparks are produced at certain frequency. Metal removal rate depends on longer or shorter pulse on-time period. Longer pulse duration improves the removal rate of debris from the machined area, which also affects the wear behaviour of electrode.
- Pulse interval (T_{OFF}): This parameter is to affect the speed and the stability of the cut. If the pulse interval is too short, it improves MRR because more sparks to be unstable in the machining zone.
- Duty cycle: Duty cycle is a percentage of the on-time relative to the total cycle time. Generally, the higher duty cycles mean increased cutting efficiency. The duty cycle is calculated by dividing the on-time by the total cycle time (on-time + off-time). The result is multiplied by 100 for the percentage of efficiency or duty cycle.
- Electrode gap (spark gap): It is the distance between the electrode and the part during the process of EDM. An electro-mechanical and hydraulic systems are used to respond to average gap voltage. To obtain the good performance and gap stability, a suitable gap should be maintained. For the reaction speed, it must obtain a high speed so that it can respond to short circuits or even open gap circuits.
- Polarity: It may be positive or negative connected to tool electrode or work material. Polarity can affect the processing speed, finish, wear and stability of the EDM operation. It has been proved that MRR is more when the tool electrodes are connected at positive polarity (+) than at negative terminal (–).This is because there is more transfer of energy during the charging process in this condition of machining. The machining parameters at different levels were selected to investigate their effects on the machining of aluminium metal matrix composite.

Table 1 EDM process parameters

Working conditions	*Description*
Workpiece	AA 6061/10% Al_2O_3
Discharge current (A)	2, 6, 8, 10, 14, 18
Pulse on-time (T_{ON})	15, 25, 75, 100, 200, 250, 200, 400, 600, 800, 100

Figure 6 Experimental EDM set up (see online version for colours)

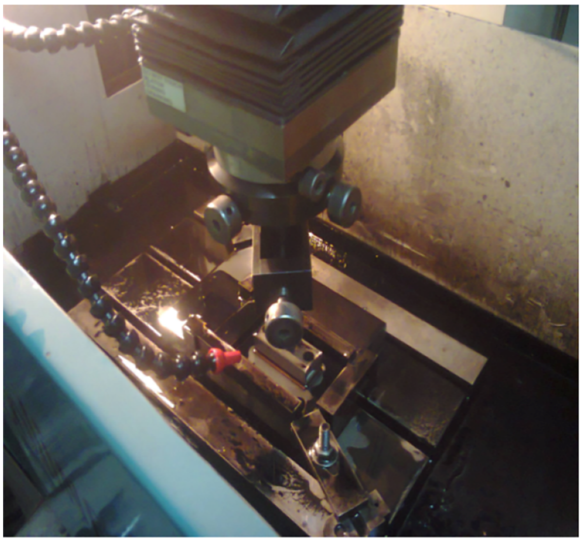


Figure 7 Machined workpiece (see online version for colours)

The experimental results confirmed that MRR increases with increase in discharge current from 2 to 18 A keeping other process parameters constant. MRR increases as pulse current increases because there is a higher energy input at elevated values of current as shown in Figure 8. From the above study, it is observed that MRR increases up to pulse duration of 400 µs as there is insufficient discharging time for melting and vaporisation. High pulse on-time (T_{ON}) produces discharge pulses with higher intensity creating deep craters on the workpiece with higher material removal. But after that MRR decreases because there is an expansion of the plasma channel in the EDM process as shown in Figure 8. The experimental results confirmed that gap size also increases with increase in discharge current from 2 to 18 A. The gap size increases as pulse current increases because there is a higher energy input at elevated values of current as shown in Figure 9. Similarly, gap size increases up to pulse duration of 400 µs as there is insufficient discharging time for melting and vaporisation. But after that gap size decreases because there is expansion of the plasma channel in the EDM process as shown in Figure 9.

Figure 8 Effect of current and pulse on-time on MRR (see online version for colours)

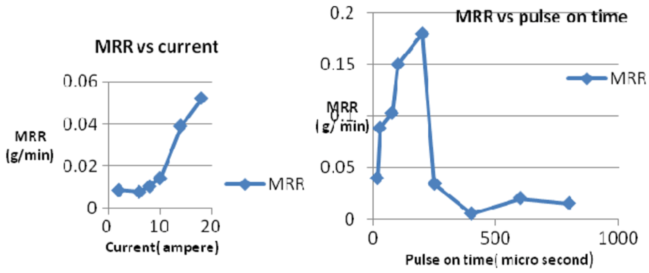
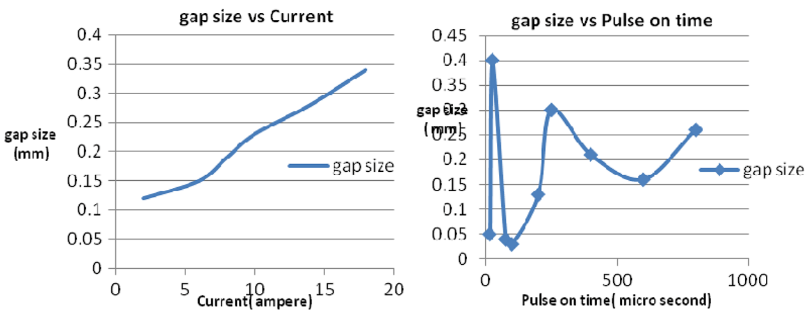


Figure 9 Effect of current and pulse on-time on gap size (see online version for colours)



4 Conclusion

From the above study, following conclusions are drawn:

- The SEM result shows the clusters of Al_2O_3 reinforcement throughout the composite structure. As a result of reinforcement of Al_2O_3, the tensile strength and hardness get improved. It indicates constrain of the stir casting process for attaining uniform micro-structure. These constrains can be removed by controlling the various parameters of stir casting process as discussed in the literature.
- The tensile strength and hardness of composite samples increased as the percentage volume fraction of Al_2O_3 reinforcement.
- The machining characteristic of MRR gets increased with increase in current because there is a higher energy input at elevated values of current.

- With the increase in pulse on-time, the MRR gets increased but up to pulse duration of 400 μs as there is insufficient discharging time for melting and vaporisation. But after that, MRR decreases because there is an expansion of the plasma channel in the EDM process. However, optimum results were obtained at lower setting of pulse duration.
- Gap size of the machined hole is mostly affected by the peak current and pulse on-time and increased with increase in current and pulse on-time.
- The optimum values of these parameters should be selected to get higher metal removal rate and lower gap size of drilled holes.

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