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Taguchi assessment on the effects of heat treatment variable on the hardness and tensile strength of silicon carbide reinforced A357 hybrid composites

The present study aims to develop stir cast A357 composite reinforced with triple particle size silicon carbide and graphite. Using Taguchi's L9 orthogonal array, the influence of heat treatment parameters on mechanical characteristics of A357 reinforced with triple-size silicon carbide and graphite particles was investigated. Tensile strength and hardness were the core mechanical properties investigated for the composites. Taguchi's observational design was used to determine the effect of solutionising temperature, soaking time, ageing temperature, and ageing time on tensile strength and hardness. The homogeneous dispersion of silicon carbide particles in A357 matrix can be observed using an optical microscope. The results showed solutionising temperature has the most favourable effect for both tensile strength and hardness followed by ageing time, soaking time, and ageing temperature.

Keywords: Taguchi assessment, sustaining temperature, reinforcement, composite material, mechanical statistics, systematic examination, signal-to-noise ratios.

1.0 Introduction

Aluminum forms the predominant metal in all aluminum alloys. Familiar alloying elements are zinc, magnesium, silicon, manganese and copper (Elhadari, Patel, Chen and Kasprzak, 2011; Ceschini, Boromei, Morri, Seifeddine and Svensson, 2009). Among the most important alloying elements are copper (Cu) and silicon (Si), but to improve flow, to obtain good casting with reduced porosity, etc. additional elements are added in small quantities. Copper and silicon both play a vital role in modifying the crystal structure, thereby increasing the hardness and tensile strength (Mohamed, Samuel, Samuel and Doty, 2009). The alloying elements are all stronger than pure aluminum, but solution treatment can make them stronger (Tash, Samuel, Mucciardi and Doty, 2007; Swamy, Ramesh and Chandrashekar, 2010). Heating an alloy to an appropriate temperature and maintaining it there long enough for one or more hardening elements to enter a solid solution is known as solution treatment. Temperatures between 400 and 600 degrees celsius are used for heat treatment, subsequently by rapid quenching in cold or hot (water), water polymer solution, spray or forced air cooling. Subsequent heat treatment at lower temperatures ensures controlled precipitation of the constituents, increasing hardness and strength (Sjölander and Seifeddine, 2010; Reddy, Kumar and Raj, 2017). In engineering structures and components, aluminium alloys light weight and corrosion resistance are significant characteristics to consider. Aluminum and its alloys play a vital role in aerospace manufacturing and the automobile industry.

Different types of reinforcements for example, aluminium oxide (Al_2O_3) and silicon carbide (SiC) have been instrumental in various properties of MMCs (Park, Crosky and Hellier, 2001; Naveen, Chethan, Gururaja, Lokesh and Chetan, 2017). Al_2O_3 reinforcement improves compressive strength and wear resistance, while SiC reinforcement improves tensile strength, toughness, density, and wear rate of aluminium alloys (Lakshmikanthan, Bontha, Munishamaiah, Koppad and Ramprabhu, 2019; Agnihotri, 2017). Boron Carbide (B_4C), which has a fracture toughness as well as high elastic modulus, is one of the hardest elements known (Lashgari, Sufizadeh and Emamy, 2010). Addition of boron carbide in the aluminum matrix increases the hardness but does not have a significant effect on the wear resistance. Zircon is the hybrid reinforcement that significantly improves wear resistance. The use of fly ash reinforcements has been significant in the last decade due to their low cost and availability as a by-product in thermal power plants. It was reported that fly ash improves the electromagnetic effect of the Al-MMC significantly (Mahendra and Radhakrishna, 2010; Murthy, Girish, Keshavamurthy, Varol and Koppad, 2017). This paper investigates the behaviour of silicon carbide reinforcement materials on aluminum-based MMCs based on the various advantages of MMCs.

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Table 1: Constituents of A357

Elements	Si	Mg	Fe	Ti	Zn	Ni	Mn	Pb	Cu	Sn	Al
weight%	6.775	0.481	0.16	0.152	0.04	0.03	0.027	0.022	0.02	0.012	Remaining

Suhail, Alam and Rahim, 2015, produced a composite material with balanced Al+4% Cu as matrix phase and 5% SiC with different grit sizes 400, 600, and 800 mesh and observed the mechanical properties with varying pouring temperatures 700, 725, and 750°C. According to the results, increasing the grit size of reinforcing SiC particles increased the mechanical properties such as UTS, BHN, and impact, with the best values achieved at the optimal pouring temperature of 725°C.

Amir Hussain, Gaurang and Vijay Sharma, 2016, found that increasing SiC weight percentage in stir casting and ultrasonic-aided stirring improved the mechanical characteristics of aluminum 5083 with SiC reinforcement. In contrast, for composites, ultrasonic stir casting has proven to be a popular method.

Dinaharan, Moses and Sekhar, 2014, deployed casting (vortex method) to make the aluminium alloy AA6061 reinforced with SiC particles at weight percentages of 0,5,10, and 15. SEM and optical microscopy were used to analyse the microstructures. SiC AMC at 15% had a stronger micro hardness than the AA6061 alloy with no reinforcement, according to the study’s data also, a rise in SiC concentration changed the fracture mode from ductile to brittle.

Sharma, Patnaik and Bhatt, 2011, for dry-sliding wear behaviour of composites, employed SN to analyse the experimental results and identify which process design was best. It was found that the following factors influence wear rate: applied load, sliding velocity, and reinforcing percentage.

Experiment design relies heavily on Taguchi-based systems (Sjölander and Seifeddine, 2010). With Taguchi orthogonal arrays, greater accuracy is achieved with the minimum number of experiments in an optimal range of input parameters. Incorporating the design of experiments into research is achieved with this technique. Statistically, the design of experiments is the most effective method to evaluate the impact of multiple variables, entails a series of steps to follow, and entails several steps in the process (Han, Samuel, Doty, Valtierra and Samuel, 2014; Taguchi, 1993).

The literature reviewed above suggests that reinforcement with varying particle sizes can increase the strength of aluminum alloys. Currently, there is no systematic examination of the impact of heat treatment settings and triple particle size reinforcement for the composites on the mechanical properties. Study examines heat treatment effect and silicon carbide particle size (80, 100, 120 microns) on mechanical characteristics of A357 matrix in this research.

2.0 Materials and methods

In recognition of its industrial importance, the alloy A357 was chosen as the matrix material. A357 base alloy is chemically composed of the elements as shown in Table 1. Reinforcements include silicon carbide with three different particle sizes (80, 100, and 120 microns), as well as graphite.

The A357 composites were fabricated by the permanent mold die casting process. For uniform dispersion of reinforcement particles, preheating, correct stirring speed, and degassing tablets (Hexachoroethane) were employed to overcome the limitation. In a furnace, the A357 ingot was placed within a graphite crucible and melted at 800°C. To remove moisture and residues, silicon carbide and graphite particles were subjected to preheating to 500^{o}C for 2h. To create a vortex, the molten metal was mixed using a stirrer at a speed of 250-300 rpm. Silicon carbide particles are maintained to a total weight percentage of 5%, graphite is kept at 1.5%, grain refiner and modifier (Strontium and Titanium Boron) at 1.5% in all the batches fabricated in the research work. The particles were introduced into the melt with the help of a funnel. Stirring at 300 rpm for 15 minutes ensured that the reinforcement particles were properly dispersed. It was then poured onto a preheated cast iron die and allowed to solidify. The composites with varying Silicon carbide percentages 1.5% 80 microns SiC_p, 1.5% 100 microns SiC_p, and 2% 120 microns SiC_p were fabricated.

An attempt has been made in this study to create hybrid MMCs using Taguchi’s design model and four process parameters i.e. solutionising temperature (500, 520, 540^{o}C), Soaking Time (30, 60, 90 min), ageing temperature (160, 170, 180^{o}C) and ageing time (2, 3, 4 hours) where each parameter has three levels.

Solutionising temperature has three levels, so its degree of freedom will be two. Similarly, the other factors all have two degrees of freedom. The four heat treatment parameters, then, account for eight degrees of freedom. So there is a minimum number of nine experiments. A suitable orthogonal array should be chosen, once the degrees of freedom required have been determined.

The basic rule is that the degrees of freedom should range from greater than or at least adequate to the process parameters. This work utilizes an L9 orthogonal array and requires the use of nine experimental runs by combining levels.

After solutionising at high temperatures, the test specimens were subsequently quenched in water at room temperature. Further, the specimens were artificially aged and authorized for room temperature cooling.

Test specimens were machined in accordance with ASTM E8 standards before being tested on a universal testing machine (Model: TUE-C-1000). At a speed of 0.2 mm per minute, the tests were conducted. Brinell hardness testing was performed according to ASTM E10 standards using a typical Brinell testing machine.

3.0 Result and discussion

The optical micrographs of all nine composites are shown in Fig.1 according to the planned design of experiments. The reinforcing particles are evenly distributed throughout the composites, and the dendritic structure can be seen. The base material has a good bond with the silicon carbide particles, the properties of which are enhanced. Table 2 summarizes the experimental results and signal-to-noise ratios for hardness and tensile strength using L9 orthogonal arrays. In Tables 3 and 4, the ANOVA results show the effect of each parameter at every level on tensile strength and hardness.

Fig.2 shows photographs taken by SEM of hybrid composites at solutionising temperatures of 500^{o}C, 520^{o}C, and 540^{o}C respectively. There are numerous dimples of varying

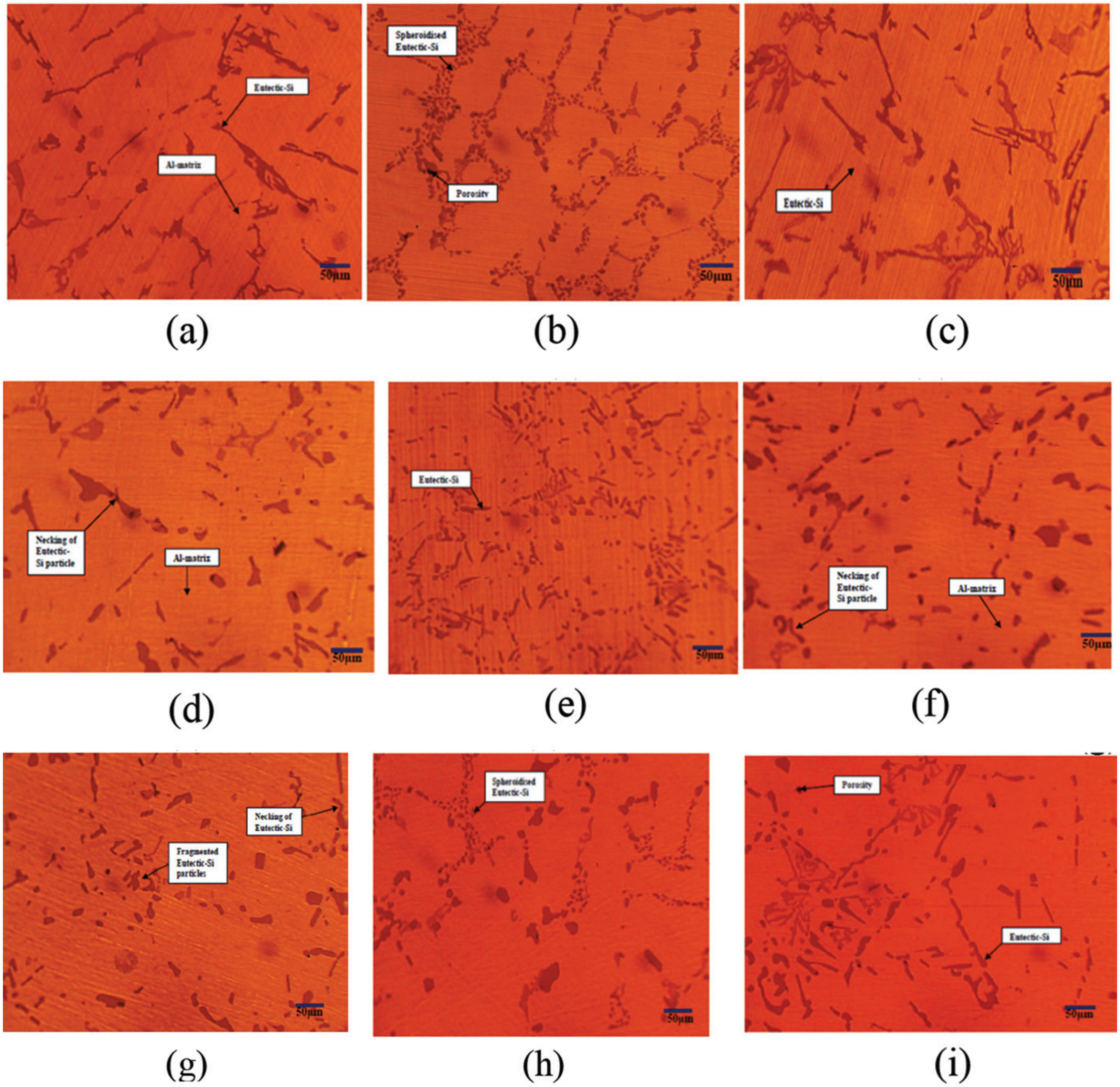
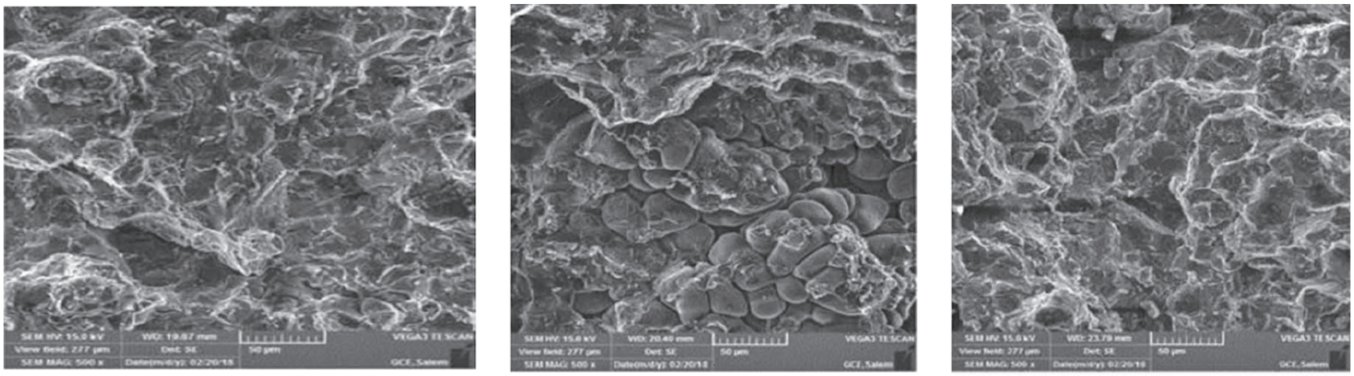


Fig.1: Hybrid metal matrix composites microstructure



(a) (b) (c)

Fig.2: Fractography of tensile specimens at solutionising temperature (a) $500^{o}C$ (b) $520^{o}C$ (c) $540^{o}C$

Table 2: Signal to noise ratios for tensile strength and hardness

Exp. No.	Tensile strength	S/N ratio	Hardness BHN	S/N ratio
1	300	49.524	56	34.938
2	303.54	49.643	57	35.115
3	305	49.660	58	35.266
4	325	50.277	61	35.706
5	304	49.675	59	35.410
6	315.14	49.971	60	35.560
7	330.4	50.380	64	36.126
8	346.21	50.788	66	36.399
9	310	49.822	62	35.848

Table 3: Tensile strength signal-to-noise ratios response

Level	Solutionising temperature	Soaking time	Ageing temperature	Ageing time
1	49.62	50.05	50.10	49.68
2	49.96	50.03	49.90	50.00
3	50.33	49.83	49.91	50.24
Delta	0.71	0.23	0.20	0.56
Rank	1	3	4	2

Table 4: Hardness signal-to-noise ratios response

Level	Solutionising temperature	Soaking time	Ageing temperature	Ageing time
1	35.12	35.60	35.64	35.41
2	35.56	35.64	35.56	35.60
3	36.12	35.56	35.60	35.79
Delta	1.00	0.08	0.08	0.38
Rank	1	3	4	2

sizes, as well as thicker tearing ridges, but no smooth cleavage plane, indicating the ductile fracture phenomenon in the illustrated sample. It suggests that heat treatment can enhance the plasticity of composite materials.

4.0 Conclusions

The following conclusions were drawn by conducting tensile strength and hardness test as per Taguchi's design of experiments on triple particle size silicon carbide reinforced A357 composites.

a. In Taguchi's experimental design, the number of experiments was reduced to nine.

b. Tensile strength is maximized at $540^{o}C$ solutionising temperature, 30 min soaking time, $160^{o}C$ ageing temperature, and 4 hours ageing duration.

c. Hardness is maximized at $540^{o}C$ solutionising temperature, 60 min soaking time, $160^{o}C$ ageing temperature, and 4 hours ageing duration.

d. The order of significant factors affecting A357 composite for both tensile strength and hardness is: solutionising temperature, ageing time, soaking time, and ageing temperature.

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