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Effect of Gas Pressure Infiltration Parameters on Mechanical Properties of AlSi12/SiC Foam Composite: An Experimental Study using Response Surface Methodology

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***Abstract*— This article presents a study on the mechanical properties of AlSi12 aluminium alloy with SiC foam composite. The composite is produced by a Gas pressure infiltration process followed to develop several composites in varying infiltration pressure (2, 4, and 6 bar) and foam porosity (10, 20, and 30). A Central Composite Design of Response Surface Methodology is used to design the experiments. To create the mathematical model for output response. The adequacy of the model for different responses has been verified using analysis of variance. The optimized value can be obtained from the response optimizer by Minitab software. The purpose of this study was to evaluate the effect of the infiltration pressure and Pores per inch on the mechanical properties of the composite. To evaluate the mechanical properties of composites such as hardness, impact, and compression were conducted. Also, the microstructure and elemental composition of the composite were examined using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). The results showed that the mechanical properties of the composite were significantly affected by the infiltration pressure and foam porosity.**

Keywords—AlSi12 aluminium alloy, Silicon carbide foam, gas pressure infiltration.

I. INTRODUCTION

AlSi12 aluminium based silicon carbide ceramic foam composite is a promising material with better properties. The composite is produced by using AlSi12 aluminium alloy as a matrix material and silicon carbide ceramic foam as a reinforcement material. It has applications in aerospace, automotive, and military. Aluminium is impact resistant and lightweight. However, it is not suitable for use in high-impact object applications. Particulate matter, fibres and ceramic foam are used to reinforce the aluminium alloy matrix and improve its impact properties.

At present, aluminium-ceramic foam composites are normally manufactured using different processes like squeeze-casting [1], pressure infiltration and gravity processes. Based on the study by researchers it is observed that the major problems in the preparation of the components include improper infiltration [2], porosity, reinforcement shifts and reinforcement breakage.

Limited studies have been done in the development of Aluminium/Ceramic foam composites. The components produced have exhibited better impact strength and tribological characteristics but reduced ultimate tensile strength. This article presents developing an Aluminium/Ceramic foam composite with better properties for various applications.

The studies investigated the effect of Silicon Carbide foam pore size, volume fraction, and processing parameters on the mechanical properties of Aluminium with Silicon particles and Silicon Carbide foam composites [3,4]. Increasing the pore size of the foam generally decreased the tensile strength but increased the compressive strength of the composite material [5,6]. Increasing the volume fraction of Silicon Carbide foam generally increased the tensile strength, hardness, and wear resistance [7], but decreased the compressive strength of the composite material [8]. Processing parameters such as sintering temperature and holding time were found to have an impact on the mechanical properties of the composite material [9,10]. Other studies also explored the use of different reinforcement materials such as Fly Ash, tungsten carbide, Boron Carbide, cenosphere, red mud, and titanium boron particles [11,12,13], and their effects on the mechanical properties of Aluminium composites [14,15]. These studies provide insights into the potential applications of Aluminium composites with Silicon Carbide foam [16] and other reinforcement materials in various fields such as electronic packaging, impact resistance, friction and wear behavior, and tribological properties [17,18].

The studies discuss various studies on the fabrication, microstructure [19,20], and mechanical properties of composites using Silicon Carbide foam [21,22] and other materials such as aluminium, silicon-based composites, and

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Vol. 15 Issue 10 , October - 2026

fibers [23]. The studies analyze the effects of different factors such as pore size, reinforcement type, foaming agent, squeeze casting, and pressure on the microstructure, strength, and failure modes of the composites [24]. The findings suggest that the properties of the composites are influenced by these factors and can be improved through proper fabrication techniques and material selection. Simulation work using software is also conducted to optimize design parameters for improved performance of the composites [25].

II. MATERIALS AND METHODS

The alloy chosen for this study is AlSi12 aluminium alloy. Silicon carbide foam typically consists of about 85-90% Silicon Carbide ceramic material and 10-15% porosity or pore volume.

A. MATRIX

Matrix was chosen as an AlSi12 Aluminium alloy for this composite. The gas pressure infiltration process is chosen for the fabrication of the composite. AlSi12alloy rods are cut into pieces as per the requirement for die capability.

B. REINFORCEMENT

Silicon carbide foam is a ceramic material. One of its key properties is its porosity. The porosity of silicon carbide foam can be varied to suit specific needs, by changing the PPI, or Pores Per Inch. The PPI rating of foam determines the number of pores present per linear inch of the material. This rating can vary from as low as 10 PPI to as high as 30 PPI, creating distinct variations in the foam's properties. The 10 PPI silicon carbide foam is a relatively dense material with small pores. This foam is used where fine filtration is required and where resistance to flow is a concern. The 20 PPI silicon carbide foam provides a balance between pore size and pore density. The 30 PPI silicon carbide foam features larger pores and lower density than the previous two types.

III. DESIGN OF EXPERIMENT

Using Response surface Methodology, a central composite design of two factors (every 3 levels) is chosen. The samples were cast with a melt temperature as 800 °C under a vacuum time of 1 min and pressure infiltrated for60 min varying the infiltration pressure (2,4 and 6 bars) and foam porosity (10,20 and 30 PPI). Factors and levels of DOE is shown in Table I.

TABLE I. FACTORS AND LEVELS OF DESIGN OF EXPERIMENT

Foam porosity (PPI)	Infiltration Pressure (Bars)	Mean Hardness Hv 05	Mean impact J	Mean Ultimate Compression kN/mm²
10	2	59.33	7.3	0.06
10	4	59.33	7.7	0.11
10	6	53.67	7.3	0.10
20	2	57.67	7	0.09
20	4	60.67	8	0.13
20	6	56.67	7.3	0.08
30	2	55.33	7.7	0.10
30	4	63.33	6.7	0.08
30	6	62.67	6	0.06

IV. MANUFACTURING OF COMPOSITES

The AlSi12/SiC composite is produced by gas pressure infiltration is shown in Fig.1. AlSi12 is melted in a graphite-coated die with preheated silicon carbide foam, and the chamber is purged with argon gas to 2-6 bar. The die serves as both the melting pot and infiltration chamber and is coated with graphite paste for non-sticking. The aluminium volume is calculated using a formula. The molten aluminium is superheated to 800°C, and the chamber is evacuated and purged with argon gas to facilitate infiltration. After solidifying and cooling, the composite is machined.

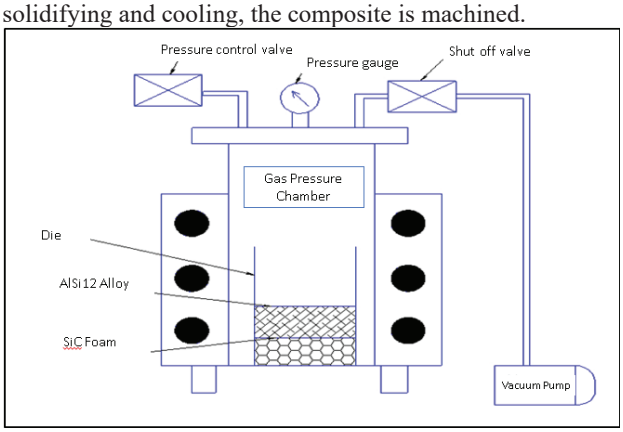

Fig. 1. Schematic diagram of gas pressure infiltration machine

V. RESULTS AND DISCUSSION

A. EDS OF AlSi12/SiC COMPOSITE

Electron dispersive spectroscopy (EDS) is a non-destructive technique used to determine the elemental composition of materials. In this study, EDS was used to analyze the elemental composition and distribution of SiC foam particles within the AlSi12 matrix of AlSi12/SiC foam composites. The EDS results of the composites (Fig. 2, Fig.3 and Fig.4) showed peaks corresponding to Al, Si, C, Fe, Mg, Zn, Ti, Ni, and Mn. The Al and Si peaks were higher than the expected composition, while the peaks for other elements were low.

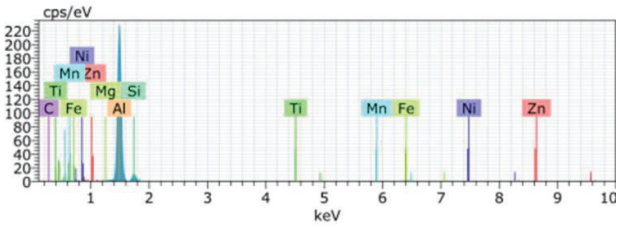

Fig. 2. EDS of AlSi12/SiC foam 10 PPI composite

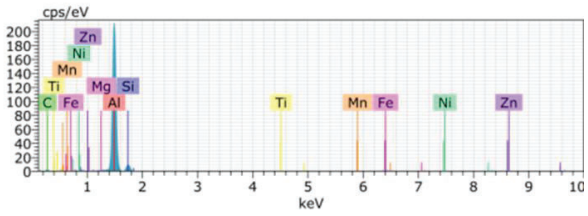

Fig. 3. EDS of AlSi12/SiC foam 20 PPI composite

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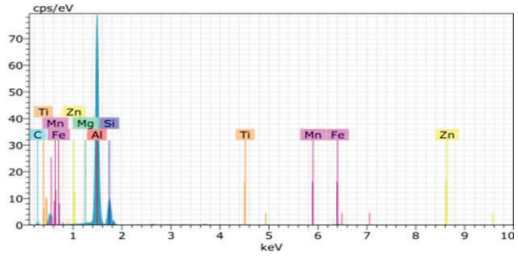

Fig. 4. EDS of AlSi12/SiC foam 30 PPI composite

The EDS results of AlSi12/SiC for 10 PPI, 20 PPI and 30 PPI foam suggest that the composite is predominantly composed of Al 82.64%, 70.63% and 61.65% while C was 5.46 , 6.13% and 19.03% indicating an increase in SIC % as PPI increases.

B. HARDNESS TEST

According to ASTM E 92: 2022 standard, the hardness of the composite is evaluated on a sample by applying a 0.5 KgF force at three distinct locations for 20 seconds at room temperature. Variability of hardness value is shown in Fig.5.

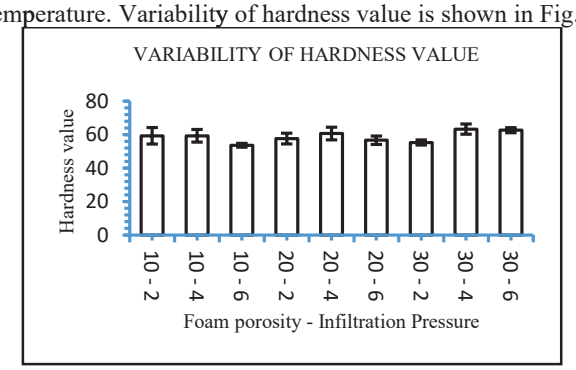

Fig. 5. Graph representation variability of hardness of composite foam

Based on the results obtained, it can be concluded that the addition of silicon carbide foam composite to AlSi12 aluminium matrix material can lead to an increase in the hardness value which is confirmed by the Vickers hardness test. This increase in the hardness value can be the presence of silicon carbide foam can act as a reinforcement and improve the strength and hardness of the composite.

The foam structure of silicon carbide also provides a high surface area for load-bearing, which can contribute to the improved mechanical properties of the composite. Therefore, the results suggest that the addition of silicon carbide foam composite can enhance the mechanical properties of AlSi12 aluminium matrix material.

Similar studies by Eivani et al. [26] and Joe et al. [27] also has reported that the hardness of aluminium foam composites can be increased by increasing the infiltration pressure when the pore size is increased due to the increase in the density of the aluminium matrix material, resulting in an increase in their hardness of the composite.

Hardness of composites is determined by Microstructure of composites of scanning electron microscope. Fig.6 shows improper pressure infiltration due to the low amount of pressure which lead to decreased hardness, Fig.7 shows proper infiltration because of the adequate level of infiltration pressure which lead to increased hardness, and Fig.8 shows the void that happened due to the excessive infiltration pressure which led to decreased hardness because of the void formed.

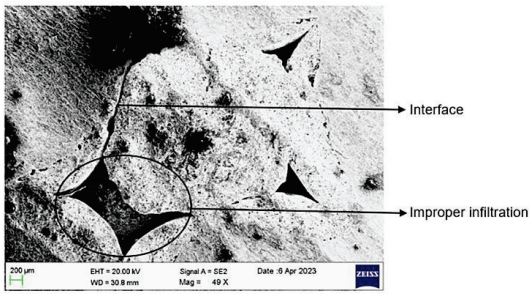

Fig. 6. Microstructure of AlSi12/SiC composite foam $_{10\ PPI\ -\ 2\ bar}$

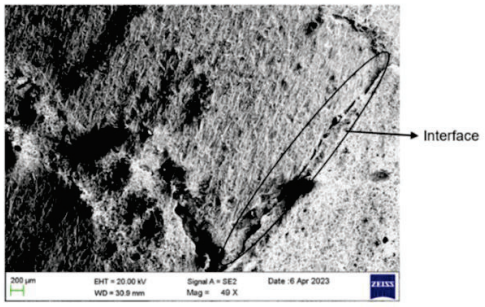

Fig. 7. Microstructure of AlSi12/SiC composite foam $_{10\ PPI\ -\ 4\ bar}$

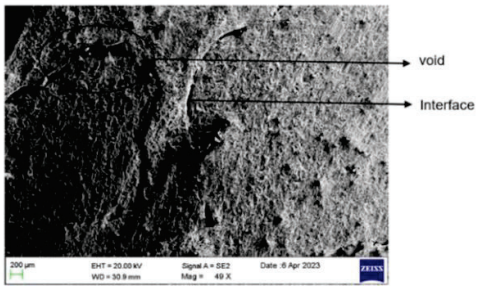

Fig. 8. Microstructure of AlSi12/SiC composite foam $_{10\ PPI\ -\ 6\ bar}$

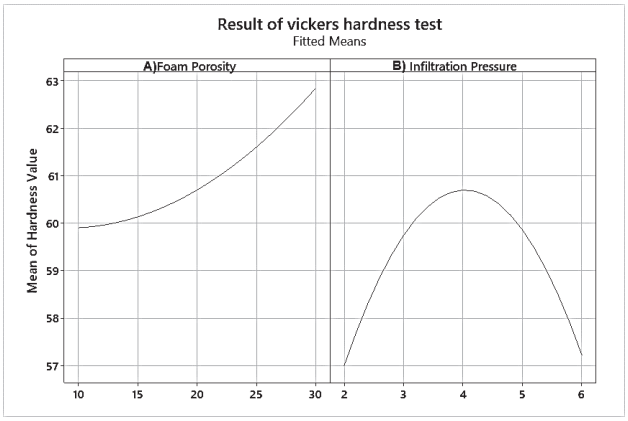

Fig. 9. Main effect plot of hardness of AlSi12/SiC foam composite

a) Effect of foam porosity on the hardness

From the graph of Fig.9, the results concluded the addition of silicon carbide foam composite to AlSi12 aluminium matrix material resulted in a significant gradual increase in the Vickers hardness and an increase in the foam porosity. The composite with 30 pores per inch has a Vickers hardness

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Vol. 15 Issue 10 , October - 2026

of 18 % change in hardness for the composite without pores. As the foam porosity increases, the hardness of the composite increases gradually.

As a result of a higher number of smaller pores, molten aluminium can infiltrate and create a stronger interfacial bond with silicon carbide ceramic foam. Therefore, a higher number of pores can increase the mechanical properties of AlSi12 aluminium composited with silicon carbide ceramic foam. These results could have a significant effect on the development of strong, lightweight materials for a wide range of applications.

b) Effect of infiltration pressure on the hardness

From the graph of Fig.9, the results concluded the Vickers hardness tests conducted on a composite of AlSi12 aluminium and silicon carbide ceramic foam, to conclude that the hardness depend on the infiltration pressure. The composite showed a lower hardness when subjected to 2 bar of pressure, indicating that the molten aluminium had difficulty infiltrating the silicon carbide ceramic foam.

As the infiltration pressure was increased to 4 bar, the composite reached its maximum hardness, indicating that the molten aluminium had successfully infiltrated the silicon carbide ceramic foam, creating a solid interfacial link between the two materials. However, at 6 bar pressure, the composite may have developed voids and other flaws because of the increased pressure, weakening the interfacial bond and so the hardness is decreased indicating that the increased pressure may have caused that defects to develop.

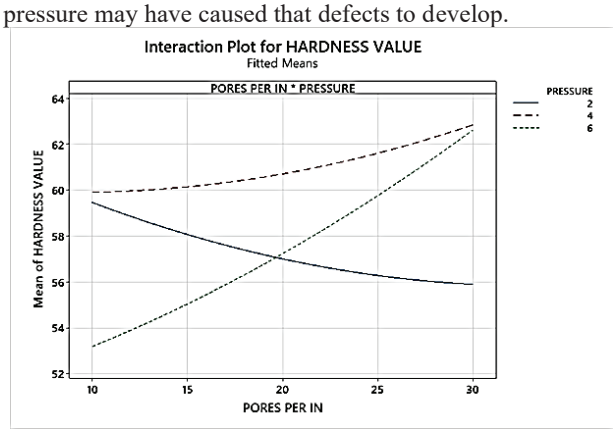

Fig. 10. Interaction plot of hardness of AlSi12/SiC foam composite

c) Effect of interaction plot of hardness of composite

From graph of Fig.10 At an infiltration pressure of 2 to 6 bar at 10 pores per inch, it is observed that the hardness decreases from 10.5 %. The increased size of the pores can be attributed to the decrease in hardness, which may have resulted in a decrease in the material's density and a resulting decrease in its resistance to external forces. The hardness is seen to increase by 7.0 % at 20 pores per inch and an infiltration pressure of 2 to 6 bar. This increase in hardness can be due to the pores reduced size, which may have increased the density of the material and thus improved its resistance to external forces.

The hardness is seen to increase by 13.2 % at 30 pores per inch and an infiltration pressure of 2 to 6 bar. The much smaller pore size and the resulting increase in density and resistance to external pressures are responsible for the material's significant increase in hardness. Also, the graph demonstrates that the material exhibits a higher hardness for each pore per inch at 4 bar pressure. This indicates that a larger infiltration pressure can improve the material's resistance to external forces, which is explained by the material's increased density.

The density and resistance to external pressures of the material can be considerably affected by the size of the pores and the level of infiltration pressure. The study also demonstrates that a higher infiltration pressure can improve a material's resistance to external forces, increasing the hardness of the material.

1) Mathematical model of hardness

A mathematical relation between input parameters and hardness is arrived

Regression equation of hardness of composite:

Hardness value = 58.88 – 0.773 Pores per inch + 3.980 Pressure + 0.00673 Pores per inch^2 - 0.8967 Pressure^2 + 0.1625 Pores per inch × Pressure (1)

Analysis of variance is used to check the fitness of the mathematical model. The value of R2 is 98.18% for the hardness value in the AlSi12/SiC foam composite.

2) Response optimizer for the hardness of composite

From the graph of Fig.11 to achieve the best mechanical properties for the AlSi12 Aluminium Silicon Carbide foam composite, the optimal PPI should be 30 and the optimal infiltration pressure should be 5 bar. This combination of processing conditions is predicted to result in the composite's highest hardness of 63.62.

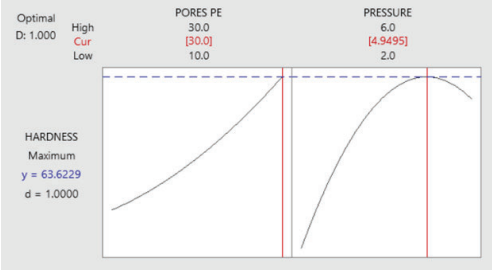

Fig. 11. Optimal solution of hardness value from Minitab software

3) Confirmation test for hardness

The test was conducted to obtain the optimum mechanical properties in terms of hardness for the AlSi12 aluminium silicon carbide foam for 30 PPI foam under 5 bar infiltration pressure and the hardness obtained was 63.33 and is 99% similar to the response optimizer's optimum value.

C. *IMPACT OF COMPOSITE*

The Charpy impact test is a standard method used to determine the impact resistance of a material, including composite materials. In this experiment, a pendulum strikes a small specimen with a notch, and the energy absorbed during the impact is measured. The specimens are prepared as per ASTM standards with a length of 50 mm, width of 10 mm and thickness of 10 mm. According to ISO 146 – 1 2016 standard, the impact of the composite is evaluated.

a) Effect of foam porosity on the impact strength

From the graph of Fig.12 shows steady decreases in impact strength in which adding up to 5% silicon carbide ceramic foam to an AlSi12 matrix increased the Charpy impact strength of the resulting metal matrix composite.

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Vol. 15 Issue 10 , October - 2026

However, increasing the ceramic foam content to 10% reduced the Charpy impact strength by nearly 30%. The reasons for the gradual decrease in impact strength with increasing ceramic foam content in AlSi12 metal matrix composites may include reduced bonding between the ceramic foam and the aluminium matrix, increased porosity, and decreased ductility.

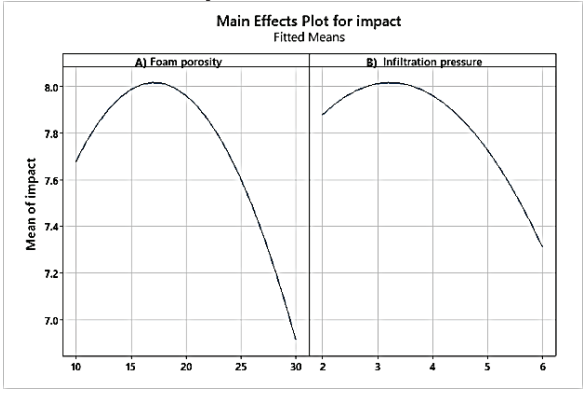

Fig. 12. Main effect plot of Charpy impact of AlSi12/SiC foam composite

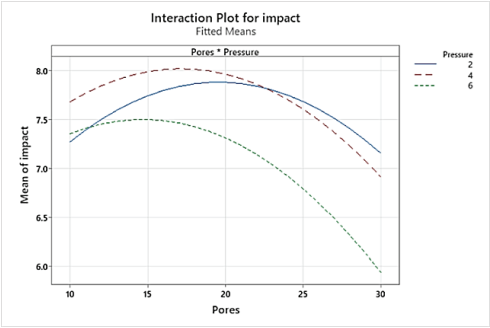

Fig. 13. Interaction plot of Charpy impact of AlSi12/SiC foam composite

b) Effect of infiltration pressure the Impact strength

From the graph of Fig.12 shows a steady decrease in impact strength on increasing pressure in which at low pressures, the material may undergo elastic deformation, where it can absorb energy without permanent deformation. But at high pressures, the material can undergo plastic deformation, which can result in permanent damage and a decrease in impact strength.

c) Effect of interaction plot of impact of composite

From the graph of Fig.13 shows that the amount of energy (in joules) produced by foam under different pressure levels and foam porosity has been measured. The results show that the 10 PPI foam produces 8 joules of energy under all pressure levels, while the 20 PPI foam produces 8 joules of energy under 2 and 4 bar pressures, but only 6 joules under 6 bar pressure. The 30 PPI foam produces 8 joules of energy under 2 bar, but only 6 joules of energy under 4 and 6 bar pressures. The reason for this variation in energy output may be due to the compression of the foam under higher pressure levels. As the foam becomes more compressed, it may not be able to produce enough energy as it would at lower pressures. Additionally, the density of the foam may also play a role in determining its energy output.

Microstructure of AlSi12/SiC foam 20 PPI has large pores and AlSi12/SiC foam 30 PPI has small pores are shown in Fig.14 and Fig.15, the impact of composite in AlSi12/SiC foam 20 PPI is comparatively higher because of the lower silicon carbide particles content in composite than AlSi12/SiC foam 30 PPI.

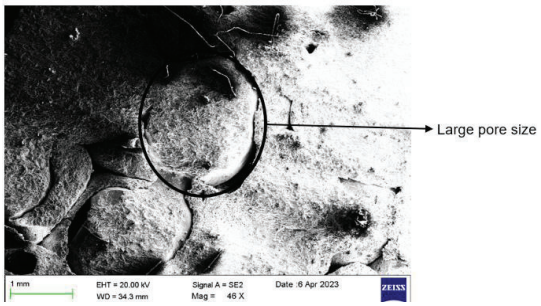

Fig. 14. Microstructure of AlSi12/SiC composite foam 20 PPI

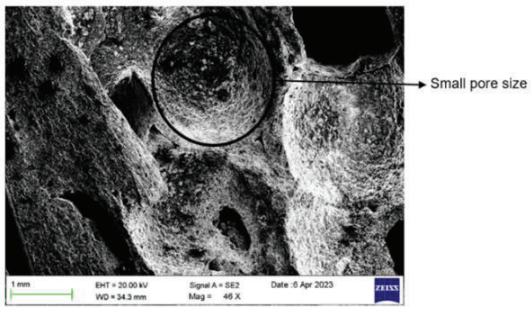

Fig. 15. Microstructure of AlSi12/SiC composite foam 30 PPI

1) Mathematical model of impact strength

A mathematical relation between input parameters and impact strength is arrived. The regression equation of the impact strength of the composite is

Impact strength = 5.561 + 0.1735 Foam porosity + 0.867 Infiltration pressure - 0.003125 Foam porosity2 - 0.0781 Infiltration pressure2 - 0.02500 Foam porosity × Infiltration pressure (2)

Analysis of variance is used to check the fitness of the mathematical model. The value of R2 is 96.65% for the impact strength in the AlSi12/SiC foam composite, impact strength.

2) Response optimizer for impact strength of composite

From the graph of Fig.16 to achieve the best mechanical properties for the AlSi12 Aluminium Silicon Carbide foam composite, the optimal PPI should be 10 and the optimal infiltration pressure should be 3 bar. This combination of processing conditions is predicted to result in the composite's highest impact strength of 8.0446

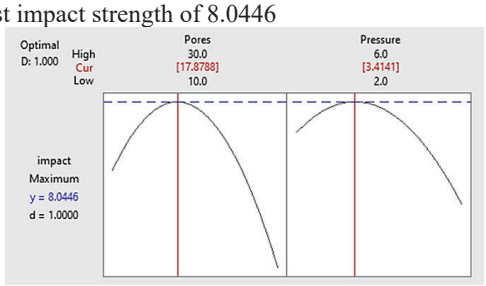

Fig. 16. Optimal value of impact strength for composite

3) Confirmation Test for impact strength

The test was conducted to obtain the optimum mechanical properties in terms of impact strength for the AlSi12

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aluminium silicon carbide foam for 10 PPI foam under 3 bar infiltration pressure and the result was obtained 8.0 and 99% similar to the response optimizer's optimum value.

D. COMPRESSION TEST OF COMPOSITE

The compression test on AlSi12/Silicon carbide foam composite is conducted by applying a compressive load to the specimen until it deforms or fractures along axial load, at which point the force and displacement during the test are measured. The specimens are prepared as per ASTM standards with cylinders that are 12.7mm in diameter and 25.4mm long. The compression strength of the composite is evaluated.

a) Effect of foam porosity on the compressive strength

From the graph of Fig.17 shows an increase in foam porosity from 10 PPI to 30 PPI to steady decreases in compressive strength where pores of silicon carbide foam increase with the increase in Silicon carbide material content in the AlSi12/SiC foam composite. As a result, the amount of aluminium material available to bear the compressive load decreases, resulting in a decrease in compressive strength.

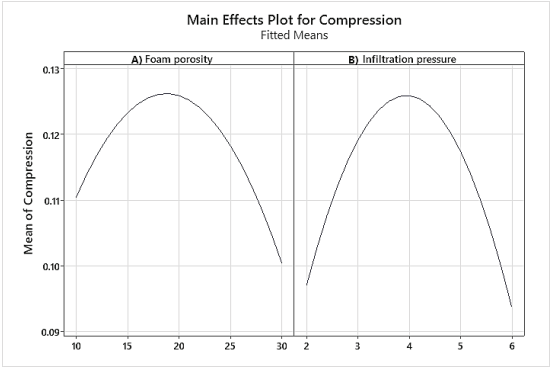

Fig. 17. Main effect plot of compression strength of composite

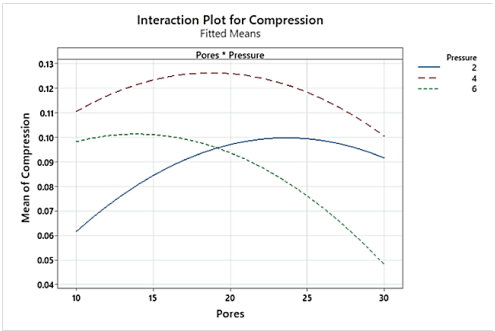

Fig. 18. Interaction plot of compression strength of composite

b) Effect of infiltration pressure on the compressive strength

From the graph of Fig.17 shows it exhibit non-linear behaviour. Compressive load values initially increase as density and pressure increase, but then begin to decrease at higher pressures. This behaviour can be attributed to structural changes in the foam as pressure increases. The presence of large void spaces, which can deform and absorb the load, allows the foam structure to withstand the load at low pressures. At higher pressures, however, the void spaces begin to collapse, reducing the foam's ability to absorb the load.

c) Effect of Interaction plot of compression strength of composite

From Fig.18, the graph shows that the amount of compressive strength produced by foams under different pressure levels has been measured. The results show that steady increase in the compressive strength of composite with increased foam porosity from 10 PPI to 30 PPI at 2 bar pressure in which lower pressure, the foam structure is not as compressed, and the additional pores provide more support to the structure. This can result in an increase in overall strength.

At 4 bar pressure is relatively higher compression strength at 10 PPI to 30 PPI were AlSi12 aluminium matrix is strongly bonded with silicon carbide particles due to equal weight ratio of aluminium – silicon carbide particles and at 6 bar pressure, an increase in foam porosity is likely to decrease compressive strength. At higher pressures, the foam structure is more compressed, and the additional pores can cause weakness in the structure. This can lead to a decrease in overall strength.

1) Mathematical model of compressive strength of composite

The regression equation predicts the value of compression strength. A mathematical relation between input parameters and compression strength is arrived. The regression equation of the compression strength of the composite is

Compression strength = - 0.06439 + 0.007595 foam porosity + 0.04812 Infiltration Pressure - 0.000075 foam porosity2 - 0.002500 Infiltration Pressure2 - 0.001375 foam porosity × Infiltration Pressure (3)

Analysis of variance is used to check the fitness of the mathematical model. The value of R2 is 98.84% for the compression strength in the AlSi12/SiC foam composite.

2) Response optimizer for compression strength of composite

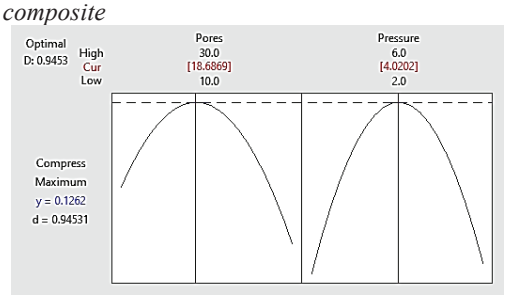

Fig. 19. Optimal value of compression strength for composite

From the graph of Fig.19 to achieve the best mechanical properties for the AlSi12 Aluminium Silicon Carbide foam composite, the optimal PPI should be 20 and the optimal infiltration pressure should be 4 bar. This combination of processing conditions is predicted to result in the composite's highest compressive strength of 0.1262.

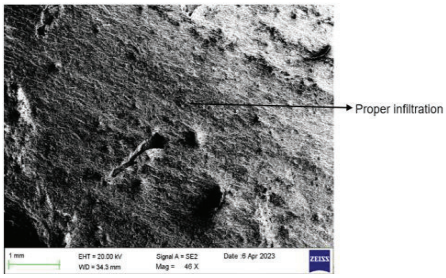

Fig. 20. Microstructure of AlSi12/SiC composite foam $_{20\ PPI\ -\ 4\ bar}$

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20PPI silicon carbide foam which infiltrated under 4 bar pressure gives the optimum hardness, impact, and compression value is shown in Fig.30. It has adequate silicon carbide content and optimum foam porosity and is infiltrated at an optimum pressure level.

3) Confirmation Test for compression strength

The test was conducted to obtain the optimum mechanical properties in terms of compressive strength for the AlSi12 aluminium silicon carbide foam for 10PPI foam porosity under 7 bar infiltration pressure and the result was 0.13 and 97% similar to the response optimizer's optimum value.

CONCLUSION

The following conclusions have been obtained from the results:

1.Increasing the silicon carbide content in the AlSi12/SiC foam composite results in a significant increase in hardness attributed to the strong interfacial bond between silicon carbide particles and the aluminium matrix.

2.Impact and compression of the composite decreased with an increase in the silicon carbide content, but a mathematical model of regression and response optimizer allowed for optimization of maximum impact and compression by varying foam porosity and infiltration pressure.

3.Elemental composition of the composite was analyzed by EDS, and the results showed variation in composition with changes in foam porosity.

4.Scanning electron microscopy showed good distribution of silicon carbide particles in the AlSi12 aluminium matrix.

5. Fo porosity and infiltration pressure were identified as the most key factors affecting the mechanical properties of the AlSi12/SiC foam composite, and response optimizer was used to obtain optimized results for hardness, impact, and compression at various conditions.

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