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OPTIMIZATION OF PROCESS PARAMETERS FOR FRACTURE TOUGHNESS OF Al6061-GRAPHITE COMPOSITES

OPTIMIZACIJA PARAMETARA ŽILAVOSTI LOMA Al6061-GRAFITNIH KOMPOZITA

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Keywords
- Al6061-graphite composites
- fracture toughness
- Taguchi's method
- CT specimens

Abstract

The present research work shows the perceptive work directed on the fracture toughness and the effect of process parameters on Al6061-graphite particulate composites. The composition used is Al6061 as matrix material and 6, 9 and 12 wt.% of graphite as reinforcement. In this research, it is intended to optimize the fracture toughness parameters: composition of the composite, a/W ratios, and thickness of the specimen using Taguchi's technique for the said composite material. Also, the effect of process parameters has also been studied using analysis of variance technique. The Analysis of Variance (ANOVA) exhibits that material composition will influence more on the fracture toughness of the material and also it is less influenced by the thickness of the specimen.

Ključne reči
- Al-6061-grafitni kompoziti
- žilavost loma
- Taguči metoda
- CT epruvete

Izvod

U radu su prikazana istraživanja usmerena na žilavost loma i uticaj procesnih parametara na Al6061-grafitne čestične kompozite. Ispitivani kompozitni materijal sastavljen je od matrice Al6061, a za ojačanje je korišćen grafit od 6, 9, i 12 tež.%. Cilj rada je i postupak optimizacije parametara žilavosti loma: sastav kompozitnog materijala, odnosi a/W, kao i debljina epruvete, primenom Taguči metode na spomenuti kompozitni materijal. Takođe je istražen uticaj procesnih parametara primenom metode analize varijanse. Metoda analize varijanse (ANOVA) pokazuje da sastav materijala ima veći uticaj na žilavost loma materijala, a istovremeno se pokazuje da je od manjeg uticaja debljina epruvete.

INTRODUCTION

Differing categories of material known as metal matrix composites (MMCs) consist of metal as a matrix material and ceramic as reinforcement. The reinforcements may be a particle, platelets, whisker, short fiber and continuously united fibers. These MMCs are used in structural applications and also in conditions where reduced weight, wear resistance, enhanced mechanical and thermal properties are required. By a long shot, the most generally perceived MMCs depend on the matrix Al, Mg, and Ti alloy with common reinforcements as Al_2O_3, graphite, SiC, etc.

The resistance to fracture of a material is known as fracture toughness. Fracture toughness is a material property and its ability of having a crack and fracture resistance. Fracture toughness is represented by K_{Ic}. Normally, it relies on the composition of material, loading conditions and rate, temperature, microstructure and geometrical constraints of the specimen, and so on /2/. Every single structural material does not have hypothetically determined strength in view of faults as inclusions, imperfections, crack and manufacturing defects, and so forth. Instead of conventional design, fracture-based design approach is the better option. Conventional design is based on the limiting strength methodology. The components in real service will fail before the limiting strength is reached.

Fracture based approach is the quantitative approach to the state of the material having a crack and it shows the resistance to brittle fracture. If a material has low fracture toughness, it will potentially encounter brittle fracture, though a material of high fracture toughness will conceivably experience ductile fracture.

In the wake of contemplating the early work of Griffith and others, Irwin reasoned that the essential apparatuses expected to examine fracture were at that point accessible /2/. Irwin's underlying significant commitment was to reinforce the Griffith's way to deal with metals just as the energy dissipated by the local plastic flow. Griffith, Irwin, and other people who did research at the conceptualisation of fracture mechanics examined the behaviour of crack in brittle material.

A wide range of techniques were utilized to inspect the fracture toughness. Principally, the American Society for Testing and Materials (ASTM) standard testing techniques were utilized to find fracture toughness of the aluminium alloys and aluminium-based composite. In ASTM standard testing procedure, two specimens are recommended to test the fracture toughness *viz.*, compact tension (CT) and single edge notch bend (SENB) specimens, /3/. According to ASTM E-399 standard testing procedure, specimens will be set up for various crack length-to-width ratios (*a/W*).

From the literature, it is identified that many methods have been developed to cast aluminium-graphite particulate metal matrix composite. Also, some new methods such as low pressure die casting process /4/, pellet method /6/, stir casting /5, 7, 8, 9, 11/ were developed to cast the metal matrix composite such as aluminium-graphite. Most of the researchers utilized stir casting method in the fabrication of particulate MMCs.

Xian-Kui Zhu et al /3/ presents a technical overview of the elastic-plastic fracture mechanics and the linear elastic fracture mechanics in the context of standardizing the fracture toughness testing /10/ and evaluation for metallic materials. Many authors have investigated fracture toughness of aluminium composites /12-18/ using compact tension specimens with different specimen thickness /19-20/ and judged against their outcomes with the unreinforced aluminium alloy.

On this foundation, the examination gap demonstrates that there is a great deal of extension for present researchers for examination with the utilization of graphite particulate as a reinforcement material. Consequently, this research work will concentrate on the fracture behaviour of aluminium-graphite metal matrix composites. In this research, it is intended to optimize the fracture toughness parameters viz., composition, *a/W* ratios, and specimen thickness using Taguchi's technique for the said composite material.

MATERIALS

Al6061-graphite particulate MMCs at 6, 9 and 12 wt.% of graphite are casted using stir casting technique /23-29/. The Al6061 slabs are permitted to dissolve in the furnace at about 720 °C temperature. To take away the gases from the molten aluminium, a degasifier has been added. Stirring at speed of 500 rpm in the liquid aluminium, the required amount of graphite particles is added. The liquid aluminium-graphite composite is poured into the split type graphite mould and is permitted for solidification. Bars, taken out from moulds are utilised for determining the required properties of the Al6061-graphite alloy.

In the microstructure, shown in Fig. 1a, of the Al6061-graphite composites, is affirmed a uniform distribution of the reinforcement. During the time spent in the blending, a spinning of liquid material is formed by the revolution of the stirrer through which the graphite particles are drain dissolved.

To determine the chemical composition of the Al6061-graphite composites, EDX measurements are carried out using scanning electron microscope (SEM) on individual samples. The resultant EDX profile examination appears in Fig. 1b and gives the atomic percentage of the components found on the Al6061-9 wt.% graphite surface. The response items are additionally seen at metal matrix-reinforcement interfaces.

From Fig. 2a it is clear that there exists a good bonding between the aluminium matrix and graphite particles. Also, it is found that there is no indication of extensive segregation or void formation at the matrix-particle interface. The great interfacial bonding and homogeneous distributions of graphite particles in the matrix have a direct impact on the mechanical behaviour of the composite material.

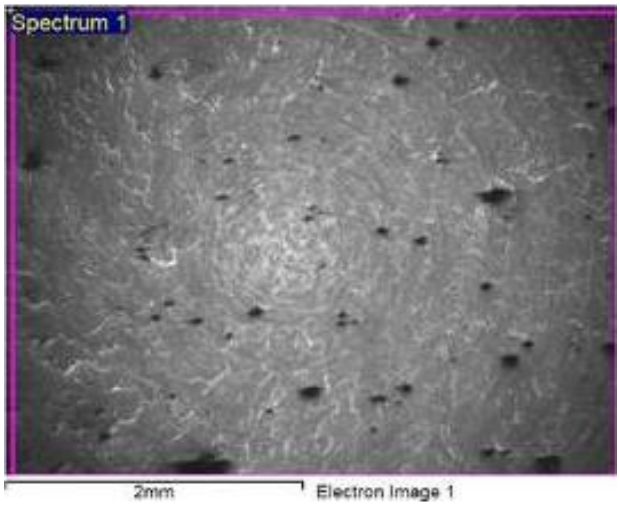

Figure 1a. SEM graph showing a distribution of graphite particles in Al6061-9 % graphite.

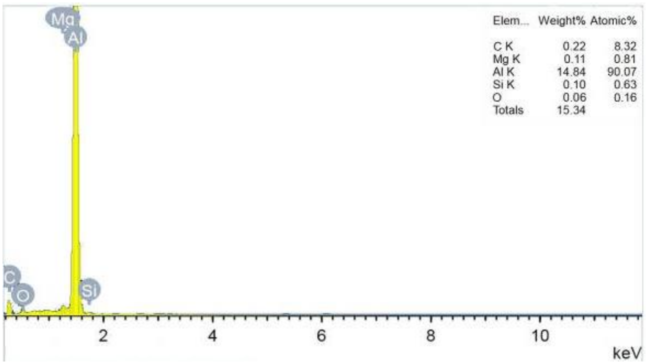

Figure 1b. EDX profile analysis of Al6061-9 % graphite surface.

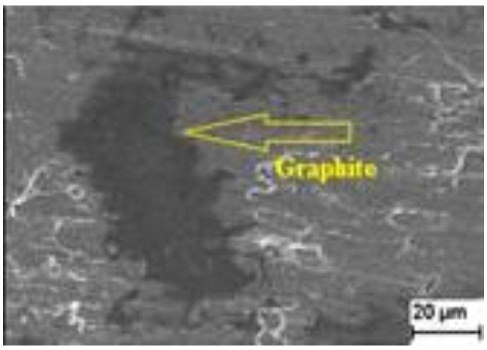

Figure 2a. SEM of Al6061-9 % graphite, demonstrating interface between matrix and reinforcement.

Due to the good bonding and uniform distribution of graphite particles in the aluminium matrix, Al6061-graphite particulate composites have greater tribological properties and outstanding antifriction properties. Figure 2b shows the particle size of graphite in the aluminium matrix.

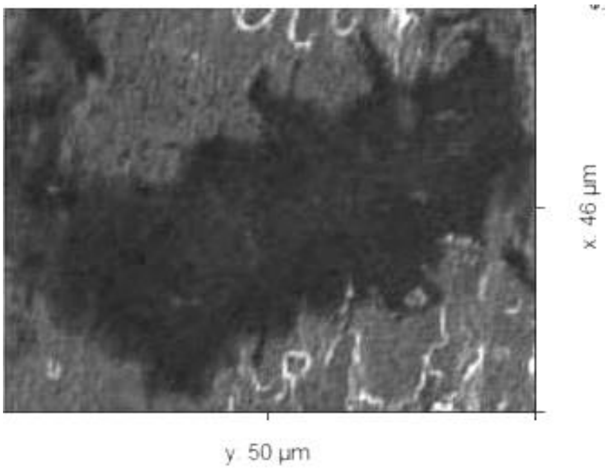

Figure 2b. SEM of Al6061-9 % graphite showing average particle size of graphite in an Al6061 matrix.

EXPERIMENTATION

Compact tension (CT) specimens

In this experimental work, among different fracture toughness testing methods, compact tension (CT) specimens /10/ are considered. Experimental examinations are directed on aluminium matrix with 6, 9 and 12 wt.% of graphite particles. This paper shows research work with fracture toughness carried out and optimizing the process parameters that influence the fracture toughness of the composite. To carry out the experimental work, the design of experiments (DOE) by Taguchi's technique has been utilized.

Design of experiments (DOE) using Taguchi design

Taguchi strategy for optimization is one of the best procedures on account of its effortlessness to direct the design of experiments. The principle point of the Taguchi system is to assess the statistical information which is the input data for optimization. The procedure is produced for the design of experiments to investigate various parameters and their impact on the process mean and variance. From the data of Taguchi's design of experiments, analysis of variance (ANOVA) can be carried out, and also, to optimize the performance behaviour, a new process parameter can be chosen.

Table 1. Taguchi's L9 orthogonal array.

Sl no	Crack length to width, *a/W* ratio	Thickness (mm)	Composition wt.% of Gr.
1	0.45	10	06
2	0.45	12	09
3	0.45	15	12
4	0.47	10	09
5	0.47	12	12
6	0.47	15	06
7	0.50	10	12
8	0.50	12	06
9	0.50	15	09

In this research, the optimization of process parameters of compact tension (CT) specimens is carried out by utilising Taguchi's techniques. To optimize the process parameters, three factors and three levels are considered.

Factors considered are the composition of the material, thickness of the specimen and *a/W* ratio. Levels considered are: *a/W* = 0.45, 0.47, and 0.50; thicknesses of specimens considered are *B* = 10, 12 and 15 mm; and composition of composite considered are Al6061 as matrix with 6, 9 and 12 wt.% of graphite as the reinforcement. The Taguchi's L9 orthogonal array is given in Table 1.

RESULTS AND DISCUSSION

Experimental results

Results of the fracture toughness experiment are shown in Table 2. From the outcomes, it very well may be revealed that with an increment in the graphite content of Al6061-graphite composite, the value of fracture toughness increases. The rise in fracture toughness is because of the influence of the added graphite particulates which act as an internal barricade to the cracks present in the microstructure.

Table 2. Fracture toughness of Al6061-graphite composite for different conditions.

Sl no	Crack length to width ratio *a/W*	Thickness (mm)	Composition of Gr (wt.%)	Fracture load, P_Q (kN)	K_{Ic} (MPa√m)
1	0.45	10	06	4.04	16.84
2	0.45	12	09	4.77	16.58
3	0.45	15	12	5.90	16.41
4	0.47	10	09	3.79	16.75
5	0.47	12	12	4.48	16.48
6	0.47	15	06	5.53	16.29
7	0.50	10	12	3.36	16.23
8	0.50	12	06	4.03	16.24
9	0.50	15	09	5.15	16.59

From Table 2 it is observed that as *a/W* ratio increases, fracture toughness decreases. Also, as the thickness of the CT specimen increases, there is a decrement in the fracture toughness of the observed composite. The decrease in fracture toughness after 9 wt.% of graphite may be the result of the graphite increment (Fig. 3b) which causes particle grouping in the neighbouring matrix.

For the Taguchi design, experimental fracture toughness and load carrying capacity are the input functions. For the given input functions, Taguchi's design has been analysed. The results of the analysis are shown in Figs. 3a and 3b.

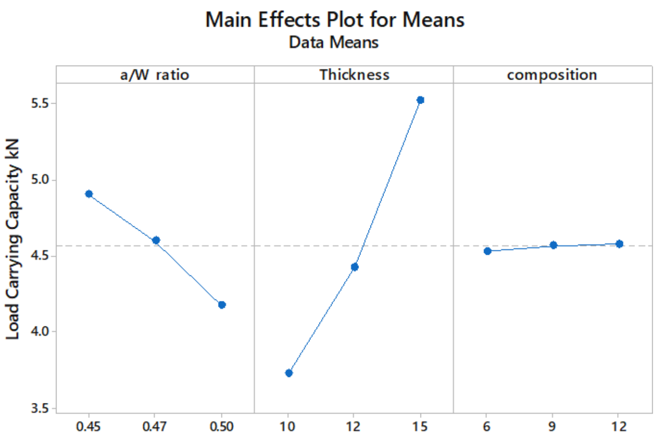

Figure 3a. Taguchi's design results for load carrying capacity.

From Taguchi's design outcomes, it is seen that the increment in *a/W* ratio causes a decrement in the load carrying capacity of the composite. With the increment in graphite content in the Al6061 matrix the load carrying capacity of the composite increases up to the 9 wt.% of reinforcement, and decrease for 12 % graphite. Also, from the graph it is clear that as specimen thickness increases, the load carrying capacity increases. From Fig. 3b it is seen that as *a/W* ratio increases, the fracture toughness of the Al6061-graphite composites decreases. It is obvious that as the load carrying capacity decreases, the fracture toughness decreases. As thickness of the specimen increases, fracture toughness of the composite decreases, and it almost follows a constant path. This is according to the trends mentioned by many researchers /21, 22, 26/.

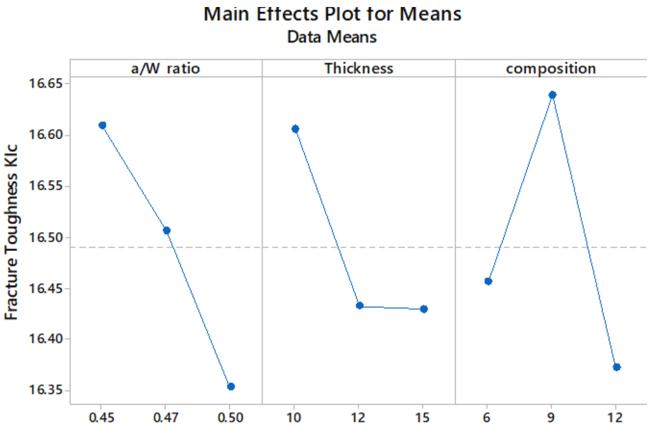

Figure 3b. Taguchi's design results for fracture toughness K_{Ic}.

Based on load carrying capacity and fracture toughness, the optimized composition is considered as Al6061-9 wt.% of graphite. For $a/W = 0.45$, the load carrying capacity and fracture toughness values are maximal in the composite. From the literature it is observed that fracture toughness decreases as specimen thickness increases until it reaches the plane strain condition. Here from 10-12 mm specimen thickness, the fracture toughness decreases and remains constant up to 15 mm thickness. Hence, 12 mm specimen thickness is considered as optimized specimen thickness.

Analysis of variance (ANOVA)

ANOVA is a statistical tool utilised to assess the degree of the individual involvement of process parameters on the responses, for example, load carrying capacity and fracture toughness, and furthermore, it gives accurate arrangement of the process parameters.

From the ANOVA, optimal values of individual process parameters can be found and their attributes. Tables 3a and 3b show outcomes of ANOVA for load carrying capacity and fracture toughness.

Table 3a. ANOVA for load carrying capacity.

Source	DF	Seq SS	Adj MS	F-Value	% confidence level
a/W ratio	2	0.79162	0.39581	1149.13	13.84
thickness	2	4.92336	2.46168	7146.81	86.08
composition	2	0.00362	0.00181	5.26	0.06
error	2	0.00069	0.00034		0.01
total	8	5.71929			100.00

Table 3b. ANOVA for fracture toughness.

Source	DF	Seq SS	Adj MS	F-Value	% confidence level
a/W ratio	2	0.10007	0.05003	0.9	26.01
thickness	2	0.06127	0.03063	0.55	15.92
composition	2	0.21167	0.05583	1	55.01
error	2	0.0118	0.00559		3.07
total	8	0.3848			100.00

From the ANOVA results, it is seen that the factors influencing the load carrying capacity of the composites are *a/W* ratio (13.84 %) and thickness (86.08 %). The ANOVA analysis reveals that specimen thickness will influence more on the load carrying capacity of the composite than the *a/W* ratio of the specimen geometry and the composition of the material. It is obvious that as crack length (*a*) increases, the load carrying capacity decreases.

Also, the factors influencing fracture toughness are the material composition (55.01 %), *a/W* ratio (26.01 %) and specimen thickness (15.92 %). ANOVA analysis reveals that the material composition will influence more on the fracture toughness of the composite than the *a/W* ratio and specimen thickness. Clearly as the increment in the crack length occurs, it decreases the load carrying capacity of the composite material, which in turn reduces the fracture toughness of the material.

The experimentally computed K_q is drawn with respect to different thickness for Al6061-9 % graphite composites. Figure 3b demonstrates the variation of K_q versus thickness for different Al6061-graphite composites. It is seen that the K_q reduces with increment in *B/W* proportions and is found to stay consistent for $B/W \geq 0.4$. This consistent estimation of K_q for $B/W \geq 0.4$ prevails the plane strain fracture toughness (K_{Ic}) of the composite.

CONCLUSIONS

From the outcomes of the study, the following conclusions are made: from the Taguchi analysis on CT specimens, Al6061-9 % graphite is the optimized composition and fracture toughness is maximum for $a/W = 0.45$. Hence Al6061-9 % graphite shall be considered as the optimized composition. Also, 12 mm specimen thickness is considered as optimized specimen thickness. ANOVA analysis reveals that material composition shall influence more the fracture toughness of the composite than *a/W* ratio and specimen thickness. Clearly as the increment in crack length occurs it decreases the load carrying capacity of the composite material which in turn reduces the fracture toughness.

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