An International Journal of Optimization and Control: Theories & Applications
ISSN: 2146-0957eISSN: 2146-5703
Vol.11, No.2, pp.152-157 (2021)
https://doi.org/10.11121/ijocta.01.2021.00990

RESEARCH ARTICLE

Taguchi's method of optimization of fracture toughness parameters of Al-SiC_p composite using compact tension specimens

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ARTICLE INFO

Article history:
Received: 14 June 2020
Accepted: 18 April 2021
Available Online: 20 April 2021

Keywords:
Al-SiC_p
Fracture Toughness
Compact tension specimens
Taguchi's method
ANOVA

AMS Classification 2010:
62J10, 74A45, 62K86

ABSTRACT

The objective of this work is to investigate the process parameters which influence the fracture toughness of aluminum-silicon carbide particulate composite prepared using the stir casting technique. The Taguchi's design of experiments is conducted to analyze the process parameters. Three parameters considered are composition of material, grain size and a/W ratio. From the Taguchi's analysis, on compact tension specimens, aluminum 6061 reinforced with 9 wt% of the silicon carbide particles composite and a/W ratio of 0.45 are considered to be optimized parameters. Taguchi's technique result shows that the increment in the a/W ratio causes decrement in the load carrying capacity of the composite. Whereas the fine grain size of silicon carbide have better toughness values. From the ANOVA outcomes it is clear that the composition and a/W ratio of the geometry has more influence on the fracture toughness than the grain size of reinforcement.

1. Introduction

A common expression for measurement of materials ability to resist the crack propagation is generally referred as fracture toughness. Estimation and examination of fracture toughness has been a serious problem being the growth for the fracture mechanics approach and their applications in engineering. The concept of fracture mechanics [1] consists of some of the significant parameters like stress intensity factor (K), energy release rate (G), the crack-tip opening displacement (CTOD) and the J integral. The resistance to the crack growth is known as fracture toughness which can be determined experimentally using many testing methods. American society for testing and materials (ASTM) [2] proposed many standard testing methods to test the fracture toughness of the metallic materials in E399-17. As per ASTM many standard specimens [3] were utilized for K_{Ic} testing such as compact tension (CT) specimen, single edge notch bend (SENB) specimens etc.

These specimens, now a days, widely used to test the metallic composites such as metal matrix composites (MMCs). These composites have been utilized when it required in the application of weight reduction, wear and corrosion resistance and thermal management. Aluminum as a matrix and silicon carbide, alumina etc as reinforcements are widely used, present day, metal matrix composites [4]. The properties of the particulate type metal matrix composites were influenced by the many factors like particle size, weight/volume fraction, inter particle spacing etc.

To prepare these metal matrix composites, among many methods, stir casting technique is widely utilized. Literature shows that the Al-SiC [5], Al-graphite [6,7] and also aluminum based hybrid [8-10] composites were prepared from the stir casting technique. Mechanical properties of the particulate reinforced with aluminum for varying weight/mass fractions has been carried out using Universal Testing Machine [5,6] (UTM). Fracture toughness [5], Indentation Fracture Toughness [11,12] tensile fracture behaviour on circumferential notched tensile (CNT) specimens [5, 13] and Compact Tension (CT) test [14] specimen and single edge notch bend (SENB) specimen [15] of aluminum alloy with different reinforcements were studied by different researchers.

Also the effect of reinforcement addition on the base metal [16], effect of specimen thickness [17], aging [18] and fatigue crack growth behavior [19] on the fracture toughness using CT specimens has been

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examined. The different fracture toughness testing methods were compared [20] and found that the results obtained from all the testing techniques agree with each other. The researchers also conducted different tensile [21], fracture toughness [5,22,23] investigation using CT specimens on aluminum silicon carbide composites.

Literature review reveals that the mechanical characterization of the aluminum silicon carbide has been studied extensively. In this background, there is a scope for the study of aluminum-silicon carbide particulate composite in the area of fracture mechanics. Through this investigation, an attempt has been made to investigate impact of process parameters on the fracture toughness of the aluminum-silicon carbide particulate (Al-SiC$_p$) composite. The Taguchi's design of experiments and ANOVA are intended to use to analyze the process parameters such as composition of the material, a/W ratio of the geometry and the grain size of the reinforcement.

2. Materials and processing

In the present work aluminum 6061 is used as a matrix and silicon carbide particles are used as reinforcement. A precipitation-hardened aluminium (Al6061) alloy has its main alloying elements as magnesium (0.81 wt%) and silicon (0.70 wt%). Some general chrestersitcs of Al6061 are mentioned in the Table 1.

Table 1. General charecterstics of Al6061

Sl no	Charecterstics	Value
1	Hardness	95 BHN
2	Yield Strength	275MPa
3	Elastic modulus	68.9GPa
4	Tensile Stength	315MPa
5	Elongation	17%
6	Density	2.65g/cc
7	Melting Temp	650^{o}C

Silicon carbide (SiC), a form of carborundum, is a ceramic material. It is a combination of silicon and carbon. SiC is one of exceptional abrasive materials used to manufacture abrasive wheels. Now a days the SiC available is of high quality technical grade ceramic with excellent physical properties. Density = 3.1g/cc, melting point – 2730°C, Appearance –Black in color, Hardness = 45.8 GPa [21] were some of the key properties of silicon carbide.

The aluminum silicon carbide particulate (Al-SiC$_p$) composites demonstrate isotropic properties [5] as well as exceptional combination of structural and physical properties. The particle size of the silicon carbide, among many factors, is the most significant variable considered which will influence the microstructure of the composite. The particle sizes of silicon carbide utilized in this work are 44 µm, 75 µm and 150 µm.

Stir casting method [6-20] is used to cast the Al-SiC$_p$ MMCs at 6, 9 and 12% weight fractions of SiC. The aluminum super heated above its melting point (i.e.720°C) and predetermined quantity of reinforcement particles and degassifiers are added while stirring at speed of 500 rpm [6-10, 24]. The molten Al-SiC is poured to the graphite mold and it is allows for solidification. The block took from the mold were machined to the required size of the specimen.

3. Design of experimentation

Taguchi strategy of optimization is one of the best strategies in view of its straightforwardness to do the design of experiments [24]. The objective of the design of experiments is to determine the significant factors which influence the fracture toughness to optimize the process parameters from which can increase the toughness, minimise the crack initiation and propagation. The procedure given in the Taguchi's design of experiments is to examine the various parameters and their effect on the mean and variance. From the results of the Taguchi's design of experiments, ANOVA (analysis of variance) [25] has been carried out, to optimize the performance behavior, and to choose the new process parameter.

In the current work, optimizing the parameters of the fracture toughness tests is done utilizing the Taguchi's technique. Three factors and three levels for each are considered to analyze their performance behaviour. Factors considered are composition of material, grain size of reinforcement and a/W ratio. Levels considered are composition of materials considered are 6, 9 and 12 wt% of SiC reinforcement, grain size of reinforcement considered are 44µm, 75µm and 150µm and a/W ratio = 0.45, 0.47 and 0.50, and. The Taguchi's L9 orthogonal array has been given in Table 1.

4. Experimentation

The CT specimen's geometry used, as given in the Figure 1, is as per the standard testing procedures for fracture toughness of metallic materials as prescribed by the ASTM. Fracture toughness testing for Al-SiC$_p$ is conducted using the standard universal testing machine (UTM) as per the available testing procedure. Some of the standard specifications are mentioned in the Table 2.

The servo-hydraulic testing machine is used to carry out, in the room temperature, the fracture toughness experiments. The crack length developed, for a/W ratios varied from 0.45 to 0.50, is measured using visual method. By this way the specimens are fatigue pre-cracked under the mode 1 (tensile) loading. Below equation (Eq.1) [3] is utilized to determine the fracture toughness of Al-SiC$_p$ composites using the load at fracture (P_f). The plot of load applied versus crack opening displacement gives the type III curve [2,3,14]. Hence the load at fracture, for type III curve, is itself is critical load (P_Q).

Table 2. Standard specifications of UTM

Sl no	Charecterstics	Value
1	Capacity, Ton	20
2	Test Speed, mm/min	0.01 to 500
3	Test Temperature °C	Room Temp
4	Display	Digital
5	Testing Standard	ASTM E83
6	Accuracy	0.5µm
7	Transmission	Hydraulic
8	Loading frequency	5 Hz
	Calibration standard	
9	Crosshead speed	ASTM E2658
10	Crosshead displacement	ASTM E2309
11	Strain and load rate	ASTM E2309
12	Measurement of tension	ASTM E4

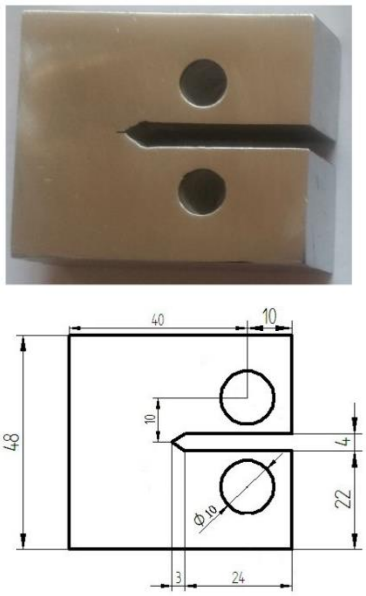

Figure 1. CT Specimen with geometry

$$K_{Ic} = \frac{P_Q}{B\sqrt{W}} f\left(\frac{a}{W}\right) \quad (1)$$

Where f(a/W) is expressed as follows:

$$f\left(\frac{a}{W}\right) = \frac{\left(2+\frac{a}{W}\right)}{\left(1-\frac{a}{W}\right)^{3/2}}\left(0.886+4.64\left(\frac{a}{W}\right)-13.32\left(\frac{a}{W}\right)^2+14.72\left(\frac{a}{W}\right)^3-5.6\left(\frac{a}{W}\right)^4\right) \quad (2)$$

5. Results and discussions

5.1. Experimental results

In the Table 3, the results of the fracture toughness testing as per the Taguchi's design of experiments (DOE) are listed. From the results, it might be uncovered that with an addition in substance of the SiC in Al-SiC composite the increment in the value of fracture toughness. The improvement in the fracture toughness is a direct result of the impact of the additional SiC particulates which goes about as an inward blockade to the internal microstructural cracks. The values in the Table 3 shows, the decrement in the fracture toughness with the increase in the a/W ratio.

Table 3. Taguchi's DOE and fracture toughness of Al-SiC_p composite

Sl no	Composition % of SiCp	a/W ratio	Grain Size µm	Load at Fracture (P_Q) kN	Fracture Toughness MPa√m
1	6	0.45	44	2.260	9.42
2	6	0.47	75	2.013	8.89
3	6	0.50	150	1.786	8.62
4	9	0.45	75	2.367	9.87
5	9	0.47	150	2.114	9.33
6	9	0.50	44	1.839	8.87
7	12	0.45	150	2.148	8.96
8	12	0.47	44	2.084	9.20
9	12	0.50	75	1.725	8.32

From the Table 3 it is seen that as a/W proportion increases there is a decrement in the value of the fracture toughness. Also it is observed that the increment in the fracture toughness for the fine sized grains of the silicon carbide reinforcement. Taguchi's design has been used to analyze the two input functions viz., values of the experimental fracture toughness and the load carrying capacity which were the major input functions. The results of the examination are appeared in Figure 2(a) and (b).

Taguchi's technique result shows that the increment in the a/W proportion causes decrement in composite's load carrying capacity. As the addition in the SiC reinforcement in Al6061 matrix the load carrying capacity increases up to 9 wt% of SiC and reduces for 12 wt% of SiC. Also from Figure 2(a) it is also apparent that as the grain size of the SiC increases, load carrying capacity decreases. It is obvious that the bigger particle size of reinforcement causes weak bonding between the matrix and reinforcement hence reduces its load carrying capacity.

Figure 2(b) shows the performance of Al-SiC_p composite for different process parameters. For the increment in the parameter a/W ratio, there is the reduction in fracture toughness of material. The increment in a/W ratio is nothing but the increase of crack length for the given width, which causes the decrease of load carrying capacity, hence reduces the fracture toughness. The fine grain size of the reinforcement enhances the matrix and reinforcement bonding and acts as the barrier to the crack initiation and propagation which in turn increases the fracture toughness.

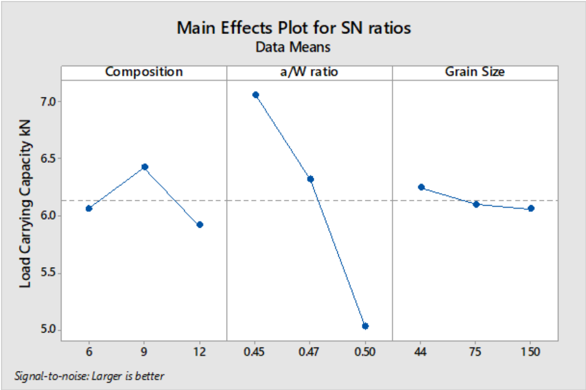

Figure 2(a). Taguchi's design results for load carrying capacity

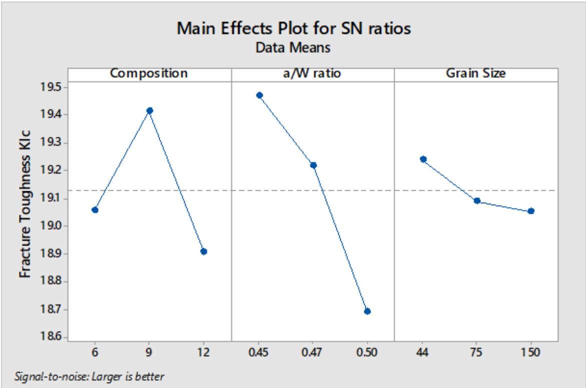

Figure 2(b). Taguchi's design results for fracture toughness

In view of fracture toughness and load carrying capacity the optimized composition is considered as Al6061-9 wt% of SiC, a/W ratio = 0.45 and finer grain size of reinforcement.

5.2. ANOVA (analysis of varience)

Statistical tool utilized to examine the level of individual contribution of the process parameter on the responses is ANOVA. Example: the toughness and load carrying capacity and moreover it gives exact plan of the process parameters. Using ANOVA technique one can analyze and optimize the individual process parameters and their influence on the process. The results of the analysis of the parameters toughness and load carrying capacity are displayed in the Table 4 (a) and (b).

Table 4(a). Analysis of variance for Load carrying capacity

Source	DF	Seq.SS	Adj.MS	P.Value	% contri bution
Composition	2	0.0234	0.011	0.288	6.16
a/W ratio	2	0.3433	0.171	0.027	90.54
Grain Size	2	0.0031	0.001	0.755	0.81
Error	2	0.0094	0.004		2.49
Total	8	0.3792			

Table 4(b). Analysis of variance for Fracture Toughness

Source	DF	Seq.SS	Adj.MS	P.Value	% contri bution
Composition	2	0.447	0.223	0.264	26.43
a/W ratio	2	1.026	0.513	0.136	60.57
Grain Size	2	0.059	0.029	0.731	3.50
Error	2	0.160	0.080		9.50
Total	8	1.694			

From the Table 4(a-b), the it is observed that the P_value for the a/W ratio is 0.027 which is less than the 0.05. Thus the parameter a/W ratio is considered to be statistically significant. It is also true that, as the a/W ratio increases, crack length (a) increases, thus the load carrying capacity of the material decreases. However, for the fracture toughness, the P_value is slightly higher for the a/W ratio, still affect more on the fracture behaviour of the material.

From the Table 4(a), it is observed that the crack length to width (a/W) ratio majorly effect the load carrying capacity by 90.54% whereas grain size and composition of SiC have a little impact. It is obvious that as crack length (a) increases load carrying capacity decreases.

Also, factors influencing fracture toughness is a/W ratio (60.57%) followed by the composition (26.43%) whereas the grain size of the reinforcement has the least influence on the fracture toughness. This might be due to the use of fine grained reinforcement. The bigger size of the particles (i.e. >150µm) may gives comparably lesser fracture toughness values.

6. Conclusion

From the outcomes of the study, the following conclusions are made: The improvement in the fracture toughness is a direct result of the impact of the addition of fine sized SiC particulates which goes about as an inward blockade to the internal microstructural cracks [16]. Taguchi's technique result shows that the increment in the a/W ratio causes decrement in the composite's load carrying capacity [20,24]. It is obvious that the bigger particle size of reinforcement causes weak bonding between matrix and reinforcement hence reduces the load carrying capacity which in turn decreases fracture toughness of the material. The ANOVA analysis reveals that the a/W ratio [25] followed by the material composition will influence more on the fracture toughness than grain size of the SiC.

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