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Feature article

Machinability analysis of multi walled carbon nanotubes filled alumina composites in wire electrical discharge machining process

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ABSTRACT

The approach of machining ceramics with electrical discharge machining process is a great challenge till date due to its low electrical conductivity. Machining is made possible by reinforcing with a conductive phase which increases the overall electrical conductivity. Present work focuses on machining of multi walled carbon nanotubes filled alumina composites. Samples with concentrations ranging from 2.5 to 12.5 vol.% are considered for machining. At lower concentration of 2.5 vol.%, effective machining is not possible. Wire lag phenomena is observed during machining at 5 vol.% sample concentration. Proper machinability is observed with concentration of 7.5 vol.% or more. Also, long micro-cracks are obtained during machining that leads to the workpiece breakage. Spalling effect is observed as the most dominating material removal mechanism. A comparison between alumina composites and conducting metallic alloys were carried out for surface characteristics.

1. Introduction

Electrical Discharge Machining (EDM) or Wire Electrical Discharge Machining (WEDM) process is a well-known method of machining various materials regardless of its hardness, as long as they are conductive in nature. It is a non-contact type process where a minute gap, called the spark gap is maintained between the tool and the workpiece. The gap is filled with a dielectric fluid; generally a hydrocarbon based oil for EDM and deionized water for WEDM. To ensure optimum material removal, the workpiece is made as anode and the tool as cathode. A potential difference is generated between the tool and the workpiece when power is supplied. Under the influence of it, breakdown of the dielectric fluid occurs in the region which is in immediate vicinity between the tool and the workpiece. This enables a flow of electrons, coupled with immense heat from cathode to anode. The intense heat causes a localised heating that leads to removal of materials from the workpiece. The zones where the temperature is more than the melting point are removed by heating and evaporation process. Moreover, flushing action of the dielectric fluid also contributes to material removal mechanism.

Material revolution is evolving from metallic alloys to other materials like ceramics owing to their diverse material properties. This diverse property enables them to be used in various sectors, ranging from marine to aerospace industries. As a result of the recent advancement, the applications of ceramics have increased considerably [1]. However, machining of such materials is still a major challenge. The conventional machining processes suffer a lot while machining such materials due to its brittleness and hardness. On the other hand, non-conventional machining techniques have proven to be a means to machine such materials to a certain extent. Over the period, few researchers have reported the use of laser beam machining to successfully machine the ceramics [2]. However, the efficiency, associated cost and the final output are still a big constraint.

EDM/WEDM process has shown some positive outcome in machining electrically non-conductive materials. Researchers have reported two basic approaches to machine non-conducting ceramics using EDM/WEDM. The first method is the incorporation of a conductive layer over the surface of the workpiece to be machined. This concept is called the Assisting Electrode (AE) method [3]. In this method, the AE layer serves as a conductive medium and helps in triggering an initial spark between the tool and the workpiece. The entire machining process is performed with kerosene as the dielectric fluid. The same process is followed in WEDM by incorporating an additional sink [4,5]. It has been observed and identified that a

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continuous machining is possible after the AE layer by generation of a pyrolytic carbon layer from the dielectric fluid (kerosene). The newly formed carbon layer sticks onto the surface of the workpiece, acting as a conductive medium to enable continuous machining process. An important aspect in machining ceramics using AE layer is the nature of removal of material by spalling effect in the form of small chips [6,7]. Over the years, researchers have used copper tape [3] colloidal carbon baking [8] and physical/chemical vapour deposition [8] process to make the AE layer. To further strengthen this process, a lacquer form of AE [5] is also employed where better material removal rate is observed as compared to previous approaches. The material removal by this technique is very low and time consuming method. Also, the process cannot be carried out for any dielectric fluid. Hence, as a result of it, researchers have been focussing on an alternate approach to machine such non-conducting materials in EDM/WEDM.

Another method is performed by reinforcing the non-conducting ceramics with a conductive particle. The conductive particle reinforcement increases the overall electrical conductivity of the composite, thus allowing machining by EDM/WEDM process. Martin et al. [9] analysed the machinability characteristics of Silicon Nitride (Si_3N_4) and Alumina (Al_2O_3) by reinforcing with 40 vol.% of TiC, TiN and combination of both. A decent possibility in machining these composites was found in EDM process. Matsuo and Oshima [10] observed that the machining of Zirconia (Zr_2O) is possible in EDM by adding 23 vol.% of NbC or TiC. However, for practical feasibility, the threshold percentage of the reinforcing agent was maintained around 28–30 vol.%. More feasible machining characteristics were observed with increase in the overall conductive particles. But, the alteration in the material properties was found concomitantly. Lauwers et al. [11] experimented on the material removal mechanisms in EDM of ceramic based composites (Zr_2O-TiN, Si_3N_4-TiN and Al_2O_3-SiC_w-TiC) in 60/40 vol.%. He observed that a major portion of the materials are removed by spalling effect, rather than the normal heating and evaporation process. The researcher further reported that the oxidation and decomposition effect on the base material resulted in undesired surface effects. Patel et al. [12] investigated and analysed the EDM process of Al_2O_3 filled with SiC and TiC particles. At lower current range, melting and evaporation are the main phenomena of material removal process. However, at higher current range, thermal spalling effect is the main cause of material removal coupled with flake detachment process. The associated surface finish was found to be in an appreciable range at lower current values. But at higher current range, high surface roughness value was observed. This condition implicates the nature of material removal mechanism by spalling effect at higher current range. Ferraris et al. [13] compared the overall performance of Al_2O_3-TiCN and Zr_2O-TiN ceramics (60/40 vol.%) with the machining process of steel in EDM. A similar inference in MRR was obtained due to increased electrical conductivity of the ceramic composites. However, a notable difference was identified towards the tool wear in machining of ceramics composites as compared to steel. The wear value was found approximately four times lower than that of steel. Landfried et al. [14] made a thorough comparison of the machinability aspect of Zirconia Toughened Alumina (ZTA) composites. A 24 vol.% of TiC, TiN, TiCN, TiB_2 and WC were individually reinforced as the conductive phase in ZTA. Among these, the machining process was feasible only in ZTA-WC, ZTA-TiC and ZTA-TiB_2 composites.

Different researchers reported the machinability characteristics of various ceramic materials (Al_2O_3, Zr_2O and Si_3N_4) doped with electrically conductive fillers like TiB_2, TiN, TiC, WC, TiCN [15–17]. A better improvement in the material removal mechanism of ceramics was observed with the incorporation of the electrical conductive fillers. A notable impact that can be seen from the various work reported is the percentage addition of the conductive fillers. In most cases, a threshold limit of 24 vol.% of conductive particles are added to make the ceramic composite machinable using EDM/WEDM. However, from practical point of view, effective machining process was possible with 40 vol.% of the reinforced particles. This leads to a major change in the overall material properties which is actually not desired.

To reduce the concentration of filler materials in the overall ceramic composites, researchers started adopting carbon nanotubes (CNT). Malek et al. [18] made an attempt to identify the machinability of Si_3N_4 filled with 5.3 vol.% of CNT and 40 vol.% of TiN particles. At same conditions, the MRR in CNT filled Si_3N_4 were found to be almost double when compared TiN filled Si_3N_4. Also, lesser tool wear was observed in CNT filled composites. With improvements in the machining aspect of ceramic composite using CNT, Tak et al. [19] conducted an experimental comparison to determine the effect of CNT concentration in alumina composites. The machining capabilities observed with 5 vol.% of CNT were very good. This encouraged the researcher to increase the CNT concentrations to 10 vol.%. However, violent sparks were generated which lead to a relatively poor dimensional accuracy. Melk et al. [20] reported that machining was feasible with a very low concentration of multi walled carbon nanotubes (MWCNT) in zirconia composites. A major dependence on spalling effect for material removal was also observed.

An increase in the overall conductivity of the ceramic composite leads to alteration in the physical and chemical properties of the composite from the parent material. So, it is always desired to minimize the overall effect of the composites from the ceramic material. A low concentration of the reinforcing particle has a lesser probability in the overall alteration of the material properties. The fabrication technique laid out by Hanzel et al. [21] provides a better overall electrical conductivity of the composites as compared to other approaches. A significant but appreciable variation in hardness value is observed in this technique. The decrease in hardness of the composites with MWCNT concentration is due to the low hardness of the carbon nanotubes. A decreasing trend of thermal properties is also observed with gradual increase in the MWCNT concentrations [22].

The current work focuses on the machinability aspect of MWCNT filled alumina composites in WEDM process. A series of experiment is performed to check the influence of MWCNT concentrations in the alumina composites. A detail analysis of the effect of MWCNT content on the material removal and the surface integrity is represented. A comparison of the nature of surface integrity with the conducting metallic alloy is also discussed.

2. Materials fabrication

The adopted fabrication process for alumina-MWCNT composites consists of several steps as already described by Hanzel et al. [21]. First, the multi-wall carbon nanotubes with outer diameter of 8–15 nm and length of 50 μm (Chengdu Organic Chemicals Co. Ltd., China) are stirred and ultrasonicated in a mixture of concentrated sulphuric and nitric acids. The mixing process is performed for duration of 7 h, in the volume ratio of 3:1. Later, the CNTs are filtered from this mixture and thoroughly washed by distilled water to be acid-free. The CNTs are then finally dried at 80 °C overnight. In the next step, water based dispersion of treated MWCNTs are prepared along with addition of stabilizing agent of sodium dodecyl sulphate (SDS, Alfa Aesar GmbH, Germany). The weight ratio of SDS and MWCNTs are 1.5:1. Alumina powder (Martoxid MR-70, Al_2O_3 ~ 99.8%, specific surface area 6–10 m^2/g) are added into the stabilized dispersion of MWCNT in order to prepare the mixtures with various content of carbon nanotubes in the range of 2.5–12.5 vol.%. Finally, the mixture are ball milled with