BİTLİS EREN ÜNİVERSİTESİ
FEN BİLİMLERİ DERGİSİ

ISSN: 2147-3129 / e-ISSN: 2147-3188

Article Type : Research Article		**Year**	: 2025
Received : August 26, 2025		**Volume**	: 14
Revised : October 13, 2025		**Issue**	: 4
Accepted : November 7, 2025		**Pages**	: 2639-2663
DOI : 10.17798/bitlisfen.1772701			

THE EFFECT OF POROSITY RATIO ON BONDING STRENGTH IN ADHESIVELY BONDED COMPOSITE ALUMINIUM FOAMS

Anıl ŞAHİN [1,*], Nilhan ÜRKMEZ TAŞKIN [2], Vedat Taşkın [2]

[1] *Trakya University, Vocational College of Technical Sciences, Aircraft Technology, Edirne, Türkiye*

[2] *Trakya University, Department of Mechanical Engineering, Edirne, Türkiye*

*** Corresponding Author:** *anilsahin@trakya.edu.tr*

ABSTRACT

Metal foams are lightweight materials with unique physical and mechanical properties, including high specific strength, stiffness, and energy absorption capacity. These materials are becoming increasingly popular because they can be used in a variety of applications, including crash boxes in the automotive industry, chassis pillars, and structural elements in the aerospace industry, artificial bone and implants in the biomedical industry, and structural elements in the ship and construction industries. Metal foams could be made up of aluminium, titanium, nickel, and several other materials. Ultimately, what kind of material the metal foam should be made up of depends on the field of application. Nowadays aluminium composite foam materials are being used more frequently. This is due to its low density. It is also resistant to corrosion and a low melting point. In this study, the effect of surface porosity ratios of aluminium composite foam material on adhesive bond strength has been examined. The surface porosity ratios of aluminium composite foam materials were examined, and the specimens were divided into five groups based on their surface porosity ratios: those less than 40%, those between 40% and 50%, those between 50% and 60%, those between 60% and 70%, and those greater than 70%. Aluminium composite foam materials with various surface porosity ratios were assembled using the single lap joint method with aluminium blocks by using epoxy adhesive. The bonding strength was then evaluated under a compressive shear load using a modified procedure based on ASTM D905-08. The results indicate that aluminium composite foams with a surface porosity ratio between 40% and 50% tend to exhibit relatively higher adhesive strength compared to other porosity ranges. Aluminium composite foams with a surface porosity ratio exceeding 60% tend to exhibit lower adhesion strength compared to those with lower porosity ratios.

Keywords: Aluminium composite foams, Bonding strength, Adhesively bonded, Surface porosity ratio, Epoxy-based adhesive.

1 INTRODUCTION

Humans have sought solutions to their issues from the very beginning of existence by utilizing diverse structures and materials available in nature. Today's engineering issues are primarily solved by being inspired by the structures and materials found in nature. For instance, the great energy absorption capacity, rigidity, and low specific gravity of the porous structure found in bones, trees, and corals are particularly remarkable [1-4]. Metal foam materials have been developed for engineering applications, taking inspiration from these forms of nature.

Metal foams are lightweight materials with unique physical and mechanical properties, including high specific strength, stiffness, and energy absorption capacity [5]. Metal foams could be used in a variety of applications, ranging from mechanical to thermal ones, due to their superior strength /weight ratios [6].

Beneficial physical and mechanical properties are combined in metal foams, such as high toughness and a very low specific gravity, or high gas permeability and a high thermal conductivity. The unique combination of properties is the main potential of cellular metals. For a single requirement, other materials often provide better solutions. However, when several properties are needed at the same time, such as sound absorption and thermal stability, metal foams show clear advantages [7].

One of the unique advantages of foams is that their mechanical properties can be controlled by adjusting pore size, density, geometry, and material. Foam structures exist in different types, including open-cell foams (allowing matter to pass through interconnected pores), partially open foams, and closed-cell foams (with isolated pores filled with gas) [8]. Metal foams are produced through various methods, including melt foaming and powder metallurgy techniques [9]. The mechanical properties of metal foams and other cellular metal structures are directly related to the properties of the matrix material. The mechanical properties mostly depend on density, although the strength of the cell structure, cell roundness, diameter distribution, and fraction of solid contained in cell meshes, edges, and cell surfaces all influence quality [5, 6]. These materials retain beneficial properties of their base metals while offering improved characteristics like thermal insulation and recyclability [10].

These materials are becoming increasingly popular because they can be used in a variety of applications, including crash boxes in the automotive industry, chassis pillars, and structural elements in the aerospace industry, artificial bone and implants in the biomedical industry, and structural elements in the ship and construction industries. Metal foams could be made up of aluminium, titanium, nickel, and several other materials. Ultimately, what kind of material the metal foam should be made up of depends on the field of application [1, 6].

Aluminium foam is the most commonly used metallic foam nowadays. This is due to its low density. It is also resistant to corrosion and a low melting point. [11]. Aluminium composite foams are advanced materials made by incorporating reinforcing particles (such as ceramics, fly ash, or hollow spheres) or layers (like steel or polymers) into an aluminium foam matrix. This structure results in a material that is both lightweight and strong, with a cellular (porous) architecture that provides unique mechanical and functional properties. These foams can be produced using various methods, including stir casting, pressure infiltration, and additive manufacturing, and may be further enhanced by combining with other materials to form sandwich or hybrid composites [12-18].

Replacing costly honeycomb structures with foamed aluminium sheets or metal foam sandwich panels in aerospace applications may result in improved performance at a lower cost. The other most important advantage is the isotropy of the properties of such metal foam panels. It can also help maintain the integrity of the main structure during a fire [1, 19]. Aluminium composite foams can be applied in the automotive industry [20], construction [21], defense and safety sectors [15, 16, 22], industrial machinery production [23], and electromagnetic shielding.

Without secondary processing techniques such as forming, surface finishing, or bonding, a new material cannot be used industrially. Mass production of components is impossible until proper bonding technologies are developed, and if metal foams are to be utilized for engineering structures, methods of bonding them to other materials must be developed [24-26].

As cellular metals have a similar structure to wood, the same bonding and bolting techniques used for wooden components can also be used to join cellular metals. Welding and brazing, commonly used for joining metal parts, can also be applied to the assembly of cellular metals. When joining metal foams with mechanical fasteners, the bonding strength is primarily depending on the density and pore size of the foam, strength increases as the foam has a solid surface layer [6, 24, 25].

Bonding has been identified as an appropriate joining technology for aluminium foams [27]. Metallic foams could be bonded with any adhesive recommended for bonding cell wall metals. Aluminium foams could also be bonded with any type of adhesive used to bond aluminium. Joins could be made quickly, easily, and flexibly. One of the primary benefits of bonding with adhesive is the efficient transfer of applied forces. The strength of this type of bonding is generally higher than the strength of the basic foam structure. Even common epoxy adhesives create bonds that are stronger than most foams. Adhesive bonding is an economical and mechanically effective method, provided the other design requirements are met. Adhesive bonding is recommended for the preparation of permanent joints due to its simplicity and flexibility [6, 24-26]. However, the use of adhesive may be impossible in some metal foam bonding applications. The use of adhesives in the joints used to integration metal foams into heat exchangers, for example, results in an undesirable high thermal resistance [28].

Adhesively bonded aluminium foam composites exhibit high bending stiffness, strength, and excellent damping properties, making them suitable for automotive and structural applications [29-31]. The addition of fiber reinforcements (e.g., glass or carbon fiber) and optimized adhesive selection (such as methacrylate or epoxy) further improves mechanical performance and damage tolerance [29, 30, 32].

Metal foam components must be joined to other parts, and adhesive bonding is a suitable method. In high-density foams, failure occurs in the adhesive layer, while in low-density foams it usually occurs within the foam. Bond strength increases with density. At low densities, adhesive joints are stronger than screwed joints, whereas at high densities their performance is comparable [33].

Metal foams can be joined using adhesives applied to the base metals, and the adhesive joints are often stronger than the foam itself. However, disadvantages include low thermal stability, mismatch in thermal expansion, and the formation of thermal or electrical insulation barriers. If these factors are not critical for design, epoxy-based adhesives provide a simple and effective solution. A common example is the bonding of face sheets to foam cores in sandwich panels [6].

Olurin et al. (2000) investigated various joining techniques under monotonic and cyclic tension–compression loads, modeling the effects of fastener geometry on damage behavior. Four types of mechanical fasteners—wood screws, nails, threaded inserts, and studs—were evaluated, either applied directly to the foam or inserted into pre-drilled holes reinforced with epoxy. The findings showed that epoxy-reinforced joints were consistently stronger than the foam itself, with failures occurring away from the joint. Cyclic loading reduced maximum load capacity to as low as 35% of the static value, yet epoxy joints maintained superior performance under all conditions. The study concluded that foams can be joined by adhesives, mechanical fasteners, or welding, and that adhesives are both economical and mechanically effective when compatible with design requirements. Overall, properly selected joining methods provide sufficient strength, while poor designs may fail under relatively low loads.

Adhesive bonding is a suitable joining technique for metal foams, independent of the presence of a solid surface such as a coating or face sheet. When no solid surface is available, the bonding area in contact with the surface is reduced. However, the viscosity of the adhesive is low enough to penetration the pores. The loss of surface area can be compensated by an additional form-fit mechanism [24].

Chung et al. (2008) applied nitrogen plasma treatment to enhance the adhesion strength between aluminium foam and aluminium sheets. Three specimen types were prepared: foam/aluminium, foam/plasma-treated aluminium, and plasma-treated foam/aluminium. Al 5052 sheets (1 and 5 mm) and aluminium foam (5 mm, 0.4–0.5 g/cm³) were bonded with epoxy using a secondary joining process. Bending and shear tests were conducted, with shear tests following ASTM D906-95. Plasma treatment of aluminium sheets increased bending strength by 13% and shear strength by 30%. In contrast, plasma treatment of the foam did not improve strength but increased sheet hydrophilicity by forming functional groups. The improved adhesion of sheet interfaces was attributed to stronger bonding due to this hydrophilicity. The study concluded that plasma treatment is more effective on aluminium sheets than on foams, and that cell size must be considered when assessing the mechanical behavior of foams.

In joining metallic foams, both material properties and joint weight must be considered. Methods such as screws, bolts, rivets, welding, and brazing increase joint mass. Adhesive bonding, by contrast, enables weight optimization due to low density and easy processing. Epoxy adhesives are most common, offering high adhesion and strength. However, determining the required amount of adhesive remains a challenge. Joint strength is related to stiffness, and the thinnest possible adhesive layer is preferred. In addition, wetting the pore edges with adhesive, rather than applying only to the surface, is recommended [35].

Timari et al. (2018) examined the use of aluminium foam as a supporting element in motorcycle frames. Tensile and three-point bending tests were conducted on bonded specimens. Al 6061 foam with a density of 0.6 g/cm³ and two adhesives (Loctite 9466 and Terokal 5055) were used. Different joint profiles were tested, and a maximum tensile strength of 8.87 MPa was achieved. Since fracture occurred outside the bonding surface, the adhesive joints proved stronger than the foam itself. The authors noted that the main challenge is wider market adoption, requiring further testing and cheaper joining solutions. They suggested repeating the experiments with lower-cost adhesives for more economical applications.

Yan et al. (2018) investigated the effect of epoxy resin fluidity on the mechanical properties of aluminium foam sandwiches. Resin fluidity was modified by adding different amounts of alcohol and acetone. Single-lap shear tests showed that these additives increased resin fluidity but reduced bonding strength. Three-point bending tests revealed that higher fluidity decreased strength but enhanced energy absorption. The authors emphasized that higher shear strength requires full resin penetration into the foam cells to enable a locking mechanism.

Nowacki and Sajek (2019) compared welding, brazing, and adhesive bonding in AlSi-SiC composite foams with 75–85% porosity. Tensile tests showed that arc welding caused thermal deformation of thin cell walls, leading to foam collapse. Brazing was hindered by the porous surface, but was suitable for high-temperature applications. Adhesive bonding provided minimal filler penetration, low thermal effects, and high tensile–compressive strength, making it the most favorable method. However, due to temperature limits, adhesives are recommended mainly for lightweight structures below 100 °C.

The adhesive bonding strength is affected by the size and number of pores on the surface of aluminium composite foams. Adhesive applied to the aluminium composite foam surface flows into these pores and increases the strength of the adhesion bond in accordance with the mechanical interlocking theory. However, in some low-viscosity adhesives, the adhesive filled into the pores either does not cure or cures too slowly, reducing bonding strength.

Investigating the usability of aluminium composite foams with adhesive joints and determining the usage limits of these connections are both highly attractive scientific topics. Within this scope, examining the influence of surface pore ratio on the bonding behavior of aluminium composite foams in adhesive joints is considered essential.

In this study, aluminium composite foams with varying surface porosity ratios were bonded to aluminium blocks using the single lap joint method and an epoxy adhesive. The joint strength was evaluated under compressive shear loading using a modified procedure based on ASTM D905-08. The tests revealed the influence of surface porosity ratio on both joint strength and failure modes. This research contributes to a better understanding of the applicability of aluminium composite foams in various industrial applications.

In the literature, there are only a limited number of studies that investigate the adhesive bond strength of aluminum composite foams and determine their surface porosity ratios.

However, no study has specifically examined the effect of surface porosity ratio on adhesive bond strength. The key distinction of the present study from previous research is its focus on evaluating how the surface porosity ratio of bonded surfaces in aluminum composite foams influences their adhesive bond strength.

2 MATERIAL AND METHOD

2.1 Properties of Material

In the adhesive joints, aluminium composite foams are bonded to solid aluminium blocks to evaluate their joint performance. The aluminium composite foam materials used in the experiments were produced directly using the semi-solid stirring method [39]. AlMg3 (EN AW 5754) aluminium alloy as matrix material, SiCp powders as reinforcement material, and TiH_2 powders as foaming agent were used for metal foam production (Table 1).

The surface morphology of all specimens used in the analyses was imaged using a Samsung S9+ smartphone camera, positioned at a fixed working distance of 10 cm and aligned perpendicularly (90°) to the specimen surface. Image capture was performed under automatic exposure and focus settings. The porosity of the surfaces to which the aluminium composite foams would be bonded was determined using the ImageJ image processing program [40]. According to the measured surface porosity, the specimen surfaces of the aluminum composite foams were categorized into five distinct groups, each labeled with a surface porosity ratio (SPR) code: below 40% (SPR40), 40-50% (SPR40-50), 50-60% (SPR50-60), 60-70% (SPR60-70), and above 70% (SPR70).

Table 1. Mechanical properties of aluminium composite foam [39].

Material	Compressive Strength (MPa)	Shear Modulus (MPa)	Density (g/cm^3)
EN AW 5754/SiCp (vol.%20) Foam	25-30	5-7	0.5

Aluminium alloy AlMg1Si0.8CuMn (EN AW 6013) was used as the block material for the experiments' metal foam bonding. The mechanical properties of 6013 aluminium alloy are given in Table 2.

Table 2. Mechanical properties of AlMg1Si0.8CuMn (EN AW 6013) [40].

Mechanical properties	Value
Yield Strength	250 MPa
Tensile Strength	330 MPa

2.2 Adhesive Selection

The experiments conducted as part of this study used Akfix brand E340 type general fast epoxy adhesive (Product code: EA012, Akkim Yapı Kimyasalları industry and Trade inc., Istanbul/Türkiye). It is a two-component (resin and hardener), epoxy-based adhesive that can be mixed and then cured at room temperature. At 23 °C, the full cure takes around 24 hours and has fine gap-filling ability. Table 3 contains the product details provided by the manufacturer.

Table 3. Akfix E340 product feature.

TECHNICAL DATA			
Product Information			
Feature	E340 Resin	E340 Hardener	Mixture
Color	Transparent	Pale yellow	Pale yellow
Density@25 °C(gr/cm^3)	1,16	1,13	1,15
Viscosity@25 °C (cps)	12.000-13.000	10.000-11.000	
Set Time@23 °C(min.)	-	-	4-5
Mix Ratio			
Component	By weight		By volume
Resin	-		1
Hardener	-		1
VOC Content (%)	0 (by weight) (Resin and Hardener)		
Application Temperature (°C)	5– 25		
Full Cure Time@23 °C (hr.)	24		
Service Temperature (°C)	-23 to +60		
Hardness Shore D	80±2 (after 7 days)		

2.3 Preparation of Specimens

Specimens with dimensions (10x12.5 mm) (Figure 1) were taken out to determine the strength of adhesive bonds in accordance with the modified ASTM D905-08 standard [41].

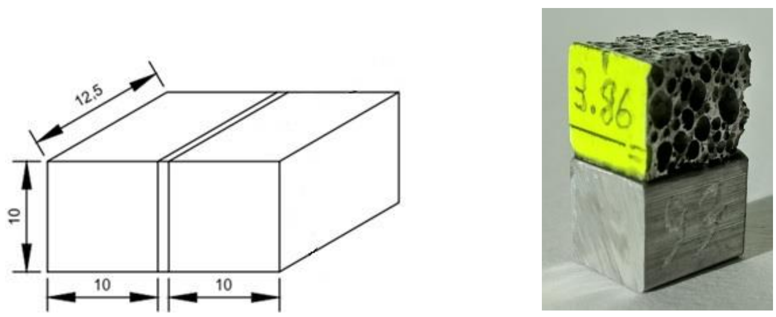


Figure 1. The dimensions of the bonded surfaces and the specimen (dimensions in mm).

The specimen surfaces were cleaned with acetone (industrial grade and 99.9% purity) prior to the adhesive process to remove mold-release oil, metal chips, and coolant liquid. In order to improve the adhesion strength, the surfaces of aluminium specimens were roughened with silicon carbide sandpaper with the P400 number, as stated in the adhesive technical catalog. An acetone bath has been used to clean the metal and sandpaper particles that formed on the surfaces during the roughening process. Before bonding, the bonding surfaces of aluminium and aluminium composite foam specimens were cleaned with Loctite brand SF 7063 cleanser to get rid of contaminants (dust, moisture, oil from hands, sweat, etc.) that could weaken the adhesive. All of the prepared specimens were bonded in an indoor environment at a temperature range of 22–24 °C. The adhesive was applied to the surfaces within a maximum of three minutes after the resin and hardener were thoroughly mixed. Care was taken to ensure that the surfaces were fully wetted. After the adhesive is applied on the surfaces, the surfaces are combined pressing. A uniform adhesive thickness (0.05–0.1 mm) was maintained across all sample surfaces, and an identical bonding procedure was followed for all specimens.

In order for the adhesive to dry and reach its maximum strength, all adhered specimens were cured for 24 hours at 22 °C (ambient temperature) in accordance with the adhesive technical catalog.

2.4 Shear Tests

A specially developed and manufactured shear test apparatus constructed of surface-hardened steel material was used to conduct shear tests in accordance with the modified ASTM D905-08 standard (Figure 2b). Stable Micro Systems Texture Analyser (Model: Ta.Hd.plus, Stable Micro Systems, Godalming/United Kingdom) test equipment was used for the testing (Figure 2a).

All studies were conducted at an ambient temperature of 23°C and cross-head speed of 1.8 mm/min. Cutting force (N), displacement (mm), and test time (s) measurements were obtained from the device during the shear tests. Shear strength was calculated as the ratio of the applied force to the bonding area. Owing to slight dimensional deviations among specimens caused by the cutting process, the actual bonded surface area was measured individually for each sample to ensure accurate determination of maximum shear strength.

a) b)

Figure 2. Compressive shear test; a) test equipment, b) a specially developed and manufactured shear test apparatus.

Table 4. Shear strength results obtained from compressive shear tests conducted according to the modified ASTM D905-08 standard.

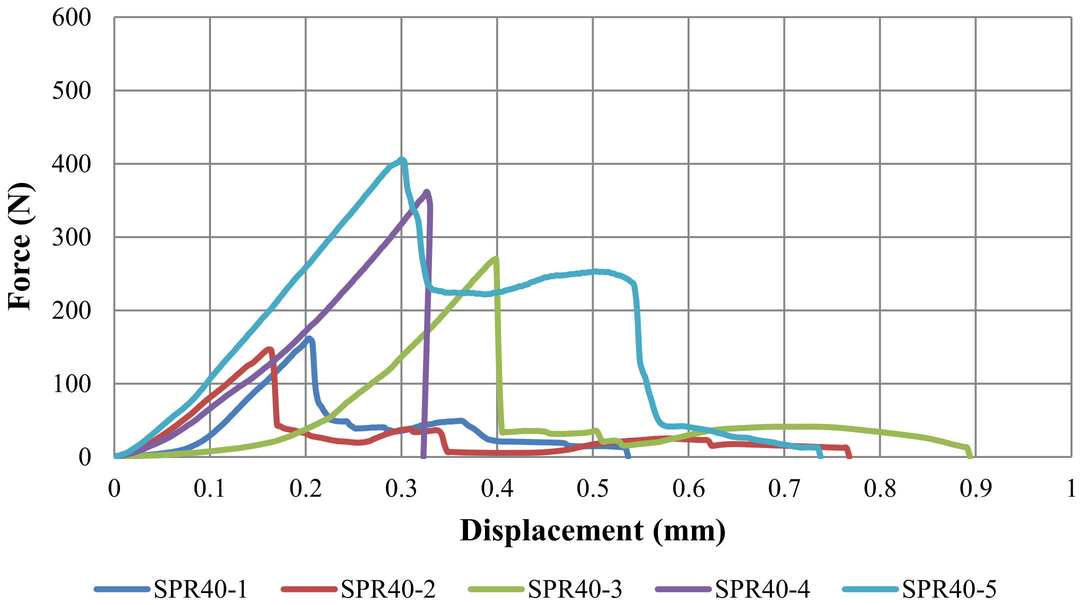
Experiment Number	Surface Porosity Ratio (%)	Bonding Surface Area (mm^2)	Maximum Shear Load (N)	Shear Strength (MPa)	Average Shear Strength (MPa)
SPR40-1	37.57	129.00	161.61	1.25	2.16±0.9355
SPR40-2	39.29	122.55	146.60	1.20	
SPR40-3	36.96	124.00	269.54	2.17	
SPR40-4	38.76	124.00	361.04	2.91	
SPR40-5	37.00	125.00	405.96	3.25	
SPR40-50-1	46.44	122.50	259.34	2.12	3.02±0.9431
SPR40-50-2	44.78	126.50	303.26	2.40	
SPR40-50-3	45.31	128.50	505.63	3.93	
SPR40-50-4	45.45	129.00	321.92	2.49	
SPR40-50-5	44.50	124.00	513.59	4.14	
SPR50-60-1	54.75	123.52	391.54	3.17	2.65±0.7880
SPR50-60-2	56.93	128.50	337.05	2.62	
SPR50-60-3	56.37	121.39	421.09	3.47	
SPR50-60-4	55.34	125.00	176.81	1.41	
SPR50-60-5	54.55	123.50	321.74	2.60	
SPR60-70-1	67.34	118.75	134.96	1.14	2.07±0.8364
SPR60-70-2	65.76	120.61	350.26	2.90	
SPR60-70-3	68.75	123.84	158.22	1.28	
SPR60-70-4	63.10	125.00	356.59	2.85	
SPR60-70-5	63.37	129.00	281.80	2.18	
SPR70-1	70.35	129.00	381.06	2.95	1.96±0.7499
SPR70-2	71.80	125.77	315.70	2.51	
SPR70-3	71.51	128.00	227.76	1.78	
SPR70-4	78.46	128.00	154.96	1.21	
SPR70-5	70.57	126.00	170.53	1.35	

3 RESULTS AND DISCUSSION

To investigate the effect of varying surface porosity on adhesive strength in aluminium composite foam materials, specimens were divided into five groups based on surface porosity ranges: less than 40% (SPR40), 40-50% (SPR40-50), 50-60% (SPR50-60), 60-70% (SPR60-70), and greater than 70% (SPR70), and 5 specimens were tested in each group. The specimens obtained by bonding aluminium blocks and aluminium composite foam surfaces with varying surface porosity ratios were subjected to a shear test under compression force. With the help of the obtained values, force (N) - displacement (mm) curves were obtained for all specimens tested. Following the shear tests, the adhesive surfaces of the bonded specimens were photographed, and the surface damages were evaluated.

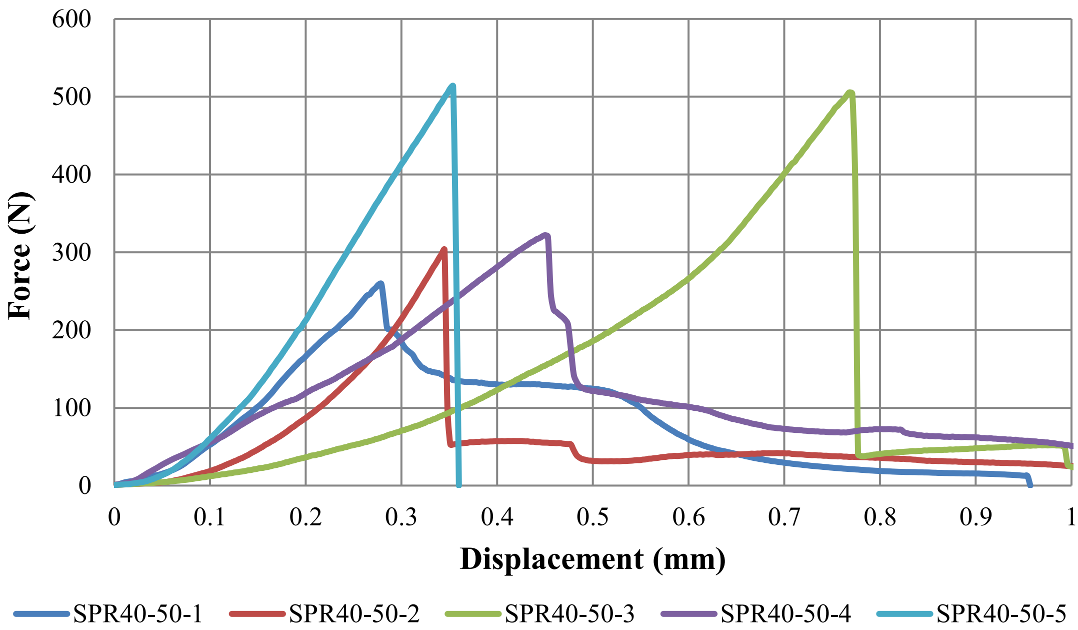
3.1 Evaluation of the Effect of Surface Porosity on Adhesion Strength

Figure 3 shows the shear force (N) - displacement (mm) curves that were obtained after the shear test was conducted on the bonding specimens. When the curves are examined, it becomes clear that as the surface porosity ratio increases, so does the joint's flexibility. Although the specimens gave their maximum shear strength at around the same displacement, as the surface porosity increased, the joint required more displacement and time to completely failure. They have been able to support the load for longer periods of time at values lower than the ultimate shear strength before the connections fail as the surface porosity increases.

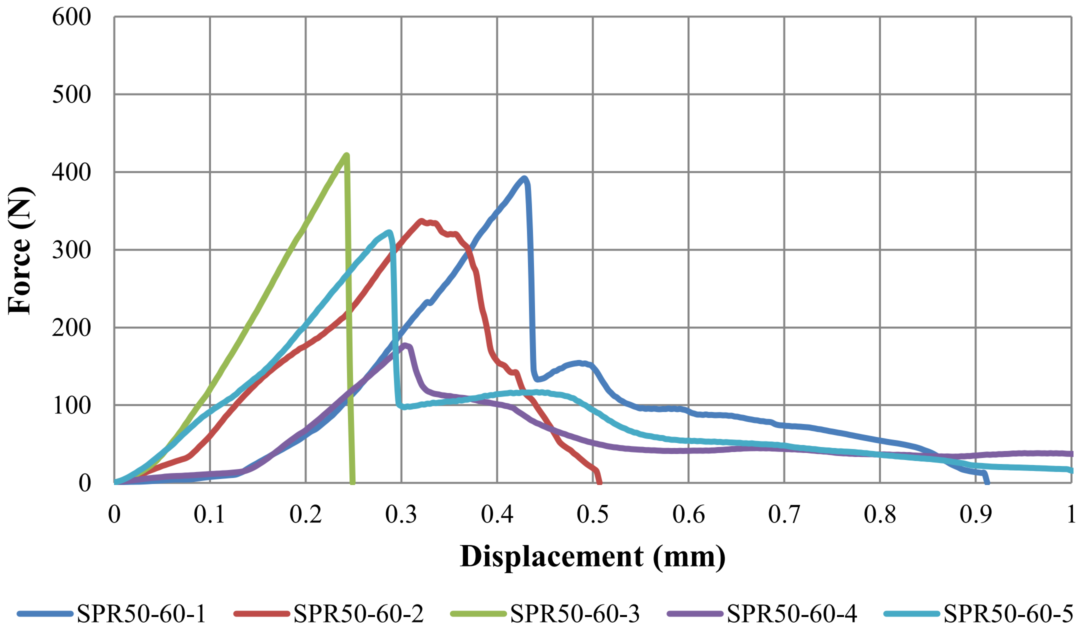


(a)

Figure 3. Comparison of force and displacement according to % porosity of specimen surfaces a) <%40, b) %40-50, c) %50-60, d) %60-70, e) >%70.

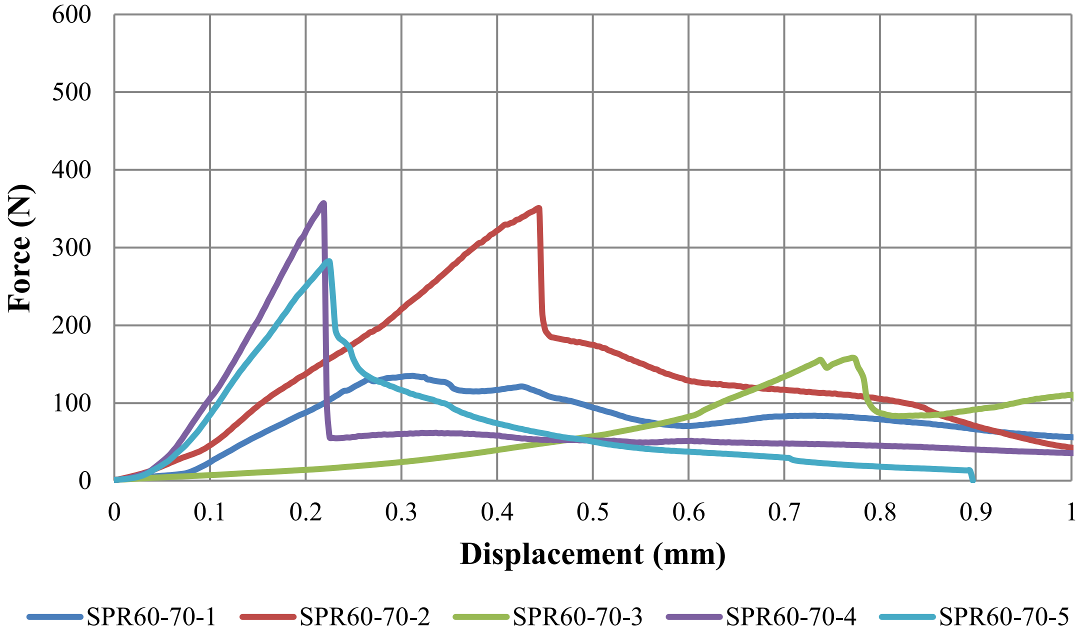


(b)

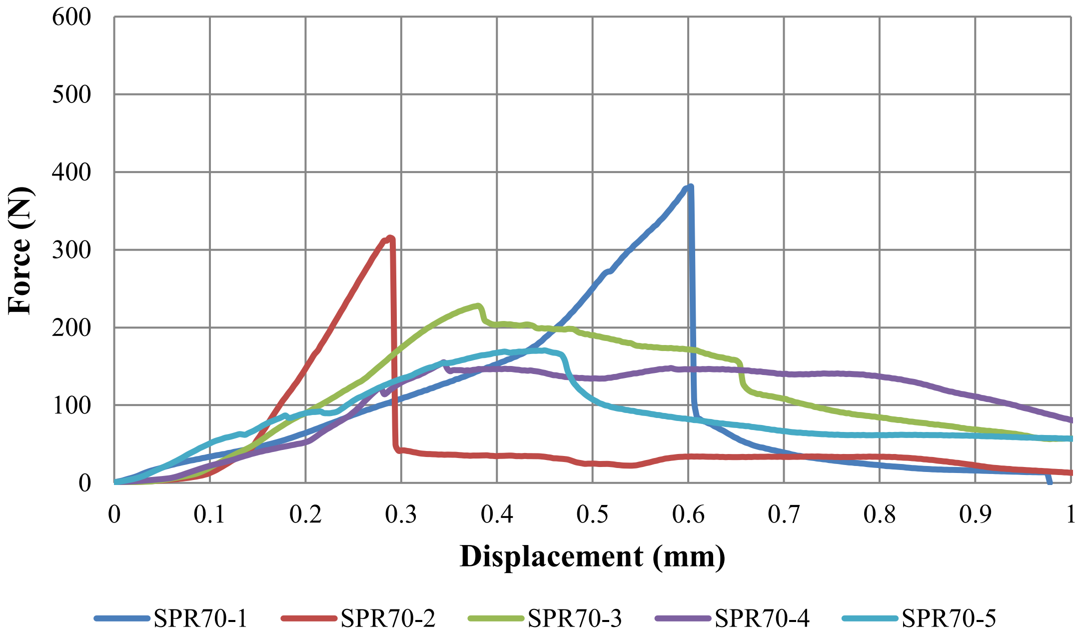


(c)

Figure 3 (continued). Comparison of force and displacement according to % porosity of specimen surfaces a) <%40, b) %40-50, c) %50-60, d) %60-70, e) >%70.



(d)



(e)

Figure 3 (continued). Comparison of force and displacement according to % porosity of specimen surfaces a) <%40, b) %40-50, c) %50-60, d) %60-70, e) >%70.

The aluminium composite foams with a surface porosity ratio between 40% and 50% attained the highest adhesive strength following the shear test applied to specimens obtained by bonding aluminium blocks and aluminium composite foam surfaces with varying surface porosity ratios (Figure 4). The epoxy adhesive employed in the bonding process exhibits a medium viscosity of approximately 11,500 cps, making it suitable for filling surface voids and irregularities, which facilitates mechanical interlocking. According to Darcy's law, the flow rate under applied pressure is inversely proportional to viscosity ($Q \propto \Delta P / \eta$). Hence, either lower viscosity or higher pressure improves the adhesive's fluidity and its capacity to fill gaps [42]. This enables the adhesive to penetrate pores, indentations, and irregular features of the surface, where it becomes mechanically "locked," thereby enhancing bond strength. Such interlocking is particularly advantageous on rough or porous surfaces. However, this mechanism alone does not fully explain adhesion, as strong bonding can also occur on smooth surfaces [43].

Analysis of samples with surface porosities of 50–60% (SPR50-60), 60–70% (SPR60-70), and above 70% (SPR70) revealed a decline in adhesion strength as porosity increased (Table 4). This reduction is primarily attributed to thinner cell walls, which limit the available bonding area, and to incomplete curing of the adhesive within large pores under ambient conditions. Consequently, mechanical interlocking may not have fully developed, or, if developed, the adhesive may not have achieved its full strength. For aluminium composite foams with porosities exceeding 70%, shear testing showed that the thin walls fractured, indicating that bond strength was governed by the structural integrity of these walls (Figure 9). Previous studies on closed-cell aluminium foams similarly report that increased porosity and reduced density—resulting in thinner cell walls—lead to decreased compressive strength and diminished energy absorption capacity [44].

When the average adhesion strength of aluminium composite foams with a surface porosity below 40% (SPR40) and between 40–50% (SPR40-50) was examined, it was found that the samples with 40–50% porosity exhibited higher average adhesion strength compared to those with less than 40% porosity. In fact, the cell walls in contact with the adhesive are thicker in samples with porosity below 40%. However, the pores available for the adhesive to fill are relatively small. In contrast, the surface pores in samples with 40–50% porosity are larger, thereby increasing the likelihood of mechanical interlocking. When all samples are considered, the higher adhesion strength of the 40–50% porosity group can be attributed to two factors: (i) thicker cell walls compared to samples with 50–60%, 60–70%, and above 70% porosity, which enhances material strength, and (ii) higher mechanical interlocking compared to samples with porosity below 40%. Therefore, it is suggested that in samples with 40–50% porosity, bonding is achieved at an optimal level through the combined contribution of surface adhesion and mechanical interlocking.

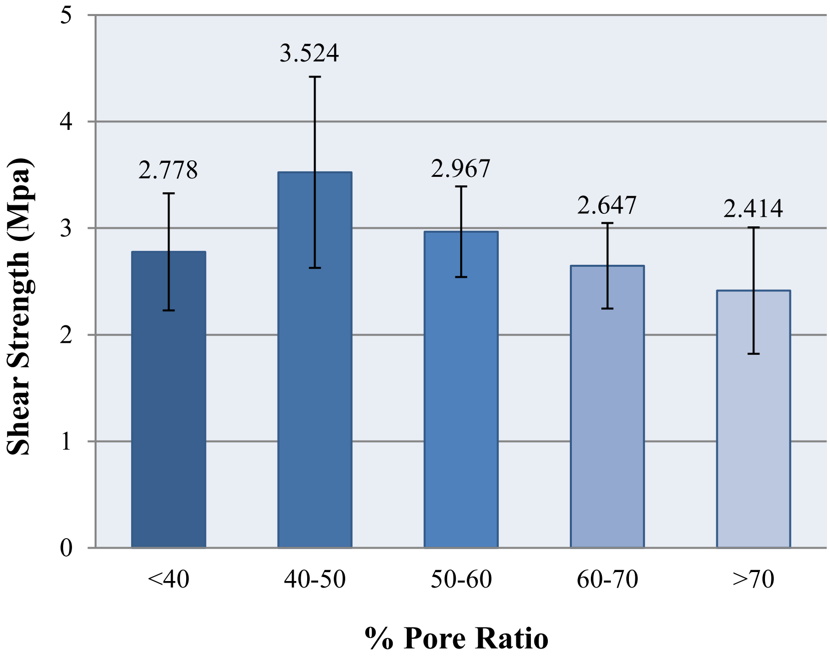
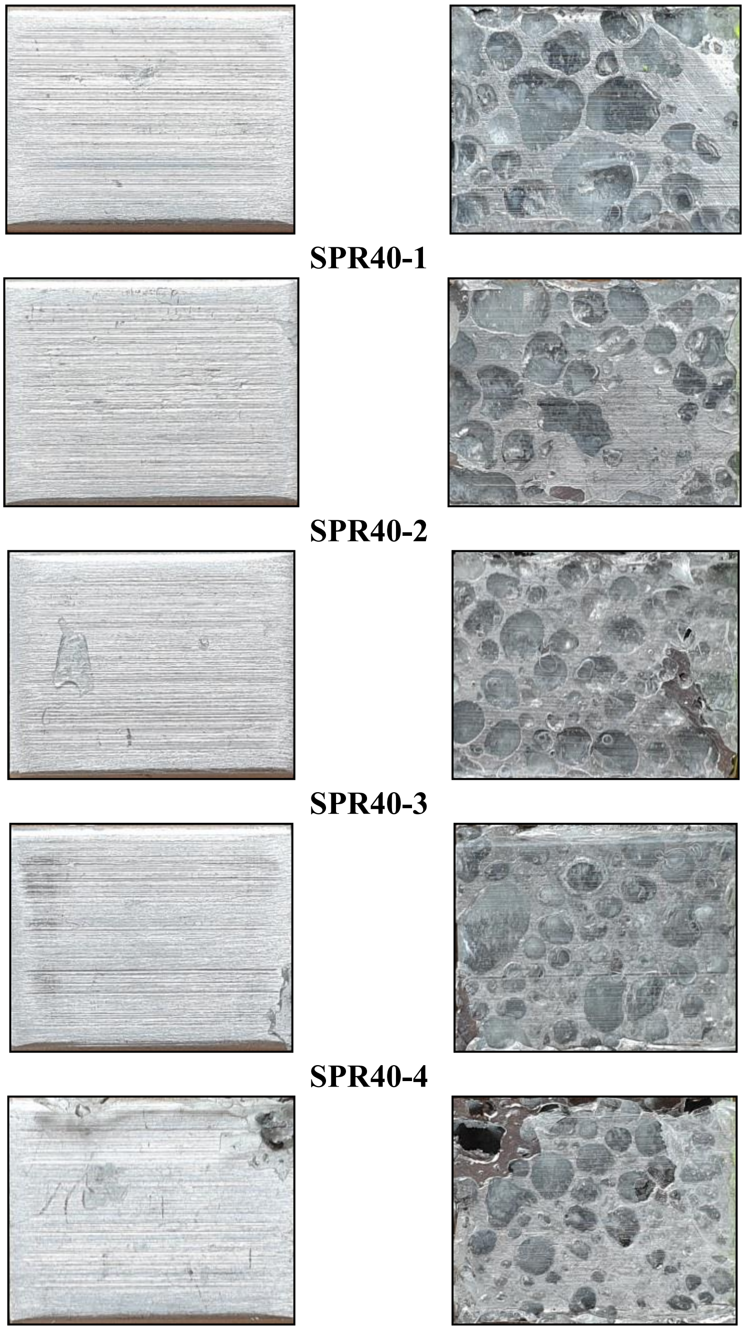


Figure 4. Bond strengths of specimen surfaces according to % porosity ratios.

3.2 Assessment of the Effect of Surface Porosity Ratio on the Occurring Bonding Damage

Figures 5–9 illustrate the specimen surfaces after shear testing for aluminium composite foam and aluminium block specimens with varying surface porosity ratios. When these are examined:

When the bonded surfaces of the specimens (SPR40) with surface porosity ratios less than 40% were examined (Figure 5), the bonding damage was mainly in the form of adhesion damage and low cohesion damage. The adhesive generally remained on the aluminium composite foam surface, although bonding damage developed between it and the bonded surface.

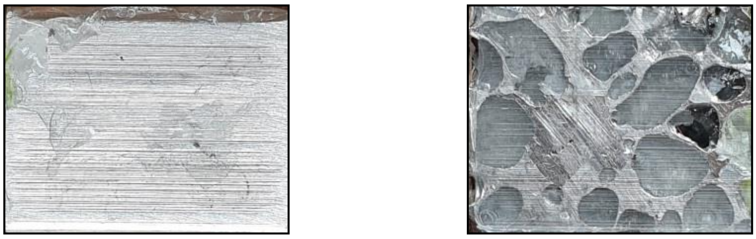


SPR40-5

Figure 5. Bonding Surfaces of Aluminium Block and Specimens with Surface Porosity <40% (SPR40) after Shear Test.

Bonding damage occurred in the form of adhesion and cohesion damage when the bonded surfaces of the specimen (SPR40-50) with a surface porosity of 40 to 50% were examined (Figure 6). The adhesive is clearly visible on both surfaces, and bonding damage occurred between adhesive and the bonded surface.

SPR40-50-1



SPR40-50-2

SPR40-50-3

SPR40-50-4

SPR40-50-5

Figure 6. Bonding Surfaces of Aluminium Block and Specimens with Surface Porosity Ratio 40-50% (SPR40-50) after Shear Test.

As shown in Figure 7, the bonded surfaces of the specimens with 50–60% surface porosity (SPR50–60) exhibited a combination of adhesive and cohesive failures, indicating mixed-mode bonding damage. In some specimens, adhesion damage as well as cohesion damage occurred at close levels. The adhesive is clearly visible on both surfaces, and there is bonding damage between the adhesive and the bonded surface. It has detached more from the adhesive surface, particularly in the enlarging pores.

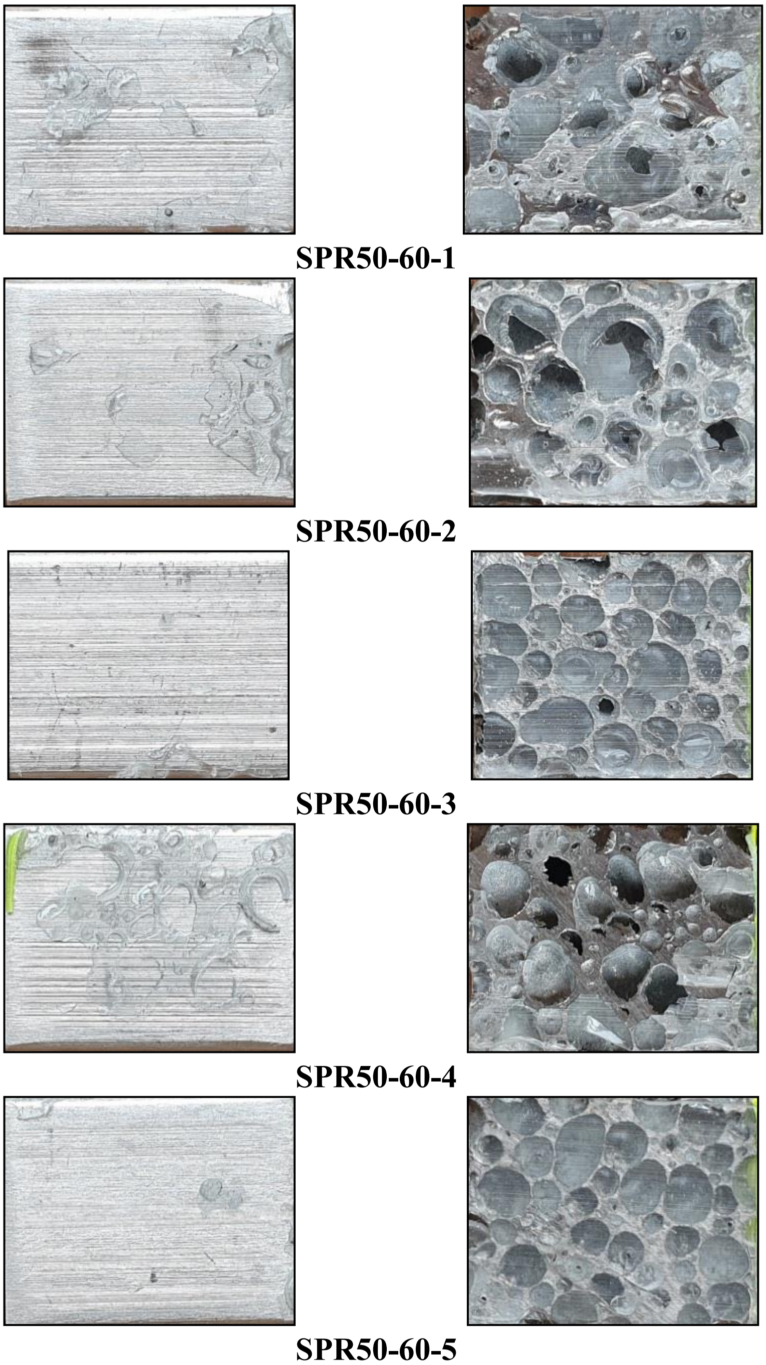


Figure 7. Bonding Surfaces of Aluminium Block and Specimens with Surface Porosity Ratio 50-60% (SPR50-60) after Shear Test.

When the bonded surfaces of the specimens (SPR60-70) with surface porosity ratios ranging from 60 to 70% were examined (Figure 8), the bonding damage was mostly in the form of cohesion damage. In some specimens, bonding damage occurred as adhesion damage. Bonding damage occurred at the interface between the adhesive and the bonded surface, with adhesive residue visible on both surfaces.

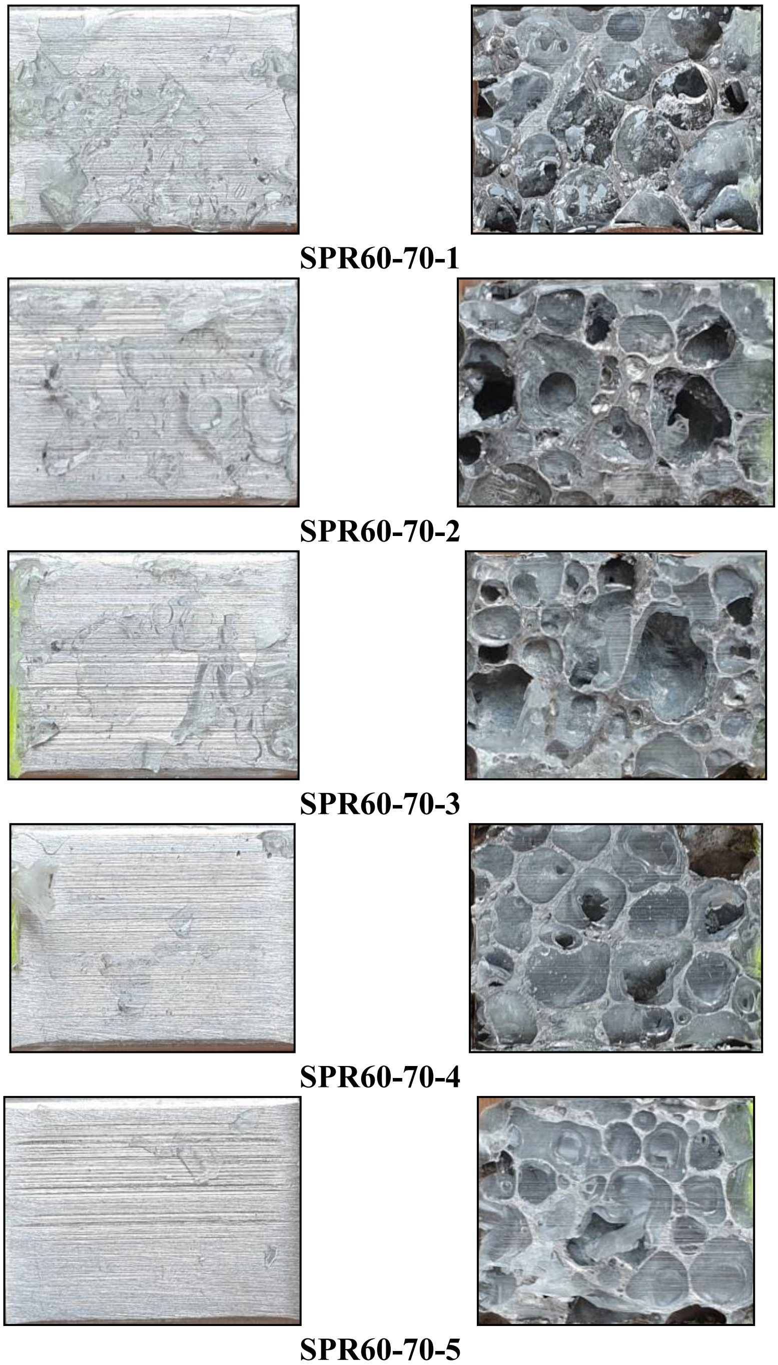


Figure 8. Bonding Surfaces of Aluminium Block and Specimens with Surface Porosity Ratio 60-70% (SPR60-70) after Shear Test.

Bonding damage occurred in the form of adhesion, cohesion, and cohesive material damage when the bonded surfaces were examined (Figure 9) on specimens with a surface porosity of more than 70% (SPR70).

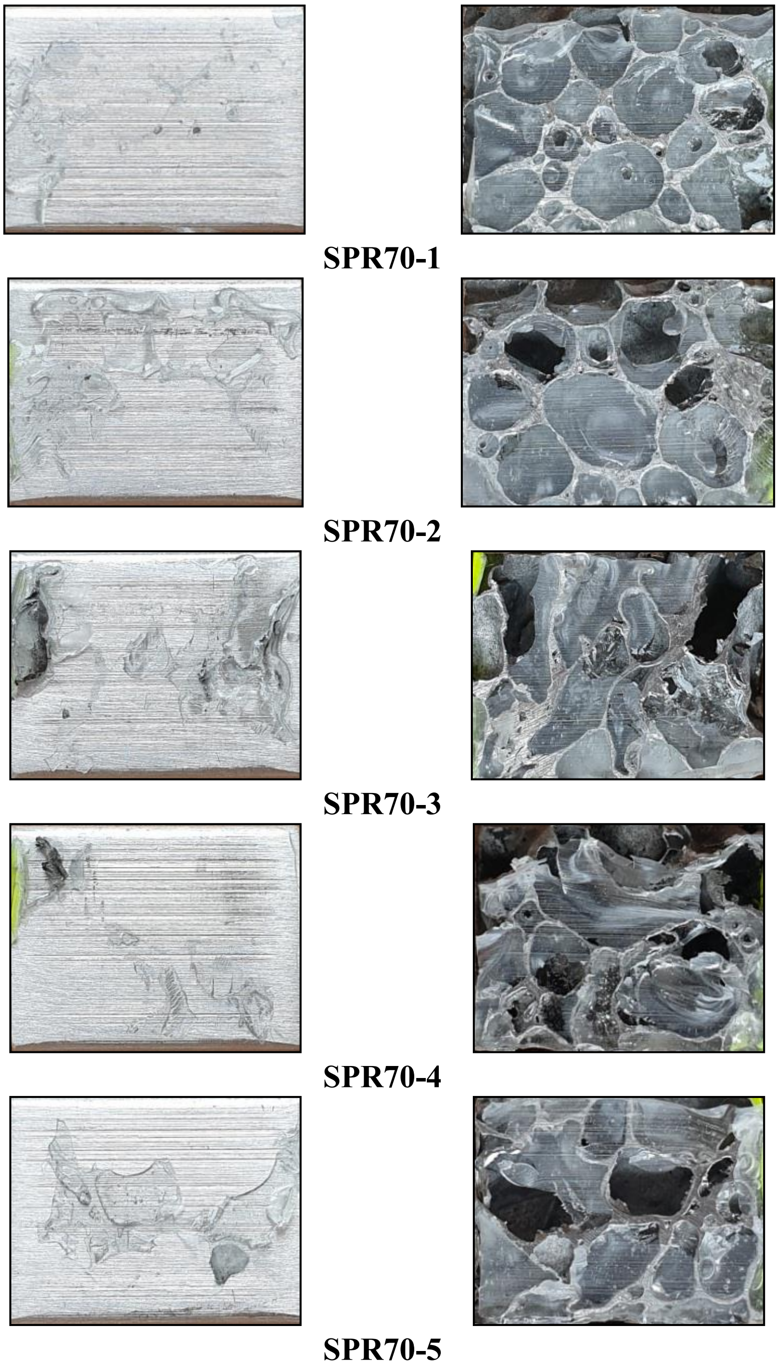


Figure 9. Bonding Surfaces of Aluminium Block and Specimens with Surface Porosity Ratio >70% (SPR70) after Shear Test.

The consistent presence of adhesive residue on both bonded surfaces across all specimens indicates effective adhesion, suggesting that the selected adhesive, surface abrasion technique, and applied surface treatments adequately promoted interfacial bonding.

Adhesion strength decreased with increasing porosity ratio and pore size on the bonded surfaces. This reduction is attributed to the diminished rigid aluminium regions on the surface of the aluminium foam material, which correlates with the increased surface porosity. As observed in Figure 14 for the SPR60-70-2 specimen, the adhesive lacked substrate contact in the majority of pores, leading to detachment from the surface during the shear test and consequently reducing the adhesive bond strength. Nevertheless, the adhesive remained bonded to the rigid cell walls.

Examination of the surfaces resulting from the shear test on specimens with a surface porosity ratio exceeding 70% reveals that some portions of the metal foam material detached from the cell wall structure and remained adhered to the aluminium surface (Figure 9 - SPR70-3/4). As a consequence, the increase of the surface porosity ratio, in addition to the adhesive, played a role in the carrying of the maximum shear force. Pore diameters increase in general as the surface pore ratio increases. The cell walls of aluminium composite foams become thinner as the pore diameter increases, and their strength decreases. Cell walls with reduced strength break during the shear test. The bonding strength in this instance is determined by the material's cell wall rather than by the adhesive. The greater the cell wall strength, the greater the bonding strength [6, 45]. The adhesive strength formed between the surfaces of the two specimens is greater than the material's strength because the detachment occurs within the structure of the material rather than at the adhesion interface.

On surfaces with surface porosity ratios of 40%, 40-50%, and 50-60%, similar bonding damages and close adhesion strengths were obtained. Specimens with surface porosities of 60-70% and >70% showed similar bonding damage. The bonding strength starts to decrease when the surface porosity ratio reaches 60% or higher. This is owing to a decrease in adhesive forces that provide bonding strength and mechanical interlocking, as well as a weakening of material strength due to thinning of material cell walls.

4 CONCLUSION AND SUGGESTIONS

In our previous study, the surface porosity, average pore diameter, and pore count of aluminium composite foams were determined using the open-source image processing program ImageJ. In this study, the effect of the surface porosity ratio of aluminium composite foams bonded with aluminium blocks on the bond strength was investigated.

This study investigated the bonding performance of aluminium composite foams with varying surface porosity ratios, joined to aluminium blocks using a single lap joint configuration and an epoxy-based adhesive. Joint strength was evaluated under compressive shear loading using a modified procedure based on ASTM D905-08. The results of these tests are presented below.

- It has been discovered that adhesive bonding is an applicable method for connecting aluminium metal foams and aluminium blocks.
- It has been noticed that when the general epoxy adhesives suggested in the literature are used to join aluminium metal foams, the bonding connection occurs but only weak bonding strengths are obtained.
- The results indicate that aluminium composite foams with a surface porosity ratio between 40% and 50% tend to exhibit relatively higher adhesive strength compared to other porosity ranges.
- Aluminium composite foams with surface porosity ratios under 60% tend to exhibit greater bonding strength relative to those with higher porosity levels.
- As the strength of the aluminium composite foam material increases, material damage within the joint is expected to be eliminated, leading to an improvement in the bonding strength.

Future research may focus on evaluating the adhesive bond strength of aluminium composite metal foams with varying porosity levels. The performance of different adhesive types, such as cyanoacrylate, methyl methacrylate, and acrylic, could be assessed, as well as the influence of adhesives with different viscosities—particularly those with high viscosity and limited gap-filling ability—on bond strength. Such investigations are anticipated to provide valuable insights and contribute to the literature, thereby supporting the industrial utilization of aluminium composite metal foams.

Acknowledgment

The authors gratefully acknowledge the constructive comments of the reviewers, which helped to improve the quality of this paper.

This research was supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under project number 119M001.

Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this paper.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors

Contributions of the Authors

Conceptualization A. Şahin and N. Ü. Taşkın, Methodology A. Şahin, Testing A. Şahin and N. Ü. Taşkın, Writing A. Şahin and V. Taşkın, Review and editing A. Şahin and V. Taşkın, Supervision V. Taşkın. All authors have read and agreed to the published version of the manuscript.

REFERENCES

[1] J. Banhart, “Manufacture, characterisation and application of cellular metals and metal foams,” *Progress in Materials Science*, vol. 46, no. 6, pp. 559–632, Dec. 2001, doi: 10.1016/S0079-6425(00)00002-5.

[2] L. J. Gibson and M. F. Ashby, *Cellular Solids: Structure and Properties*, 2nd ed. Cambridge, U.K.: Cambridge Univ. Press, 1997.

[3] A. A. Gokhale, N. V. R. Kumar, B. Sudhakar, S. N. Sahu, H. Basumatary, and S. Dhara, “Cellular metals and ceramics for defence applications,” *Defence Science Journal*, vol. 61, no. 6, pp. 567–575, Nov. 2011, doi: 10.14429/dsj.61.640.

[4] F. Sımančík, “Metallic foams—ultra light materials for structural applications,” *Inżynieria Materiałowa*, vol. 5, pp. 823–828, 2001.

[5] A. Kulshreshtha and S. K. Dhakad, “Preparation of metal foam by different methods: A review,” *Materials Today: Proceedings*, vol. 26, pp. 1784–1790, 2020, doi: 10.1016/j.matpr.2020.02.375.

[6] M. F. Ashby, A. G. Evans, N. A. Fleck, L. J. Gibson, J. W. Hutchinson, and H. N. G. Wadley, *Metal Foams: A Design Guide*. Boston, MA, USA: Butterworth-Heinemann, 2000.

[7] C. Körner and R. F. Singer, “Processing of metal foams—challenges and opportunities,” *Advanced Engineering Materials*, vol. 2, no. 4, pp. 159–165, Apr. 2000, doi: 10.1002/(SICI)1527-2648(200004)2:4<159::AID-ADEM159>3.0.CO;2-O.

[8] P. Parthkumar, P. P. Bhingole, and D. Makwana, “Manufacturing, characterization and applications of lightweight metallic foams for structural applications: Review,” *Materials Today: Proceedings*, vol. 5, pp. 20391–20402, 2018, doi: 10.1016/j.matpr.2018.06.414.

[9] B. Parveez, N. A. Jamal, H. Anuar, Y. Ahmad, A. Aabid, and M. Baig, “Microstructure and mechanical properties of metal foams fabricated via melt foaming and powder metallurgy technique: A review,” *Materials*, vol. 15, no. 15, pp. 5302, Aug. 2022, doi: 10.3390/ma15155302.

[10] D. K. Rajak, L. A. Kumaraswamidhas, and S. K. Das, “On the influence of porosity and pore size on AlSi17 alloy foam using artificial neural network,” *Ciência & Tecnologia dos Materiais,* vol. 29, pp. 14–21, 2017, doi: 10.1016/j.ctmat.2017.05.004.

[11] J. Baumeister, J. Banhart, and M. Weber, "Aluminium foams for transport industry," *Materials & Design*, vol. 18, no. 4–6, pp. 217–220, 1997, doi: 10.1016/S0261-3069(97)00050-2.

[12] J. Zhang, Y. An, and H. Ma, "Research progress in the preparation of aluminium foam composite structures," *Metals*, vol. 12, no. 12, p. 2047, Dec. 2022, doi: 10.3390/met12122047.

[13] V. Thulasikanth and R. Padmanabhan, "Processing of aluminium/fly ash composite foams for sustainable green products," *Journal of Porous Materials*, vol. 30, pp. 459–469, 2022, doi: 10.1007/s10934-022-01360-9.

[14] M. Spratt, J. W. Newkirk, and K. Chandrashekhara, "Aluminium matrix syntactic foam fabricated with additive manufacturing,", Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium (2017, Austin, TX), pp. 242-248, University of Texas at Austin, Aug 2017.

[15] D. Ren, Y. Xu, W. Du, B. Wang, Y. Lin, Z. He, and Y. Chen, "A novel sandwich aluminium foam composite reinforced with steel prepared by arc spraying," *Advanced Engineering Materials*, vol. 27, 2025, doi: 10.1002/adem.202402114.

[16] L. Vendra, *Processing and Characterization of Aluminium-Steel Composite Metal Foams*. Ph.D. dissertation, Graduate Faculty of North Carolina State University, 2008.

[17] J. Wu, L. Wang, and F. Wang, "Preparation of aluminium foam composite," in *Proc. IET Conf. Publications*, 2010, doi: 10.1049/CP.2010.1345.

[18] S. Kumar, R. Pandey, and O. Pandey, "Effect of foaming temperature on polyhedron structure of particulate reinforced aluminium composite foams," *Procedia Materials Science,* vol. 5, pp. 891–897, 2014, doi: 10.1016/j.mspro.2014.07.376.

[19] N. Sinha, V. C. Srivastava, and K. L. Sahoo, "Processing and application of aluminium foams," in *Special Metal Casting and Forming Processes*, pp. 54–63, 2008.

[20] M. Sangeetha, S. Prakash, K. Sridharraja, and J. Muralimano, "Development, testing and microstructural study of aluminium foam in automobile application," *International Journal of Ambient Energy*, vol. 43, no. 1, pp. 2568–2576, 2020, doi: 10.1080/01430750.2020.1723690.

[21] C. Fiebig and M. Koch, "Lightweight hybrid composites of CFRP and aluminium foam," *Materials Science Forum*, vols. 825–826, pp. 482–489, 2015, doi: 10.4028/www.scientific.net/MSF.825-826.482.

[22] G. Yao, H. Luo, and Z. Cao, "The manufacturing technology of aluminium foam material and some special equipments," in *Proc. Int. Conf. on Materials Science and Applications (ICMSA)*, 2015, doi: 10.2991/ICMSA-15.2015.161.

[23] T. Hipke, J. Hohlfeld, and S. Rybandt, "Functionally aluminium foam composites for building industry," *Procedia Materials Science*, vol. 4, pp. 133–138, 2014, doi: 10.1016/j.mspro.2014.07.550.

[24] H. P. Degischer and B. Kriszt, Eds., *Handbook of Cellular Metals: Production, Processing and Applications*. Weinheim, Germany: Wiley-VCH Verlag GmbH, 2002, doi: 10.1002/3527600558.

[25] O. B. Olurin, N. A. Fleck, and M. F. Ashby, "Joining of aluminium foams with fasteners and adhesives," *Journal of Materials Science*, vol. 35, no. 5, pp. 1079–1085, 2000, doi: 10.1023/A:1004735011463.

[26] N. Sedliaková, F. Simančík, J. Kováčik, and P. Minár, "Joining of aluminium foams," in *Proc. Symposium Metallschäume*, 1997, pp. 177–185.

[27] J. Burzer, T. Bernard, and H. W. Bergmann, "Joining of aluminium structures with aluminium foams," in D. S. Schwartz, D. S. Shih, A. G. Evans, and H. N. G. Wadley, Eds., *Porous and Cellular Materials for Structural Applications*. Warrendale, PA, USA: Materials Research Society, 1998, pp. 159–164.

[28] J. A. Hamzah and M. A. Nima, "Experimental study of heat transfer enhancement in double-pipe heat exchanger integratiod with metal foam fins," *Arabian Journal for Science and Engineering*, vol. 45, no. 8, pp. 5153–5167, Aug. 2020, doi: 10.1007/s13369-020-04371-3.

[29] A. Hackert, C. Drebenstedt, T. Timmel, T. Osiecki, and L. Kroll, "Composite sandwich with aluminium foam core and adhesive bonded carbon fiber reinforced thermoplastic cover layer," *Key Engineering Materials*, vol. 744, pp. 277–281, 2017, doi: 10.4028/www.scientific.net/KEM.744.277.

[30] W. Ningzhen, X. Chen, A. Li, Y. Li, H. Zhang, and Y. Liu, "Three-point bending performance of a new aluminium foam composite structure," *Transactions of Nonferrous Metals Society of China*, vol. 26, no. 2, pp. 359–368, Feb. 2016, doi: 10.1016/S1003-6326(16)64088-8.

[31] K. Stöbener and G. Rausch, "Aluminium foam–polymer composites: Processing and characteristics," *Journal of Materials Science*, vol. 44, no. 6, pp. 1506–1511, Mar. 2009, doi: 10.1007/s10853-008-2786-8.

[32] Z. Sun, J. Jeyaraman, S. Shi, S. Sun, X. Hu, and H. Chen, "Processing and property of carbon-fiber aluminium-foam sandwich with aramid-fiber composite adhesive joints," *Journal of Adhesion Science and Technology*, vol. 28, no. 18, pp. 1835–1845, 2014, doi: 10.1080/01694243.2014.925385.

[33] R. Neugebauer and T. Hipke, "Parameters of construction for applications of metal foams," *Materials Research Society Symposium Proceedings*, vol. 521, pp. 265–270, 1998.

[34] H. J. Chung, K. Y. Rhee, B. S. Han, and Y. M. Ryu, "Plasma treatment using nitrogen gas to improve bonding strength of adhesively bonded aluminium foam/aluminium composite," *Journal of Alloys and Compounds*, vol. 459, no. 1–2, pp. 196–202, 2008, doi: 10.1016/j.jallcom.2007.05.006.

[35] J. Nowacki and A. Sajek, "Optimizing glue joint of aluminium metallic foams," *Journal of Achievements in Materials and Manufacturing Engineering*, vol. 75, no. 1, pp. 14–23, 2016.

[36] A. Timari, M. Berczeli, J. Liska, and Z. Weltsch, "Bending and tensile test of glued aluminium foams," *IOP Conference Series: Materials Science and Engineering*, vol. 448, p. 012067, 2018, doi: 10.1088/1757-899X/448/1/012067.

[37] C. Yan, X. Song, C. Jing, and S. Feng, "Effects of epoxy resin liquidity on the mechanical properties of aluminium foam sandwich," *Journal of Adhesion Science and Technology*, vol. 32, no. 6, pp. 673–691, 2018, doi: 10.1080/01694243.2017.1375173.

[38] J. Nowacki and A. Sajek, "Trends of joining composite AlSi-SiC foams," *Advances in Materials Science*, vol. 19, no. 1, pp. 70–82, 2019, doi: 10.2478/adms-2019-0006.

[39] "Espacenet bibliographic data: Publication number WO2015094139," European Patent Office, 2015.

[40] A. Şahin, *Kompozit Alüminyum Köpüklerin Yapıştırma Bağlantılarında Bağlantı Dayanımını Etkileyen Parametrelerin İncelenmesi*. Doktora Tezi, Fen Bilimleri Enstitüsü, Trakya Üniversitesi, Edirne, Türkiye.

[41] V. Casalegno, M. Salvo, S. Rizzo, L. Goglio, O. Damiano, and M. Ferraris, "Joining of carbon fibre reinforced polymer to Al-Si alloy for space applications," *International Journal of Adhesion and Adhesives*, vol. 82, pp. 146–152, 2018, 10.1016/j.ijadhadh.2018.01.009.

[42] J. Chen, Y. Liu, Y. She, Y. Yang, X. Du, J. Yang, and Y. Wu, "The effect of epoxy resin on the infiltration of porous metal parts formed through laser powder bed fusion," J. Compos. Sci., vol. 8, no. 3, p. 99, 2024, doi: 10.3390/jcs8030099.

[43] S. Ebnesajjad and A. H. Lanck, Eds., Adhesives Technology Handbook, 3rd ed. Burlington, MA, USA: Elsevier, 2014.

[44] T. Fiedler, V. Vendra, and A. Öchsner, "Mechanical properties and energy absorption of closed-cell aluminium foams," J. Mater. Sci., vol. 41, no. 12, pp. 3899–3905, 2005.

[45] F. García-Moreno, "Commercial applications of metal foams: Their properties," *Materials*, vol. 6, no. 2, pp. 175–183, Feb. 2016, 10.3390/ma9020085.