Investigation of the Effect of Wire Electrical Discharge Machining on the Fracture Toughness of Aluminum-Boron Carbide Composite

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Abstract. Aluminum metal matrix composites reinforced by ceramic particles have a wide acceptance in engineering applications due to their mechanical and physical properties. One of the major challenges in machining these composites by the conventional machining operations is the presence of the abrasive particles, which affects the tool life and the required surface finish. Electro discharge machining process is widely used instead of conventional methods to overcome these challenges. Therefore, it is essential to study the influence of the electro-discharge machining on its fracture toughness, as it is the most important structural integrity indicator in the wide range applications of the studied composites. In this work, all samples were prepared by the stir casting method with using a squeezing pressure during the solidification. Samples were reinforced by (0, 2, 4, and 6wt %) of B₄C particles with a size of 0.387μm. The fracture toughness studied were based on the stress intensity factor, determined experimentally by using compact tensile test and numerically using the finite element method. The fracture toughness improvement was recorded for the samples containing 4wt% of B₄C.

Keywords. Aluminum base composite, B₄C Particles, Fracture toughness, EDM, Compact tensile test.

1. Introduction

Metal matrix composites (MMCs) are made of a continuous metallic matrix and a discontinuous reinforcing phase. Composites reinforced by ceramic particles have a wide acceptance in engineering applications. Nowadays, these are replacing conventional materials in many applications due to their superior properties such as high strength to weight ratio, hardness, stiffness and wear and corrosion resistances [1]. Aluminum base composite materials are still subject for intense studies to improve their characteristics. Such materials are strengthened by reinforcing with hard particles like SiC, Al₂O₃, B₄C, and other ceramic particles [2]. The particles may improve the fracture strength of the composite over that of the matrix by preventing or impeding crack propagation through the matrix, either physically blocking and stopping cracks or diverting and splitting them to hamper their progression across the piece. They may also improve the stiffness and strength of the composite over that of the matrix, by carrying a proportion of the load [3]. The reinforcements in the metal matrix composite (MMCs) make the material difficult to machine by the traditional methods. This is related to the effects of the abrasive particles on the surface integrity and on the tool life. Therefore, there is a need for a non-conventional type of machining that produces a good surface finishing with the required dimensional accuracy. Electro discharge machining (EDM) as a non-contact type process can
produce products with good dimensional accuracy, complexity, and a good surface finish [4]. Therefore, it is essential to study the influence of such machining process on the fracture toughness of the composite, as it is very important indicator in the wide range applications of the studied composites. The current study is conducted on aluminum base composite reinforced by B₄C and prepared by stir casting and squeezing during the solidification. The fracture toughness is investigated experimentally and numerically by determining the stress intensity factor based on compact tensile test. Finite element method via Ansys 16 was used to achieve the numerical analysis.

2. Experimental procedure

2.1. Test for basic materials

The materials used in this work are aluminum wire with a purity of 99.7% and powder of B₄C with an average particle size of 0.387μm. Table (1) demonstrates the chemical composition of the used wire according to the test of (UR State Company for Engineering Industries /Nassyria-IRAQ).

|       | Al (%) | Si (%) | Fe (%) | Cu (%) | Mn (%) | Mg (%) | Zn (%) | Ti (%) | B (%) | V (%) | Cr (%) | Others total (%) |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|-------|-------|--------|------------------|
| S1    | 99.7   | 0.06   | 0.12   | 0.01   | 0.01   | 0.02   | 0.03   | 0.01   | 0.005 | 0.01  | 0.01   | 0.015             |

2.2. Preparation of al base composite

Samples with (zero, 2, 4, and 6wt %) of B₄C were prepared and coded as (S1, S2, S3, and S4), respectively. All samples were prepared by two-step stir casting method [5]. Short cuts of aluminum wire were charged into ceramic crucible in electric furnace type (ORH5-F102200) and heated slowly above liquidus temperature (720°C) to melt the pieces of the wires then the temperature dropped to (620°C). Magnesium ribbons, enveloped in aluminum foil, were immersed inside the melting (with 1.5wt %). For 7 minutes, the semi-solid was mixed via four-blade stirrer at a speed of 870 rpm. Then, the temperature was raised slowly again to (850°C), and the preheated and enveloped B₄C particles were gradually added to the melt. The stirring was conducted under a shield of argon. The melting was poured into a (250°C) preheated steel molds. During solidification, the metal inside the molds was subjected to a squeezing pressure of (95MPa) via electric press (EOH), and then the solidified cast was left to cool in a still air. The cast samples were heated to (300°C) for 3 hours for stress relief. Figure (1) shows the stir casting and the squeezing systems used in the casting process.

![Figure 1. The stir casting and the squeezing systems used in the casting process.](image)

3. Tensile test

Standard specimens were prepared according to ASTM (B557m-15) [6]. The test was conducted on universal testing machine model (WDW-200) using a speed rate of 0.1 mm/min. Figure (2) shows specimens before and after the test, while Figure (3) shows the corresponding results of the tests [5].
Figure 2. Tensile specimen: (a) Before testing, and (b) After testing.

Figure 3. Effect of $B_4C$ particles on the tensile properties of the composites.

4. Fracture toughness
The stress intensity factor was used to study the fracture toughness of the studied composite. The first mode (opening mode) critical stress intensity factor ($K_{IC}$) was determined based on compact tensile test specimens prepared according to the American Standard E399 as shown in Figure (4) [7]. The figure shows that the dimensions of the prepared specimen were the thickness, $B=12.7\text{mm}$; and the width, $W=25.4\text{mm}$. Preparing of the specimens included the required face milling and drilling operations for the cast samples. These machining operations were achieved on a milling machine type (FU: 251M) and a drilling machine type (WDM Z5050). The Notch and the pre crack of the specimen with the required dimensions was achieved on a CNC wire EDM machine using a brass wire (CuZn37) with a diameter of (0.25mm). Wire EDM was used instead of usual fatigue pre cracking method because this machining operation is widely used to overcome the challenges of the conventional machining processes of the studied composite. Figure (5) shows the specimen at the final steps of its preparation.

Figure 4. Standard compact tensile test specimen [7].
Figure 5. The specimen at the final steps of preparation: (a) Notched and pre-cracked specimen after machining on wire EDM CNC machine; and (b) Final shape of the specimen after machining on a drilling machine.

Plain strain conditions must be compatible with the specimens dimensions. According to ASTM E399, the stress intensity factor was determined by the following equation [7]:

\[ K_I = Q_{CT}.\sigma_Q\sqrt{\pi a} \]  \hspace{1cm} (1)

Where \( Q_{CT} \) is a dimensionless function of \((a/W)\) calculated as:

\[ Q_{CT} = 16.7 - 104.7 \left( \frac{a}{w} \right) + 369.9 \left( \frac{a}{w} \right)^2 - 573.8 \left( \frac{a}{w} \right)^3 + 360.5(a/w)^4 \]  \hspace{1cm} (2)

\[ \sigma_Q = P_0/(Bw) \]  \hspace{1cm} (3)

The \( K_I \) value computed from Equation (1) is a valid \( K_I \) result only if all validity requirements in the standard are met, including:

\[ 0.45 \leq a/W \leq 0.55 \]  \hspace{1cm} (4)

\[ B, a, \geq 2.5 \left( \frac{k_I}{\sigma_{yp}} \right)^2 \]  \hspace{1cm} (5)

\[ P_{max} \leq 1.10P_0 \]  \hspace{1cm} (6)

The compact tensile test was achieved on a universal testing machine type (WAW-200). Figure (6) shows arrangement of the specimen during the test and the clamping device used to the extensometer fixed on each specimen for recording its opening displacements versus the loads during the test.

Figure 6. (a) Specimen arrangement during the test, and (b) Clamping device of extensometer on the specimen.
Figure (7) shows the load displacement response for the specimen reinforced with 4wt. percentage of B₄C. The results indicate a typical behavior with a linear pattern initially, and then a large increment in the crack displacements with low loads. The variables of the equations used to compute $K_{IC}$ for each specimen were obtained based on its load displacement response. Table (2) demonstrates the obtained values of these variables and the computed values of $K_{IC}$. The computed values of the stress intensity factor are close to that ranging from (21-25 MPa√m) recorded in [8, 9, 10] for aluminum matrix reinforced by ceramic particles. The results indicated that the fracture toughness increases with the added percentage of B₄C up to 6% when it decreases due to the agglomeration of the reinforcing particles and their weak interface with the aluminum matrix.

![Figure 7. Load-displacement response for the specimen reinforced by 4wt. percentage of B₄C.](image)

| Sample Code | $\sigma_y$ (MPa) | $P_0$ (N) | $P_{max}$ (N) | $K_{IC}$ (MPa√m) |
|-------------|-----------------|-----------|--------------|------------------|
| S2          | 65              | 6100      | 6680         | 16               |
| S3          | 83              | 7500      | 8210         | 19               |
| S4          | 71              | 4300      | 4666         | 11               |

5. Numerical modeling of fracture toughness
Finite element analyses were used via ANSYS ver16 to study the fracture toughness of the reinforced aluminum by (2, 4, and 6wt%) B₄C particles. Compact specimen was simulated in 2- dimension model according to the size and geometry of the used specimens in the experiments. The meshing used in the simulation was characterized by a maximum element separation of (1), so it contains (2264) element and (7060) nodes. Figure (8) shows the used meshing in finite element analysis. A load was used at one side of the specimen while the other side was fixed as shown in the Figure. The material properties needed for the analysis were used as the same as the mechanical tests results.
Figure 8. compact specimen meshing and the boundary condition used in the analysis.

The stress distribution obtained by the finite element analysis are demonstrated in Figure (9) to Figure (11). It is clear that a maximum stress of 55, 67, and 58MPa are located at the crack tip edge of the specimens S₂, S₃ and S₄, respectively. The stress distribution around the notch are -3, -2.9, and -0.8MPa for the same specimens.

Figure 9. Stress distribution for specimen with 2wt% of B₄C.

Figure 10. Stress distribution for specimen with 4wt% of B₄C.
Figure 11. Stress distribution for specimen with 6wt % of B₄C.

Table 3 demonstrates the resulting values of the stress intensity factor of the composite specimens analyzed by finite elements.

| Sample Code | $\sigma_0$ (MPa) | $\sigma$ (MPa) by FEA | $K_{IC}$ (MPa√m) by FEA |
|-------------|-----------------|------------------------|--------------------------|
| S2          | 18.9            | 20                     | 17                       |
| S3          | 23              | 25                     | 21                       |
| S4          | 13              | 14                     | 12                       |

The SEM analysis had been carried out to compare the form of the fracture of the specimens and see the effect of adding different percentage of boron carbide (B₄C). The fracture of the composites is mainly associated with voiding in the matrix around individual particles ahead of the main crack and near the interface. Crack propagates by linking the micro cracks locating the crack path preferentially in the matrix adjacent to the interface [10]. This is clear in Figure (12a) for the relatively ductile specimen. For the specimens reinforced by 6wt% of B₄C, there is an agglomeration of the particles which leads to a cleavage-like fracture as noticed in Figure (12c). Figure (12b) shows the surface fracture of the specimen reinforced by 4wt% of B₄C. There is a combination of ductile and brittle fractures at this surface.

Figure 12. The fractured surface of (a) specimen reinforced by 2wt% B₄C; (b) Specimen reinforced by 4wt% B₄C; and (c) specimen reinforced by 6wt% B₄C.
6. Conclusions
The most important obtained conclusions are summarized as follows:
1. Fracture toughness was improved by adding boron carbide, and the best improvement was achieved by adding 4wt % of B\textsubscript{4}C.
2. The obtained values of the stress intensity factor using pre-cracked specimens via WEDM was (7-11 %) lower than that reported in the literature for Al-base composite reinforced by ceramic particles. Also, it was (5-10) % lower than that determined by numerical analyses based on FEM. Therefore, with acceptable percentage of error, WEDM can be used to pre-crack compact tensile specimens for measuring stress intensity factor of Al-base composite reinforced by B\textsubscript{4}C particles.

7. References
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