Gazi Üniversitesi
Fen Bilimleri Dergisi
PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

GU J Sci, Part C, 13(X): XX-XX (2025)

Production of Al-based Foam Using Powder Metallurgy method, Its Application Areas and Use for Energy Absorption in Polymer-based Armors

Mehmet TÜRKER[1]

[1]*Gazi University, Department of Metallurgy and Materials Eng., Ankara, 06560, Türkiye*

Article Info

Research article
Received: 25/07/2025
Revision: 03/08/2025
Accepted: 04/08/2025

Keywords

Powdered metal Al foams
Production methods
Areas of use
Armor materials reinforced with metallic foam

Makale Bilgisi

Araştırma makalesi
Başvuru: 25/07/2025
Düzeltme: 03/08/2025
Kabul: 04/08/2025

Anahtar Kelimeler

Toz metal Al köpükler,
Üretim yöntemleri,
Kullanım alanları,
Metalik köpükle güçlendirilmiş zırh malzemeleri.

Graphical/Tabular Abstract (Grafik Özet)

Metal foams stand out in sectors such as the automotive industry, aerospace, and defense industries due to their very low densities and high energy absorption properties. Despite their highly porous structure, metal foams possess high strength, low thermal conductivity, and high energy absorption capacity. This article provides general information about closed-cell Al-based metallic foam materials produced using powder metallurgy (PM) methods. It also provides general information about the production of metallic foam-reinforced integrated armor materials. / Metal köpükler, çok düşük yoğunlukları ve yüksek enerji emme özellikleri nedeniyle otomotiv endüstrisi, havacılık ve savunma endüstrileri gibi sektörlerde öne çıkmaktadır. Yüksek gözenekli yapılarına rağmen, metal köpükler yüksek mukavemet, düşük ısı iletkenliği ve yüksek enerji emme kapasitesine sahiptir. Bu makale, toz metalurjisi (PM) yöntemleri kullanılarak üretilen kapalı hücreli Al bazlı metalik köpük malzemeler hakkında genel bilgiler sunmaktadır. Ayrıca, metalik köpük takviyeli entegre zırh malzemelerinin üretimi hakkında genel bilgiler de vermektedir.


Figure A: *The porous structure of metallic foam /* ***Şekil A:*** *Metalik köpüğün gözenekli yapısı*

Highlights (Önemli noktalar)

Information is provided on the properties of porous structures and very low-density metallic foams, different production methods, and application areas/ Gözenekli yapıların ve çok düşük yoğunluklu metalik köpüklerin özellikleri, farklı üretim yöntemleri ve uygulama alanları hakkında bilgi verilmektedir.

Aim (Amaç): *Despite being relatively new, metallic foams have found widespread application. This section introduces the different production methods of metallic foams and the resulting properties./ Oldukça yeni bir malzeme olmasına rağmen, metalik köpükler yaygın olarak kullanılmaktadır. Bu bölümde, metalik köpüklerin farklı üretim yöntemleri ve ortaya çıkan özellikleri tanıtılmaktadır.*

Originality (Özgünlük): *The study presents both an extensive literature review and original experimental results. / Çalışma hem geniş bir literatür taramasını hem de orijinal deney sonuçlarını sunmaktadır.*

Results (Bulgular): *The article presents foam structures obtained using different production methods. / The article presents foam structures obtained using different production methods.*

Conclusion (Sonuç): *This article provides extensive information on the production of foam materials with different ceramic reinforcements or without reinforcement, and their general applications../ Al esaslı köpük malzemenin farklı seramik takviyeli veya takviyesiz olarak üretimi ve genel kullanım alanları ile ilgili geniş bilgiler sunmaktadır.*

*Corresponding author, e-mail: mturker@gazi.edu.tr
DOI: 10.29109/gujsc.1750808

GU J Sci, Part C, 13(X): XX-XX (2025)

Gazi Üniversitesi
Fen Bilimleri Dergisi
PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

http://dergipark.gov.tr/gujsc

Production of Al-based Foam Using Powder Metallurgy method, Its Application Areas and Use for Energy Absorption in Polymer-based Armors

Mehmet TÜRKER[1]

[1]Gazi University, Department of Metallurgy and Materials Eng., Ankara, 06560, Türkiye

Article Info

Research article
Received: 25/07/2025
Revision: 03/08/2025
Accepted: 04/08/2025

Keywords

Powdered metal Al foams
Production methods
Areas of use
Armor materials reinforced with metallic foam

Abstract

Metallic foams, which have been the subject of intense research in both academic and industrial fields in recent years, are extremely lightweight and porous materials. Their very low density and high energy absorption properties have made them prominent in sectors such as the automotive industry, as well as the aerospace and defense industries. Despite their highly porous structure, metallic foams possess high strength, low thermal conductivity, and high energy absorption capacity. The mechanical properties of metallic foams vary depending on the shape, size, and surface area of the pores, the properties of the reinforcement elements added to the structure during production, and their interaction with the matrix material. Foam materials have become particularly attractive to vehicle designers due to their light weight and energy absorption properties. Although they are used in many different areas of the vehicle, the primary goal is to minimize damage to the vehicle and minimize occupant harm in the event of a collision. Furthermore, in today's world where energy and the environment are paramount, reducing vehicle weight will reduce fuel consumption, increase efficiency, and minimize environmental damage. This article provides general information about closed-cell Al-based metallic foam materials produced using powder metallurgy (PM). It also provides comprehensive information on specialized production methods, including reinforced and unreinforced foam production, sandwich foam production, spherical foam production, and metallic foam-filled profile production. It also provides general information on the production of metallic foam-reinforced integral armor material, a very new application, and other applications.

Toz Metalurjisi Yöntemiyle Alüminyum Esaslı Köpük Üretimi, Uygulama Alanları ve Polimer Esaslı Zırhlarda Enerji Sönümleme Amaçlı Kullanımı

Makale Bilgisi

Araştırma makalesi
Başvuru: 25/07/2025
Düzeltme: 03/08/2025
Kabul: 04/08/2025

Anahtar Kelimeler

Toz metal Al köpükler, Üretim yöntemleri, Kullanım alanları, Metalik köpükle güçlendirilmiş zırh malzemeleri.

Öz

Son yıllarda hem akademik hem de endüstriyel alanlarda yoğun araştırmalara konu olan metalik köpükler, oldukça hafif ve gözenekli yapıya sahip malzemelerdir. Bu malzemeler, çok düşük yoğunlukları ve yüksek enerji emme özellikleriyle otomotiv endüstrisi başta olmak üzere havacılık ve savunma sanayi gibi alanlarda öne çıkmaktadır. Metalik köpükler oldukça gözenekli yapılarına rağmen yüksek mukavemet, düşük ısı iletkenliği ve yüksek enerji emme kapasitesine sahiptir. Metalik köpüklerin mekanik özellikleri, gözeneklerin şekline, boyutuna ve yüzey alanına, üretim sırasında yapıya eklenen takviye elemanlarının özelliklerine ve matris malzemesiyle etkileşimlerine bağlı olarak değişiklik gösterir. Köpük malzemeler, hafiflikleri ve enerji emme özellikleri nedeniyle araç tasarımcıları için özellikle cazip hale gelmiştir. Aracın birçok farklı alanında kullanılmalarına rağmen, özellikle çarpışma durumunda araçta oluşabilecek hasarın en aza indirilmesi ve yolcuların en az zarar görmesi hedeflenmektedir. Ayrıca, enerji ve çevrenin önemli olduğu günümüzde, araç ağırlığının azaltılması yakıt tüketimini azaltacak ve verimliliği artırarak çevreye verilen zararı en aza indirecektir. Bu makalede, toz metalurjisi (TM) yöntemiyle üretilen kapalı hücreli Al esaslı metalik köpük malzemeler hakkında genel bilgiler verildikten sonra, takviyeli ve takviyesiz köpük üretimi, sandviç köpük üretimi, küresel köpük üretimi ve metalik köpük dolgulu profil üretimi gibi özel üretim yöntemleri hakkında kapsamlı bilgi verilmektedir. Ayrıca, çok yeni bir uygulama olan metalik köpük takviyeli integral zırh malzemesinin üretimi ve diğer uygulamalar hakkında genel bilgiler verilmektedir.

*Corresponding author, e-mail: mturker@gazi.edu.tr
DOI: 10.29109/gujsc.1750808

1. INTRODUCTION (GİRİŞ)

Metallic foams with a highly porous and lightweight structure are considered as new engineering materials and have been developed primarily for the aerospace and defense industries and the automotive industry. Traditional solid metals are limited in achieving simultaneous weight reduction and high mechanical performance, which has driven significant research and industrial interest in metallic foams. These ultra-light materials exhibit unique mechanical properties due to their low density and toughness as well as high compressive strength, hardness, high sound and heat insulation properties, vibration damping and high impact energy absorption properties [1-15]. Due to the above-mentioned properties, many different studies have been conducted on these materials and they have found the opportunity to be used in many different areas.

Metallic foams are generally produced as open and closed pores [2, 16-24]. Photographs showing the structures of open and closed pore metallic foams are given in Figure 1 and Figure 2, respectively. Figure 3 shows the triple cell wall connection in a closed-pore foam structure. By controlling the pore size and shape in foam materials, it is possible to control many properties, especially mechanical properties [25-30]. There are quite detailed studies on the control of cell size and shape of the foam structure during production, as it affects many properties, especially mechanical properties [31-36]. In addition to the environmental conditions, the high temperature resistance of metallic foams and their ability to maintain their structure and properties at these temperatures are important. The most popular among metallic foams are undoubtedly Al foams and studies on them have been continuing for a long time both scientifically and industrially [4, 6, 24, 37-40]. Although there are different production methods, the ability to produce close to the final shape with the PM method and to control the cell structure at the same time provides a great advantage. In addition, these materials have been used in many different engineering applications due to their weldability, drilling, bending and machinability advantages. [41-50]. Among these areas, the automotive and aviation industries, where low density is particularly important, undoubtedly come first [2, 8, 19, 51-53]. Although Al foams are widely produced and used among metallic foams due to their many superior properties [6, 54-56], industrial experience shows that almost all metals can be converted into foam metal. Materials such as Mg, Zn, Pb, Fr, Ni, Ti, Cu, brass and all its alloys [57-64] and Al3Ni, Al-Cu, MMC, metallic glass can also be converted into foam metal [65].

The mechanical properties of metallic foams, especially those reinforced with ceramic particles, are far superior to polymeric foams and other unreinforced foam materials [56]. Their high temperature resistance and preservation of structure and properties at these temperatures are among their important differences [66].

In many materials, weight reduction and good mechanical properties can be achieved simultaneously with minor changes or treatments [3-5]. Therefore, composite foams reinforced with various reinforcement elements are preferred where high strength is required. Fine ceramic powders are added as reinforcement elements to ensure stability during the foam production phase with PM.

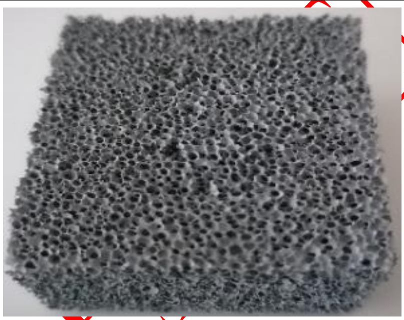

Figure 1. Pore structure of Al foam material with open pore structure. (Açık gözenek yapısına sahip Al köpük malzemesinin gözenek yapısı)

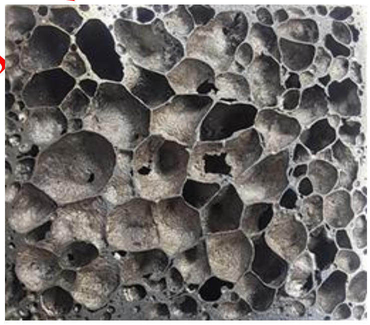

Figure 2. Pore structure of Al foam material with closed pore structure. (Kapalı gözenek yapısına sahip Al köpük malzemesinin gözenek yapısı.)

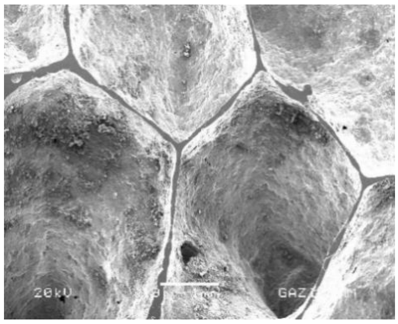

Figure 3. SEM image of the foam structure consisting of thin and homogeneous cell walls in %2 Si_3N_4 reinforced Al-based foam material. (%2 Si3N4 takviyeli Al esaslı köpük malzemesinde ince ve homojen hücre duvarlarından oluşan köpük yapısının SEM görüntüsü.)

Examples of commonly used reinforcement materials are SiC, Al2O3, TiB2, B4C or Si3N4. [67-76]. These ceramic particles increase the viscosity of the melt, make the flow more difficult and reduce the downward drainage of the liquid by pore growth, resulting in a more homogeneous pore structure [77, 78]. The homogeneous pore structure causes many properties specific to metallic foams, especially mechanical properties, to be exhibited homogeneously throughout the material. The particles added as reinforcement elements adhere to the gas-liquid interface during the foaming process and reduce the pressure differences between the plateau boundary and the pore walls by modifying the slope of the foam walls [79-81].

Although studies on open and closed pore metallic foams are being conducted, closed pore metallic foams are more popular because they exhibit higher mechanical properties. [48, 70, 82-90]. The development of foam technology has highlighted the need for a more scientific understanding of foam stability, and detailed studies have been and continue to be conducted at many universities and research institutes. [1, 91, 92]. Studies show that in addition to pore morphology, the amount, size and purity of the reinforcement elements added to the structure are effective on the stability and mechanical properties of the foam material [72, 79, 93-96]. Therefore, in cases where strength is important, the use of reinforced composite foams has been suggested in addition to foams with small pore sizes and thick cell walls. [67, 68, 77, 91, 97].

Different production methods are used in the production of closed-cell foam. The most commonly used methods are melting, casting and PM methods. Some of these are named according to their production methods, while others are named according to the manufacturer's trade name or production method. The most common ones produced with the PM method are; IFAM [98-100] Alu-Foam, Schunk and Alulight Mepura methods [52, 74, 98, 101-104].Studies have shown that many properties of the foam material depend on the pore structure, shape, size and foam density [3, 25, 32, 105]. It has been reported that the density and pore size of the foam material also depend on the amount, type, size, foaming temperature and duration of the foaming agent [27, 106]. Studies have shown that the matrix and reinforcement element powder size and the foaming agent particle size also affect the pore structure and pore size. It is important that the properties of the foaming agent used are compatible with the matrix material. The most important of these properties are the melting temperature of the matrix material and the decomposition temperature of the foaming agent. The most commonly used foaming agent in Al foam production is TiH2, but ZrH2 and CaCO3 are also used. Foaming agents such as CaH2, MgCo3, CaSO4, FeSO4, PbCO3, PbO, Na3N are also used at certain temperatures and pressures, although not very intensively [99, 106-109]. This review provide a comprehensive investigation into the production methods, types, properties, and application areas of metallic foams, with a particular focus on aluminum-based foams produced via the Powder Metallurgy (PM) method.

2. STANDARD POWDER METAL PRODUCTION METHOD (STANDART TOZ METAL ÜRETİM YÖNTEMİ)

Although PM foam production methods, known by various trade names, vary slightly from one another, the basic production method is based on the principle of homogeneously mixing a foaming agent added to metal powders, compressing them at room temperature or in a hot mold, and then foaming them at a temperature close to the melting point of the base material [28, 71, 100, 101, 110-115]. This method provides a cost-effective and scalable pathway for producing closed-cell metallic foams with controlled porosity and desirable mechanical performance, making it a cornerstone in both academic research and industrial applications.

In the production of Al foam, the process begins with mixing the starting powders (such as foaming agent, Al powder and/or reinforcement element) as shown in Figure 4. The green strength is imparted to the mixed powders by cold pressing process. [116]. The powder block, which is still in its raw density, is then hot extruded or hot rolled, taking into account the dimensions of the material to be produced [38, 87, 103, 117-119]. In case of hot pressing of powder, foaming agent and reinforcing element, a preform is obtained which can be foamed directly without any additional process such as rolling or extrusion. This process has been widely used by Gazi University PM team recently [1, 118, 120]. Thus, as shown in Figure 5, compressed and foamable preform samples with a homogeneous structure consisting of the reinforcement element, foaming agent, and base metal are produced [110, 121].

However, in the case of cold pressing, after the rolling process, cracks occur at the edges of the preform materials. In order to prevent gases from escaping from the cracks and pores formed at the edges and near-edge areas during the subsequent foaming process, these areas are cut before the foaming process. Many literature sources indicate that Al foam alloys are generally foamed with TiH_2 [122]. As a result of heating TiH_2, which is used as a foaming agent for Al and its alloys and is homogeneously distributed in the structure, to around the melting point, expansion is observed in the material with the gas released by the separation of titanium and hydrogen (hydrogen gas is released), and closed-pore foam is formed [87, 117, 123-125]. Hydrogen release in TiH_2 starts at about 450ºC and continues at higher temperatures [25, 126]. This temperature is well below the melting point of commercial Al alloys. Optimization of process parameters such as temperature, holding time, and foaming agent content is essential for achieving uniform pore distribution and avoiding collapse. Keeping the material at the foaming temperature for a long time causes the foam structure to collapse, the main structure to deform and some pores to merge and enlarge [56].

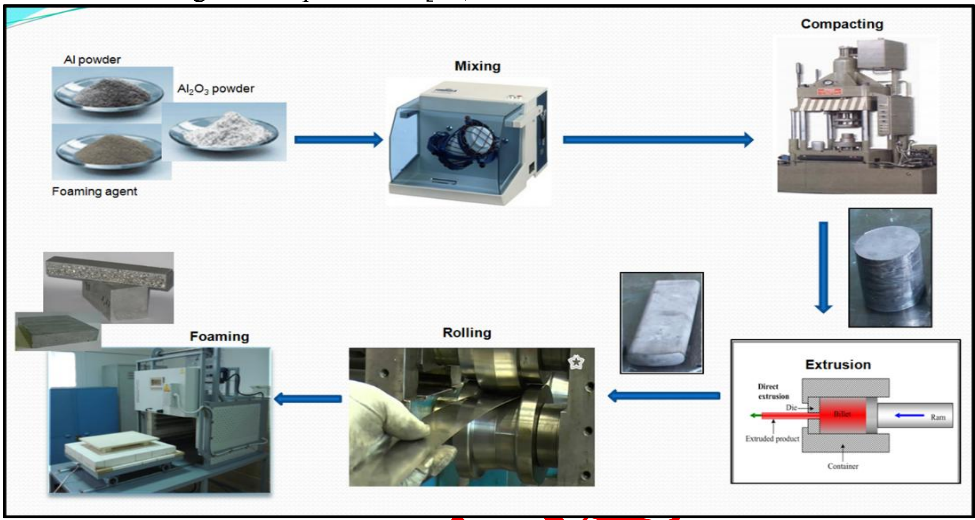

Figure 4. Illustration of the stages of classical metallic foam production using the PM method. (PM yöntemi kullanılarak klasik metalik köpük üretiminin aşamalarının gösterimi.) [1, 25, 127].

If the foaming process is carried out within appropriate parameters, a homogeneously distributed pore structure with the desired properties is obtained. In cases where mechanical properties are important, foam materials with fine pores and thick cell walls are generally preferred, while foam materials with larger pores and thin cell walls are preferred in places where sound and heat insulation are required. One of the most important parameters affecting the foam structure is the amount of foaming agent. In the case of using low amounts of foaming agent, high density and fine porous foam material is obtained, while in the case of using high amounts of foaming agent, low density, coarser porous and thin pore wall foam structure is obtained [110, 111].

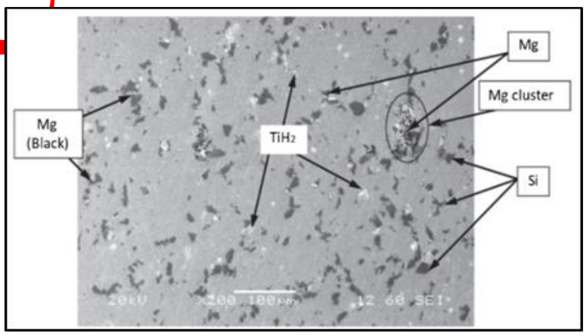

Figure 5. Appearance of homogeneously dispersed phases formed by milling and subsequently pressing the Al-based metallic foam material in a three-dimensional turbola for 45 minutes [110]. (Al bazlı metalik köpük malzemenin frezelenmesi ve ardından üç boyutlu bir turbola içinde 45 dakika boyunca preslenmesiyle oluşan homojen olarak dağılmış fazların görünümü.)

Figure 6 and Figure 7 show the foam structures of a series of materials reinforced with 5% Al_2O_3 produced at different times and temperatures using different amounts of foaming agent. As can be seen in the figure, while finer and more homogeneous foam structure is obtained at low amounts of foaming agent or low foaming temperature, foams with coarser porous structure and thin pore walls are obtained with the increase in the amount of foaming agent or foaming temperature [95, 97].

In addition, as seen in Figure 7.c and Figure 7.d, keeping the foaming time longer than necessary or increasing the amount of foaming agent will first cause the foam structure to grow and then collapse and the structure to deteriorate. Partial foam wall melting in the material occurs due to high foaming temperature, long-term foaming process or use of high amount of foaming agent. If any or all of these are excessive, the foam structure is doomed to grow by merging or collapse. Figure 8 shows the foam structure consisting of thin cell walls and the next stage of cell wall coalescence and collapse.

To prevent collapse, the prepared foamable preform material must be checked frequently during the foaming process, the foam sample must be carefully monitored during the foaming stage, and it must be removed from the furnace before collapse begins. Figure 9 shows a furnace specifically designed and manufactured by the Gazi University Powder Metallurgy team for foam material production, featuring a movable base plate, a fan for uniform heat distribution, and an inspection window for monitoring foaming stages. Figure 10 shows some examples of metallic foam produced using the PM method at the Department of Metallurgical and Materials Engineering, Faculty of Technology, Gazi University.

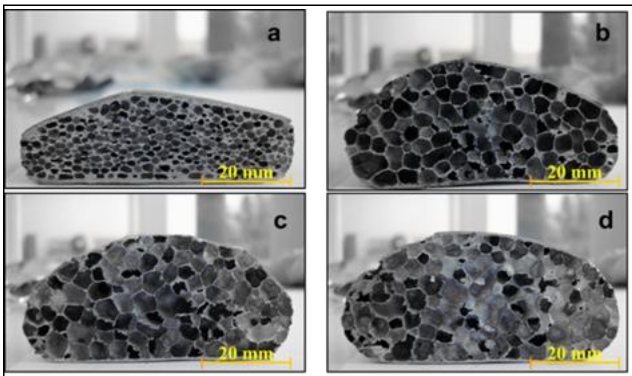

Figure 6. Pore structures depending on the TiH2 amount in samples foamed at 670°C from Alumix 231 powder 5% Al2O3. a) 0.5% TiH2, b) 1 % TiH_2, c) 1.5 % TiH_2 and d) 2% TiH_2 [97, 128]. (%5 Al2O3 içeren Alumix 231 tozundan 670°C'de köpürtülen numunelerde TiH2 miktarına bağlı olarak gözenek yapıları. a) %0,5 TiH_2, b) %1 TiH_2, c) %1,5 TiH_2 ve d) %2 TiH_2.)

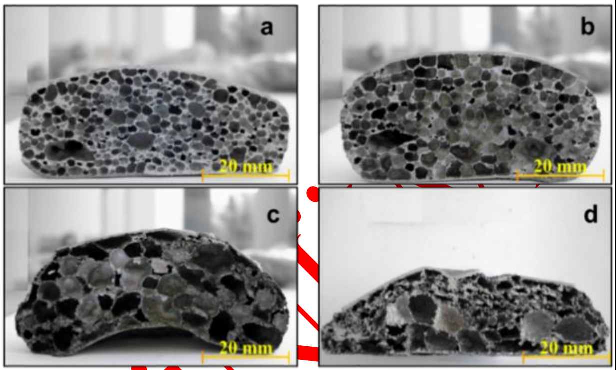

Figure 7. Pore structures depending on the TiH_2 amount in the samples produced at 710°C from Alumix 231 powders containing 5% Al_2O_3. a) 0.5 TiH_2, b) 1% TiH_2, c) 1.5 TiH_2 d) 2% TiH_2). Figures a and b show ideal foam structures with fine and coarse pore structures, respectively, while Figure c shows the beginning of collapse in the pores, and Figure d shows complete degradation of the pore structure [97, 128]. (%5 Al2O3 içeren Alumix 231 tozlarından 710°C'de üretilen numunelerde TiH2 miktarına bağlı olarak gözenek yapıları. a) 0.5 TiH_2, b) %1 TiH_2, c) 1.5 TiH_2 d) %2 TiH_2). Şekil a ve b'de sırasıyla ince ve iri gözenek yapılarına sahip ideal köpük yapıları gösterilirken, Şekil c gözeneklerde çökmenin başlangıcını, Şekil d ise gözenek yapısının tamamen bozulmasını göstermektedir.)

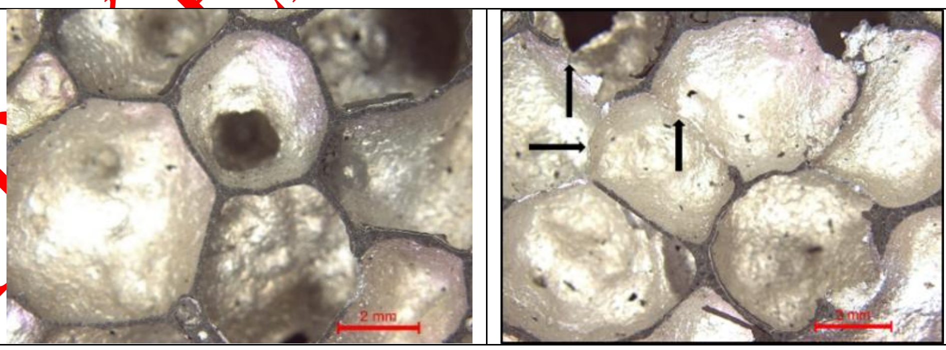

Figure 8. The macrostructure image on the left shows the general pore structure and thin, uniform wall thicknesses, while the image on the right shows partial foam wall melting due to high foaming temperature, long foaming time, or high concentration of foaming agent. Prolonged exposure to high temperatures caused the foam to collapse. The melted wall regions are indicated by arrows in the image. (Soldaki makro yapı görüntüsü, genel gözenek yapısını ve ince, düzgün duvar kalınlıklarını gösterirken, sağdaki görüntü, yüksek köpürme sıcaklığı, uzun köpürme süresi veya yüksek konsantrasyonda köpürtücü madde nedeniyle kısmi köpük duvar erimesini göstermektedir. Köpüğün yüksek sıcaklıklara uzun süre maruz kalmak köpüğün çökmesine neden oldu. Ergimiş duvar bölgeleri görüntüdeki oklarla belirtilmiştir.)

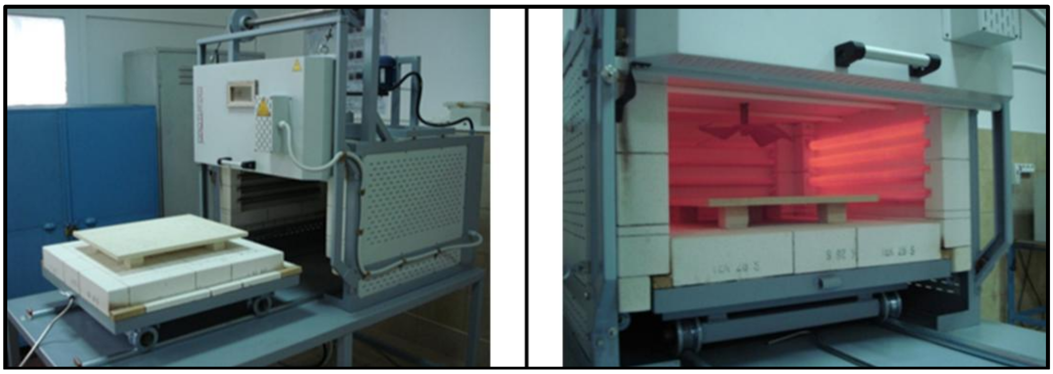

Figure 9. shows a furnace specifically designed and built at Gazi University for foam production. The furnace has a movable base plate, a fan to ensure uniform heat distribution, and an inspection window to control the foaming stages. (Şekil 9, Gazi Üniversitesi'nde köpük üretimi için özel olarak tasarlanıp kurulan bir fırını göstermektedir. Fırın, hareketli bir taban plakasına, homojen ısı dağılımı sağlayan bir fana ve köpüklendirme aşamalarını kontrol etmek için bir kontrol penceresine sahiptir.)

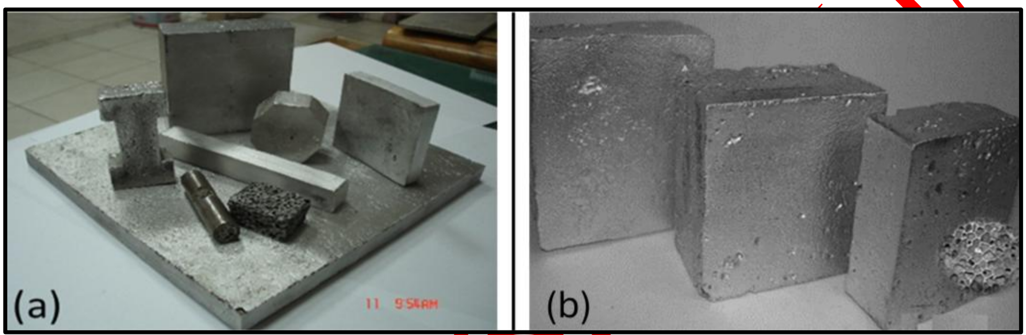

Figure 10. Examples of reinforced and unreinforced Al foam samples of various shapes produced at Gazi University Faculty of Technology [34]. (Gazi Üniversitesi Teknoloji Fakültesi'nde üretilen çeşitli şekillerdeki takviyeli ve takviyesiz Al köpük numunelerine ait örnekler.)

Figure 11 and Figure 12 show the effects of different temperatures and different foaming agent (TiH_2) ratios on the linear expansion and density in Al foam containing 5 % Al_2O_3. As seen in Figure 11, in samples produced from Alumix 231 (Al-2.5% Cu, 0.5% Mg, 14% Si) powder containing 5% Al2O3, expansion of approximately 250% was observed at 650, 670, 690 and 710 oC with the addition of 0.5% TiH2, while in samples foamed with the addition of 1% blowing agent, the highest expansion was obtained at 690 oC with 460%. The lowest expansion was obtained at 650 oC with 300%. When 1.5% and 2% foaming agent was used, there was not much change at 650, 670 and 690 °C and a very high expansion of about 460% was observed, close to the value obtained at 1%. These results indicate that more than 1% foaming agent does not contribute to foaming at these temperatures. When the graph is evaluated in general, while samples with acceptable density values (less than 0.8 g/cm3) were obtained at all temperatures tested in all samples containing 1% and above TiH2, this value could only be achieved in the sample foamed at 710 oC using low frother (0.5% TiH2).

As seen in Figure 12, the highest density in the tested sample was obtained in samples containing 0.5% TiH2 at a foaming temperature of 650 °C, while the lowest density was obtained in the sample containing 2% TiH2 at a foaming temperature of 690 °C. From these results, it can be said that the increase in the foaming temperature and the foaming agent cause a decrease in density. Since the increase TiH_2 ratio will cause more gas release in the sample at foaming temperature, the structure will be more porous and the sample will have lower density. The reason for the decrease in the density of the sample due to the increase in foaming temperature and foaming agent amount is the thinning of the pore walls, the merging in the pores and the formation of large gas voids [111, 112].

Figure 13 shows macrostructure images obtained during compression tests on Al foam. Foam metal exhibits uniform strength, as expected, during compression testing. This is one of the important properties of materials. Although the wall thickness of the foam material is not uniform throughout, crushing occurs almost uniformly throughout the compression test. Figure 14 shows the initiation and progression of a crack in the material in a transverse repture strength test. Although such porous structures are successful in compression and shock absorption, they cannot show the same strength in tensile tests and transverse repture strength tests due to the notch effect of the porous structure and surface defects they contain. As can be seen in the figure, due to a defect located on the surface of the foam material or just below the surface, these areas act as crack initiation with the tension applied to the sample and eventually fracture is occurs with the progression of the crack. If the surface of the material contains no obvious defects in the non-foaming region, known as the shell, and the pores within the structure are homogeneous, the material will exhibit uniform bending behavior without fracturing or separating, as seen in Figure 15. Figure shows the pore structure of two different foam materials deformed at 656°C and a cross-sectional view showing the deformation patterns in the pore structures. In Al foam materials with a uniform surface shell structure, more uniform deformation is observed during bending, and no cracking or fracture occurs [48, 83].

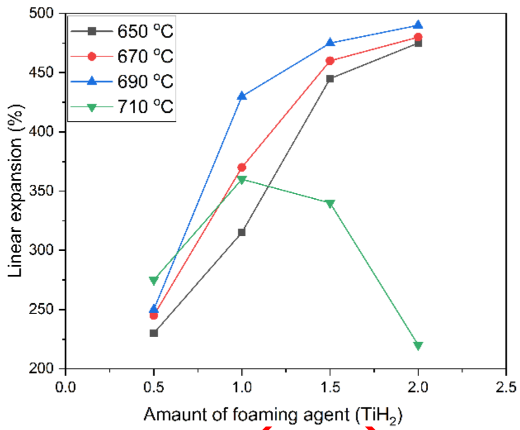

Figure 11. Effect of different temperature and amount of foaming agent (TiH_2) on linear expansion in Al foam [97, 128]. (Farklı sıcaklık ve köpük oluşturucu madde (TiH_2) miktarının Al köpüğünde lineer genleşmeye etkisi.)

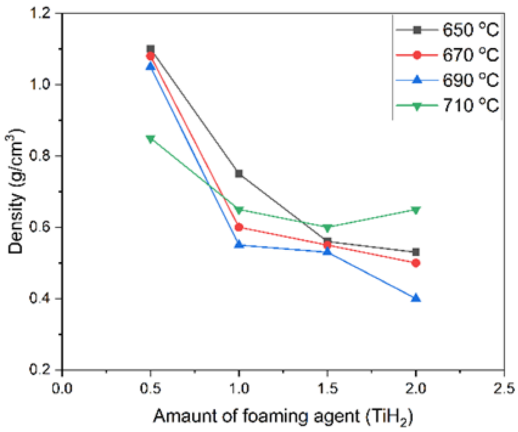

Figure 12 Effect of different foaming temperature and amount of foaming agent (TiH_2) on the density of Al foam (Farklı köpükleme sıcaklığı ve köpükleme maddesi (TiH_2) miktarının Al köpüğün yoğunluğu üzerindeki etkisi) [97, 128].

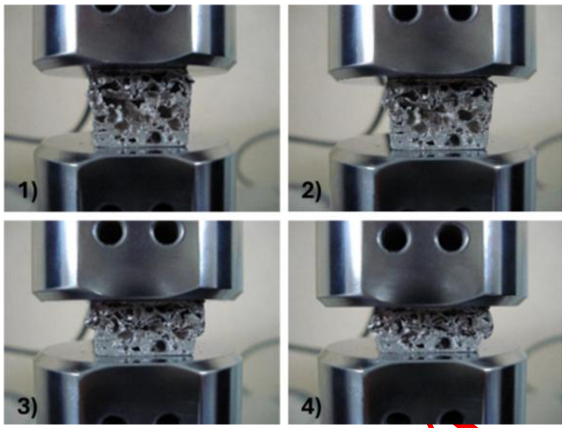

Figure 13. Gradual display of deterioration of foam material due to deformation applied during compression test. (Basınç testi sırasında uygulanan deformasyon nedeniyle köpük malzemesinin kademeli olarak bozulması)

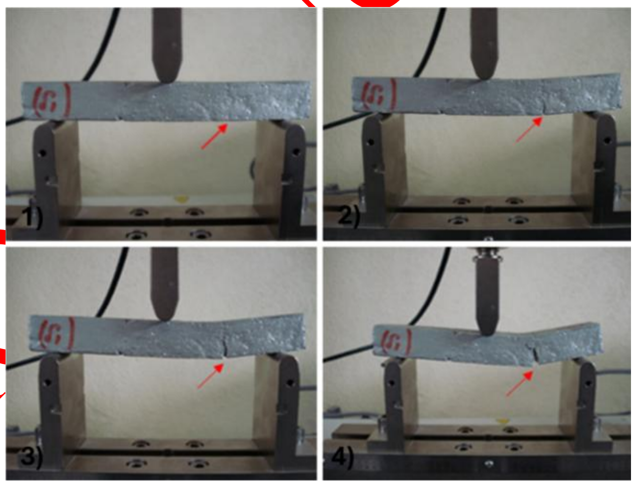

Figure 14. In transverse rupture strength test, crack initiation, propagation and fracture stages of the specimen due to a small defect in the material. (Enine kopma dayanımı deneyindeki, malzemedeki küçük bir kusurdan dolayı numunede çatlak başlangıcı, yayılması ve kırılma aşamaları)

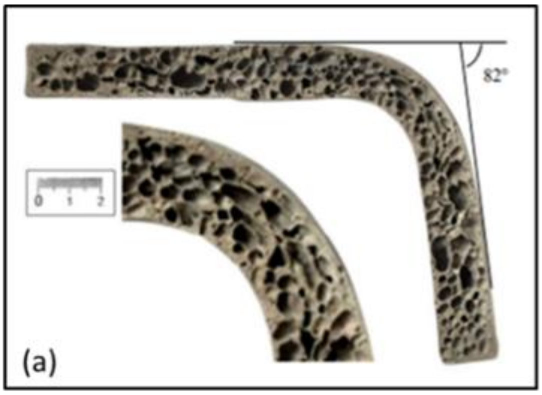

Figure 15. Change in the macrostructure after free deformation of Al (AlMg1Si0.6TiH2 0.8) foam material at 656 °C. [48, 83]. (Al (AlMg1Si0.6TiH2 0.8) köpük malzemesinin 656°C'de serbest deformasyonundan sonra makro yapısındaki değişim.)

3. POWDER METAL ALUMINIUM FOAM TYPES
(TOZ METAL ALÜMİNYUM KÖPÜK TÜRLERİ)

3.1 Al Foam Sandwich (Al Köpük Sandviç)

Sandwich foams, which are a newer method compared to the classical foam material production method, can also be produced with the PM method. In sandwich foam production, the two surfaces of the foam material are bonded with non-foaming sheet metals using different methods. This process varies according to the type of foam and the production method. Sandwich foam production is basically done in two ways in terms of bonding mechanisms: natural bonding (in-situ bonding) and artificial bonding (ex-situ bonding) [129-132]. The main difference here is whether the bond forms simultaneously with foaming or after the foaming process is completed. Natural bonding generally provides stronger and more uniform mechanical properties compared to artificial bonding.

In the production of sandwich foam with the natural bonding method, while the foam is being formed, the sandwich structure is also being formed. In this widely used method, the foamable preform material is heated together with the non-foaming sheet metal placed on its two surfaces. In this method, while the foamable material in the inner part expands in volume, the metallic foam is formed, while the non-foaming sheet metals are obtained as another layer and adhere to the foaming material from both outer surfaces. The most important disadvantage of the method is that the alloy combination is limited. This limitation is mainly due to the difficulty of matching melting points and ensuring proper adhesion without causing deformation in the outer plates. In this method, it is like a race of time for the foam to expand completely without melting the surface plates [130]. The most important issue to be considered in the production with natural bonding method is that the surface sheet metals have a higher melting point than the melting point of the foamed inner material. For this, materials such as stainless steel and Ti can be used on Al foam surfaces, while pure Al sheet metals can be used on the surfaces of foamable Al materials with a low melting point containing 12% Si. This method, developed at the Fraunhofer Institute in 1992 [133] is quite easy to apply compared to other methods. On the other hand, the surface of the preform material ready to be foamed is coated with plates by applying methods such as rolling and pressing [134]. After this process, the foamable preform (metal alloy) forms the main layer in the inner part, while the plate (usually Al, Ti or stainless steel) placed on two surfaces forms a triple layer required for the sandwich structure. If necessary, the coated sample is subjected to pre-shaping before foaming. As a final process, the sample is foamed by taking into account temperature and time. Precise control of these parameters is critical because prolonged foaming or high temperatures may cause pore collapse and poor surface bonding. As a result, a metallic bond is formed between the Al alloy foam and the plate. This dense bonding type provides maximum force transmission between the composite components [132, 135, 136].

A cross-sectional view of an Al sandwich foam is shown in Figure 16. As seen in the figure, the interior consists of porous Al foam material and a non-foaming Al-based material on both surfaces. Because prolonged foaming time or high foaming temperature will melt the metal on the exterior, foaming time and temperature must be carefully selected when producing foam using this natural bonding method [137].

Figure 16. Sectional view of Al sandwich foam. While it is seen that the material with a higher melting point than the melting point of the foam material on both surfaces of the structure is perfectly bonded to the foam by diffusion during production, the main foam structure is present in the inner parts [1]. (Al sandviç köpüğün kesit görünümü. Yapının her iki yüzeyindeki köpük malzemesinin erime noktasından daha yüksek erime noktasına sahip malzemenin, üretim sırasında difüzyon yoluyla köpüğe mükemmel bir şekilde bağlandığı görülse de, esas köpük yapısı iç kısımlarda mevcuttur.)

Another way to produce sandwich foam is to provide the desired sheet material to be formed to the surface of the previously produced foam material by various means. In this method, also known as artificial bonding, the surface sheets are bonded to the foam by various methods after the foaming process. The reason why this method is called artificial bonding is that the surface sheets are bonded to the foam by various methods after the foaming process. Bonding using various adhesives or bonding with soldering are some of the joining techniques frequently used in this method. It is a very common method due to both its ease of production and its variety. [129, 130, 138]. While this approach simplifies manufacturing, it usually results in weaker interfacial strength compared to natural bonding. Additionally, the adhesive layers may limit the thermal stability of the final component. It is quite difficult to produce sandwich foam with artificial bonding [42, 114]. Even more complex shaped samples are impossible to produce artificially. However, with the natural bonding method, it is possible to obtain products in the desired shapes by shaping the sample before or after foaming. Al sandwich panels are the most suitable foam method for automotive body structure due to their high hardness in surface layers and significant weight reduction [2]. This makes them particularly valuable in crash-prone areas such as door panels and structural reinforcements, where lightweight energy absorption is essential. Especially preferred in environments requiring high external surface resistance is stainless steel-Al-stainless steel, also known as SAS (stainless steel - aluminum - stainless steel) sandwich structures provide advantages in places where high impact resistance is required and in cases where the use of fastening elements is required [35, 47, 139].

3.2. Spherical Al Foam Production (Küresel Al Köpük Üretimi)

Spherical foams, also known as APM (Advance Pore Morphology), are a new foam production method developed at Frounhofer IFAM. In this method, which is quite suitable for mass production, a large number of spherical preform materials (usually small sheet metals cut into squares) are exposed to heat in moving conveyor furnace, during which foaming occurs. The formation of spherical shapes is mainly due to surface tension forces, which naturally minimize the surface area during heating. In laboratory production, deformed square-cut foamable sheet metals are exposed to foaming temperature and the material takes a spherical shape due to surface tension [18, 125, 140-144]. Then, the foam materials are coated with an adhesive polymeric material and placed in a mold with the desired geometry [145]. It is usually activated at medium temperature (100-200°C), cured and used by removing from the mold at room temperature. Spherical shaped foams are less prone to defects such as non-uniform pore structures, which are usually encountered in larger Al foams due to liquid drainage during the foaming process [24, 146]. Because each particle foams individually, the process is more controlled and reduces density variations that are typical in bulk foam production.

Spherical foams are generally produced with a diameter of 6-15 mm and are placed inside profiles and pipes, as well as between two or more sheet metal sheets, bonded with a suitable adhesive to form a composite structure and have high resistance to compressive stress [142, 147-149]. Although not using molds in their production provides an advantage, it is a problem that large-sized spherical foams cannot be completely spherical in their production. Gravity-induced flattening can distort large particles, but using supporting molds during foaming solves this issue. While there is no problem during production in small-sized spherical foams, flattening and deviations from sphericity are seen in the area of the foam in contact with the ground due to its own weight in the production of large-sized spherical foam. In order to prevent this, perfect sphericity can be achieved by preparing metal molds suitable for the desired spherical foam diameter. Figure17 shows profile structures filled with various diameters using foam materials produced in diameters of 6, 8, and 10 mm, using molds prepared by the Powder Metallurgy Group of Gazi University to ensure perfect sphericity. This type of spherical metal foams are used especially in the profiles of the front sides of vehicles or for energy absorption in the event of a collision in environments subject to compression [31, 55, 70, 143, 150-154]. Thanks to their composite material layers, components that increase thermal conductivity, impact energy absorption, advanced pore morphologies, vibration damping and complex internal void filling capabilities, spherical foams can be used in various applications to reinforce hollow structural parts. These materials can offer effective solutions in a wide range of industries, especially by providing resistance to local wall buckling [155, 156].

Spherical foam materials can be reinforced with various ceramic materials as in other classical production methods. In the experimental studies, it was observed that up to 8% reinforcement element did not have a negative effect on foamability in the production of SiC reinforced spherical foam, and even when a high amount of foaming agent (e.g. 2%) was used, adding more reinforcement element prevented foaming [97]. Figure 18 shows the foamability of Al foam reinforced with various amounts of SiC up to 20% depending on the amount of reinforcement element.

As seen in the figure, if there is more than 8% SiC, sufficient foaming cannot be achieved and samples far from sphericity are obtained. As seen in the cross-sectional structure of the reinforced Al foam material in Figure 19, while a regular cell structure is observed in foam materials containing up to 4% SiC, deterioration in the cell structures of materials containing more reinforcement elements is noticeable. Similarly, it has been reported that sufficient foaming cannot be observed in materials containing 8% and more SiC reinforcement elements and that homogeneous foaming cannot be achieved [56].

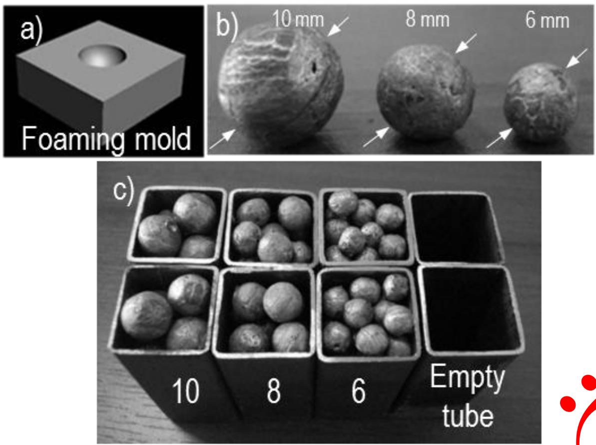

Figure 17. Mold used to ensure perfect sphericity in spherical foam production (a), foam materials produced with different diameters (b), and hollow profile structures filled with spherical foam (c) [40]. (Küresel köpük üretiminde mükemmel küreselliği sağlamak için kullanılan kalıp (a), farklı çaplarda üretilen köpük malzemeler (b) ve küresel köpükle doldurulmuş içi boş profil yapılar (c))

The graph in Figure 20 shows the effect of adding SiC particles to pure Al powder on density and linear expansion. As can be understood from the graphs and macrostructure images, SiC particles added to Al negatively affect both foaming and density and hence linear expansion when they are above 8%. Therefore, researchers recommend a reinforcement element addition of less than 8%, depending on the reinforcement element added. In this experimental study, it was reported that the most suitable result was obtained in samples with 4% SiC addition [56]. In another study on the effect of particle addition on foaming and material properties, contrary to the above results, there are also findings that the reinforcement element increases the compressive strength up to 8% and 10% [71, 84, 94].

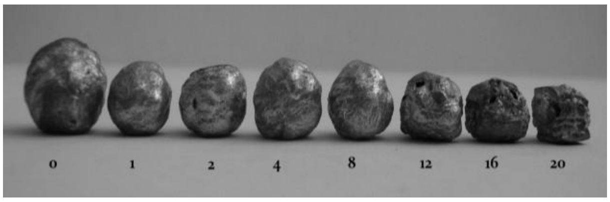

Figure 18. The effect of adding up to 20% SiC particles to pure Al powders on spherical foam formation. While the highest linear expansion is observed in the unreinforced sample, the deviation from sphericity and the increase in foaming difficulty are notable as the SiC content increases in samples with a reinforcement ratio greater than 8% [1, 56]. (Saf Al tozlarına %20'ye kadar SiC partikülü eklemenin küresel köpük oluşumu üzerindeki etkisi. En yüksek doğrusal genleşme takviyesiz numunede gözlemlenirken, takviye oranı %8'den fazla olan numunelerde SiC içeriği arttıkça küresellikten sapma ve köpürme zorluğundaki artış dikkat çekicidir.)

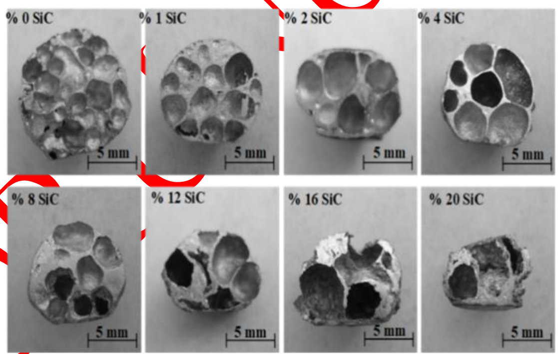

Figure 19. Sectional views of Al-based foam materials containing different proportions of SiC particles [1, 56]. (Farklı oranlarda SiC parçacıkları içeren Al bazlı köpük malzemelerinin kesit görünümleri.)

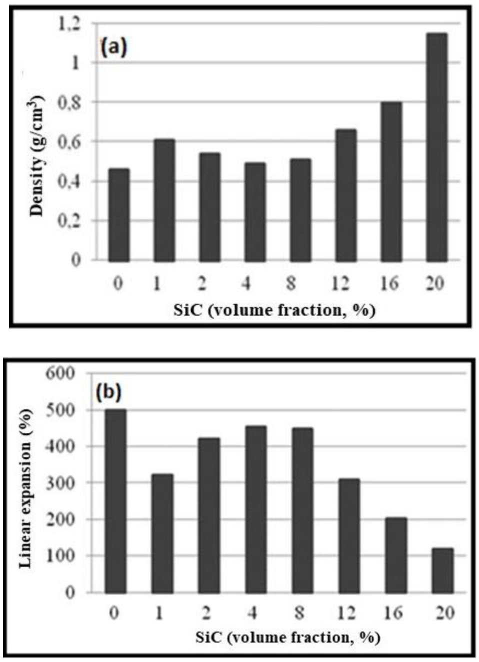

Figure 20. Effect of SiC particles added to pure Al powder on (a) density and (b) linear expansion [56, 97]. (Saf Al tozuna eklenen SiC parçacıklarının (a) yoğunluk ve (b) doğrusal genleşme üzerindeki etkisi.)

In foam production, the inability to achieve low density or sufficient linear expansion with both AFM and classical PM methods poses a problem. The reason for this is the inadequacy of the deformation applied to the material before foaming or the inability to prevent the gas trapped in the deformed preform samples from moving away from the pores or cracks during the foaming process. Another problem encountered in foam production is the collapse of the foam material caused by the gas trapped in the molten metal remaining in the structure for a long time and then leaving the structure. Collapse is usually caused by high foaming temperature, long foaming duration or excessive amounts of foaming agent. All three situations cause the pore structure to change, deteriorate and increase the density with the start of collapse in the foamed material.

Figure 21 shows the porosity rate in samples deformed at different rates and subjected to foaming at 690ºC for different durations. In this study, where the optimum foaming time was specified as 3.5 minutes, high foaming rates and homogeneous pore structure (70-80% porosity) were obtained in samples deformed by 50% and 70%, while much lower pore rate (such as 30%) and inhomogeneous pore distribution were detected in the material deformed by 10%. In almost all samples in the study, collapse in foams and deterioration in pore structure were detected in times longer than 3.5 minutes.

Figure 22. shows the linear expansion rates of 50% deformed samples at various foaming temperatures. As seen in Figure 22, while 300-400% linear expansion was observed in Al materials subjected to foaming at 650 ºC, 670 ºC and 690 ºC after 3.5 minutes, it was observed that this rate decreased with the increase of foaming time. In the samples foamed at 710 oC under the same conditions, foaming occurred in a shorter time and collapse occurred in a much shorter time. The highest linear expansion in this sample was around 250%. The appearance of the samples foamed for 3.5 minutes after being deformed at different speeds is given in Figure 23. While sufficient foaming was not observed in the samples deformed by 10%, a fairly regular spherical structure was formed in the samples deformed by 30% and 50%. When the deformation rate increased to 70%, regular foaming was observed first, and then rapid collapse occurred. The sandwich structure obtained from spherical Al foam in two sheet metals is seen in Figure 24. The behavior of spherical foams with a diameter of 10 mm under various pressure test conditions is shown in Figure 25. As seen in Figure 25, collapses during compression testing are generally caused by a defect located on the surface of the spherical foam material or just below the surface. Figure 24 shows an AFM foam material produced as a sphere and then arranged into a sandwich. When the appropriate binder is used, no separation is observed in the spherical foams, even at high deformation rates. As seen in Figure 25, materials deformed by 50% and 70% and foamed for 3.5 minutes have high volumetric porosity and a homogeneous pore structure, while less deformed materials (such as 30% and 10%) are not fully foamed and have low porosity, as can be seen from the cross-sectional images.

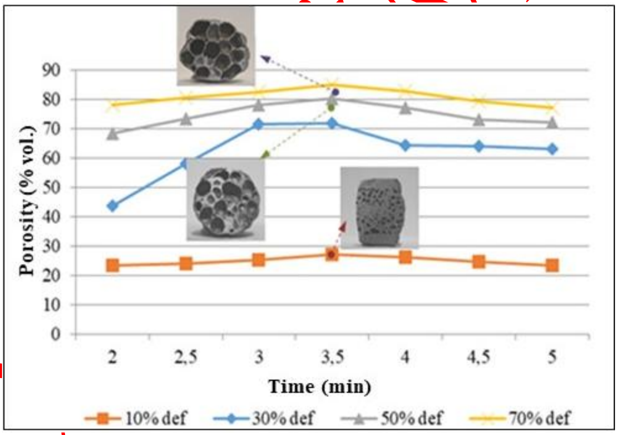

Figure 21. Sectional views of spherical foams formed after 3.5 minutes when the porosity ratio and optimum foam structure were obtained in samples subjected to foaming process at 690 ºC for different durations [140]. (690 ºC sıcaklıkta farklı sürelerde köpürtme işlemine tabi tutulan numunelerde gözeneklilik oranı ve optimum köpük yapısı elde edildiğinde 3,5 dakika sonra oluşan küresel köpüklerin kesit görünümleri.)

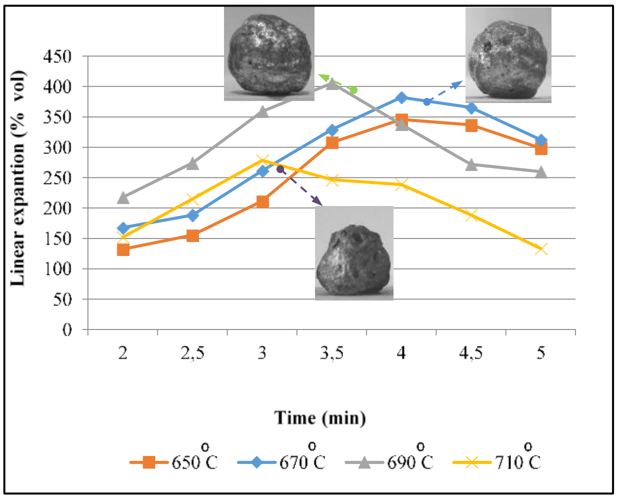

Figure 22. Linear expansion rates of 50% deformed samples at various foaming temperatures [140]. (Çeşitli köpürme sıcaklıklarında %50 deforme olmuş numunelerin doğrusal genleşme oranları.)

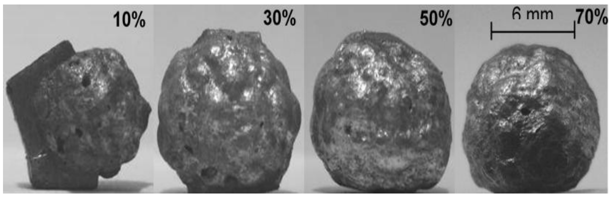

Figure 23. The appearance of the samples foamed for 3.5 min after being deformed at various rates [140]. (Numunelerin çeşitli hızlarda deforme edildikten sonra 3,5 dakika köpürdüğü gözlendi.)

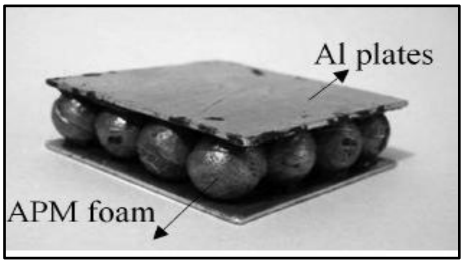

Figure 24. Sandwich spherical foam consisting of Al spherical foams placed between two sheet metal plates [140]. (İki sac levha arasına yerleştirilmiş Al küresel köpüklerden oluşan sandviç küresel köpük.)

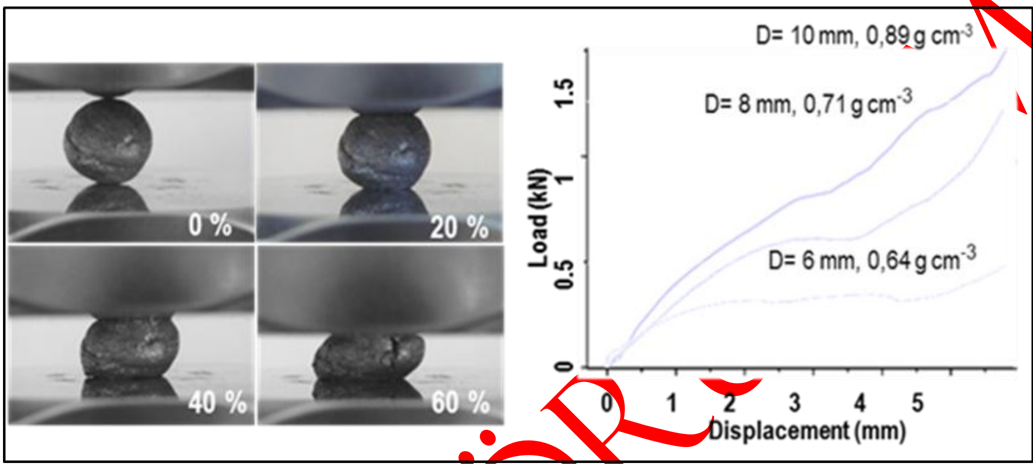

Figure 25. Deformation state of a spherical shaped foam material during compression test and force-displacement curves of spherical shaped aluminum foams with different diameters [40]. (Küresel şekilli bir köpük malzemesinin basınç testi sırasındaki deformasyon durumu ve farklı çaplardaki küresel şekilli alüminyum köpüklerin kuvvet-yer değiştirme eğrileri.)

3.3. Al Foam Filled Profile Production (Al Köpük Dolgulu Profil Üretimi)

Although designed for energy absorption to reduce injuries and ensure the safety of drivers and passengers in the event of a vehicle accident, these materials have found a wide variety of applications. By reinforcing metallic foam into hollow pipes and profiles with various methods, significant advantages can be provided in terms of impact absorption without a significant increase in weight [6, 157]. In the method widely used in the production of foam-filled profiles, the preform material ready to be foamed is placed in a hollow mold or profile and expands when heated and takes the shape of the mold in which it is placed. This process ensures that the foam fully adheres to the inner walls of the profile, improving load transfer and preventing premature buckling. The parts produced as a result of this process look like a closed profile or pipe when viewed from the outside, but their internal structure is quite porous [123, 158]. The strength of these materials is also quite high [7, 144, 159]. Pipes and profiles filled with metallic foam show interesting shape and deformation characteristics during buckling. When used as a filling material inside the pipe or profile, the total energy absorbed is greater than the sum of the energy absorbed by the foam and the pipe separately. Studies [7, 160-162] show that foam-filled profiles provide 25-32% more strength than empty profiles [161] Figure 26 shows foamed Al-based foam materials in various profiles [99].

Figure 26. Al-based foam materials produced at Gazi University in various profile and pipe materials and their cross-sectional views [1]. (Gazi Üniversitesi'nde çeşitli profil ve boru malzemelerden üretilen Al esaslı köpük malzemeler ve kesit görünümleri.)

4. AREAS OF USE (KULLANIM ALANLARI)

Nowadays, due to the increasing need for high strength and lightweight materials, interest in the use of metallic foams as structural and functional materials has increased. Due to their properties such as vibration, sound and energy damping [42] intensive studies on their use continue in these and similar areas, especially in the automotive sector, as they are suitable for special requirements such as rail transportation systems, shipbuilding, lightweight constructions, aircraft and space industry, biomedical industry, engine manufacturing industry [6, 8, 109, 152, 163-166]. The application of metallic foams is not limited to aviation and automobile industry, but is also suitable for large bridges, roofs and other high potential applications in power plants, electrical industry and chemical industry, architecture and design field, where electromagnetic protection, structural damping, flame resistance and decorative surface structure are required [2, 104] In addition, it has found use in large machines thanks to its noise and vibration damping capacity.

In the automobile industry, where metallic foams are most commonly used, the use of foam materials in many different parts continues to increase. It is preferred instead of steel parts in parts such as sheet metal body construction, structural parts, trunk lid, engine hood, sliding roof, silencer and bumper because it reduces weight [19, 53, 104, 161, 165, 167, 168]. In addition, studies are being conducted on sandwich Al and Mg materials as the base sheet material of automobiles. It is also used in battery housings in electric vehicles to reduce weight and increase efficiency, as well as studies are being conducted as various battery materials [169] [170]. Figures 27-30 provide examples of various applications of foam materials. Because foam materials have low thermal conductivity, they are thought to have a longer lifespan compared to other materials. Since foam materials have low thermal conductivity, it is thought that they can have a longer life compared to other materials used. In addition, if metallic foam materials are used in the engine compartment, it is expected to cause fewer problems since heat transfer occurs with high convection due to porosity [171].

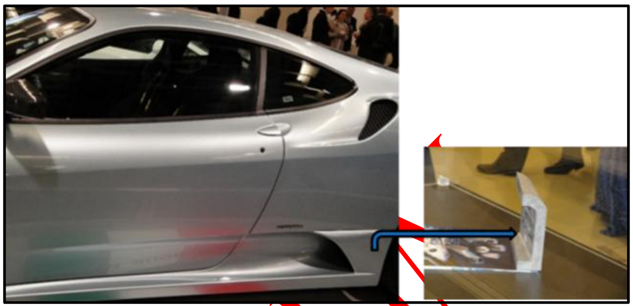

Figure 27. Use of Al-based foam as side support material in Ferrari [1, 33]. (Ferrari'de yan destek malzemesi olarak Al esaslı köpük kullanımı.)

Metallic foams are also used in the production of telescopic booms, lifting and transmission systems [172, 173], bicycle crank arms [129], helmets [174, 175], golf club carriers [135], pots production [129] production [117] and rocket parts [8]. In addition, they are used in the production of heat exchangers, catalyst supports, filters, bio- It is used in a wide range of areas such as medical implants, silencers, beds, sound and heat barriers and internal armor support plates [42]. They are used in a wide variety of applications, including heat exchangers, catalyst supports, filters, biomedical implants, silencers, bearings, sound and heat barriers, and internal armor support plates [32]. Al foam sandwich panels are widely used in the production of many products where lightness is important. It is used in the Ariane 5 Rocket as a two-cone shaped structure [8, 12]. This cone-shaped honeycomb structure has replaced high-cost and hard-to-obtain materials with Al foam sandwich panels. Thus, it both reduces weight and makes its use easier [172].

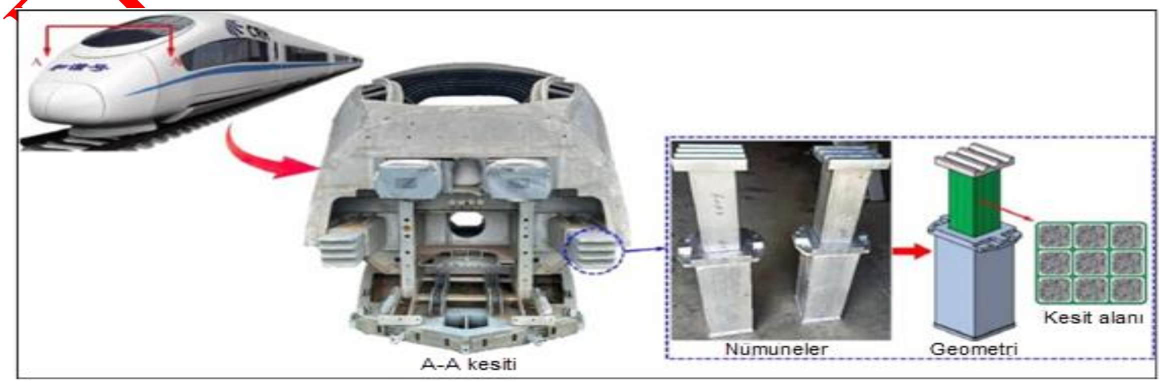

Figure 28. Al foam and honeycomb structure in MMC structure used for energy absorption in railway vehicles. Foams are placed within the profile for energy absorption purposes [165, 176]. (Demiryolu taşıtlarında enerji sönümleme amaçlı kullanılan MMC yapıda Al köpük ve bal peteği yapısı. Al köpükler profil içerisine enerji sönümleme amaçlı yerleştirilmiştir.)

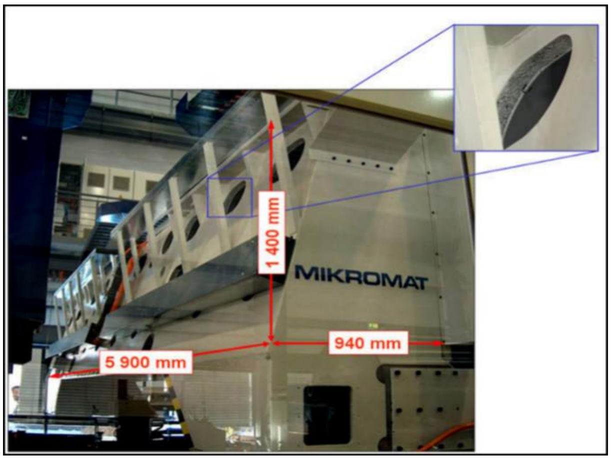

Figure 29. Foam reinforced sandwich structure used for sound and vibration damping in a 6 m long machine [177]. (6 m uzunluğundaki makinede ses ve titreşim sönümlemesi için köpük takviyeli sandviç yapı.)

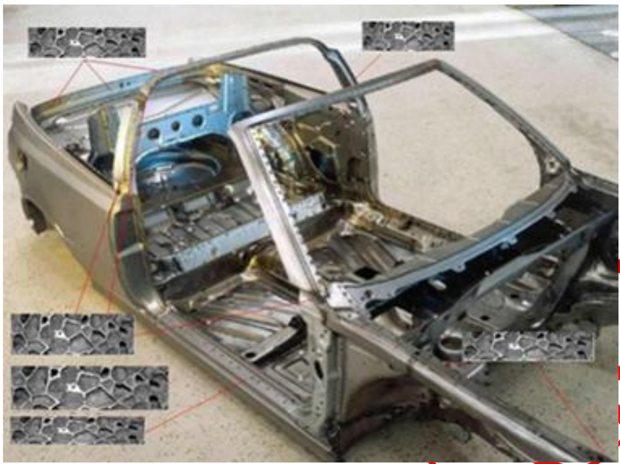

Figure 30. Use of metallic foam to protect drivers and passengers in areas of vehicles that are likely to be exposed to impact. [1, 178]. (Araçların darbeye maruz kalma olasılığı bulunan bölgelerinde sürücü ve yolcuların korunması amacıyla metalik köpük kullanımı.)

4.1 Integral Armor Material (Integral Zırh Malzemesi)

By utilizing the energy absorption feature of metallic foams, armored vehicles are covered with armor plates against the explosion effect they are exposed to. Although sufficient armoring is done and protection is provided in the vehicles, it is aimed for the personnel to receive the least damage from the shock effect at the moment of explosion. For this reason, as seen in Figure 31.a, B4C reinforced Al foam was placed inside the polymer-based composite armor plates used today and its use as a composite armor material was investigated. The main purpose here is to minimize the shock effect during the explosion. For this purpose, it was planned to use reinforced foam with both high strength and sufficient energy absorption properties, and Al-based metallic foam plates reinforced with B4C particles were used. The 25x25x1.5 cm foam plates produced with these properties were combined to form large plates of 100x150 cm and placed inside the polymer-based composite armor material to form a sandwich structure in order to absorb the shock effect during the explosion (Figure 31.b.c). It is quite difficult to produce large foams of these sizes. However, with the PM team at Gazi University, these problems were overcome and large-sized Al foam production was achieved [179]. In order to evaluate the armor performance, blast tests were performed with 6, 8 and 10 kg TNT in the experimental setup (Figure 32) prepared from this large-sized foam sample according to the NATO Stanag standard, and it was observed that the samples containing B4C reinforced Al foam in the armor provided the desired level of protection as a result of the blasting. Figure 32 shows the pictures taken at certain stages during the flashing, and Figure 33 shows the condition of the armor plate before and after the blasting.

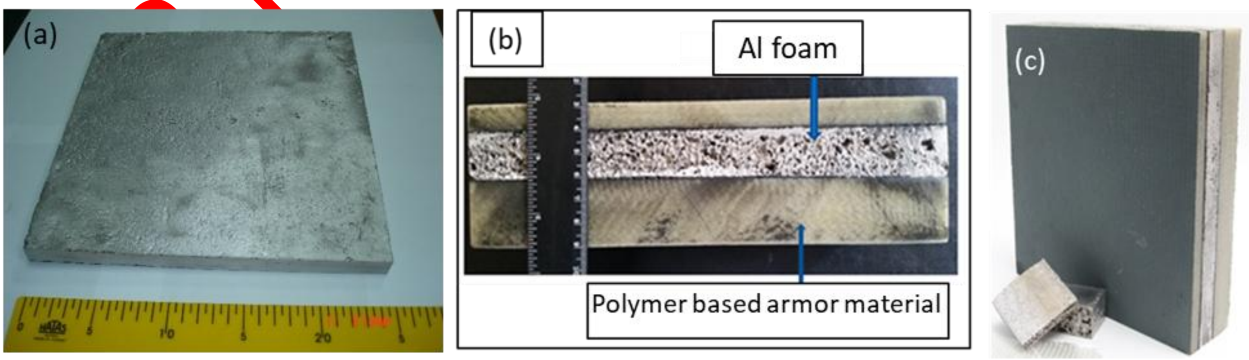

Figure 31. B_4C reinforced Al foam plate with dimensions of 25x25x1.5 cm placed between polymer-based composite armor plates for energy absorption (a), section view of the Al foam reinforced armor plate developed for armored vehicles against explosion effects (b) and general view of the armor (c) [1, 33, 179]. (Polimer esaslı kompozit zırh plakaları arasına yerleştirilen, enerji emilimi sağlayan 25x25x1,5 cm boyutlarındaki B4C takviyeli Al köpük levha (a), zırhlı araçlar için patlama etkilerine karşı geliştirilen Al köpük takviyeli zırh levhasının kesit görünümü (b) ve zırhın genel görünümü (c))

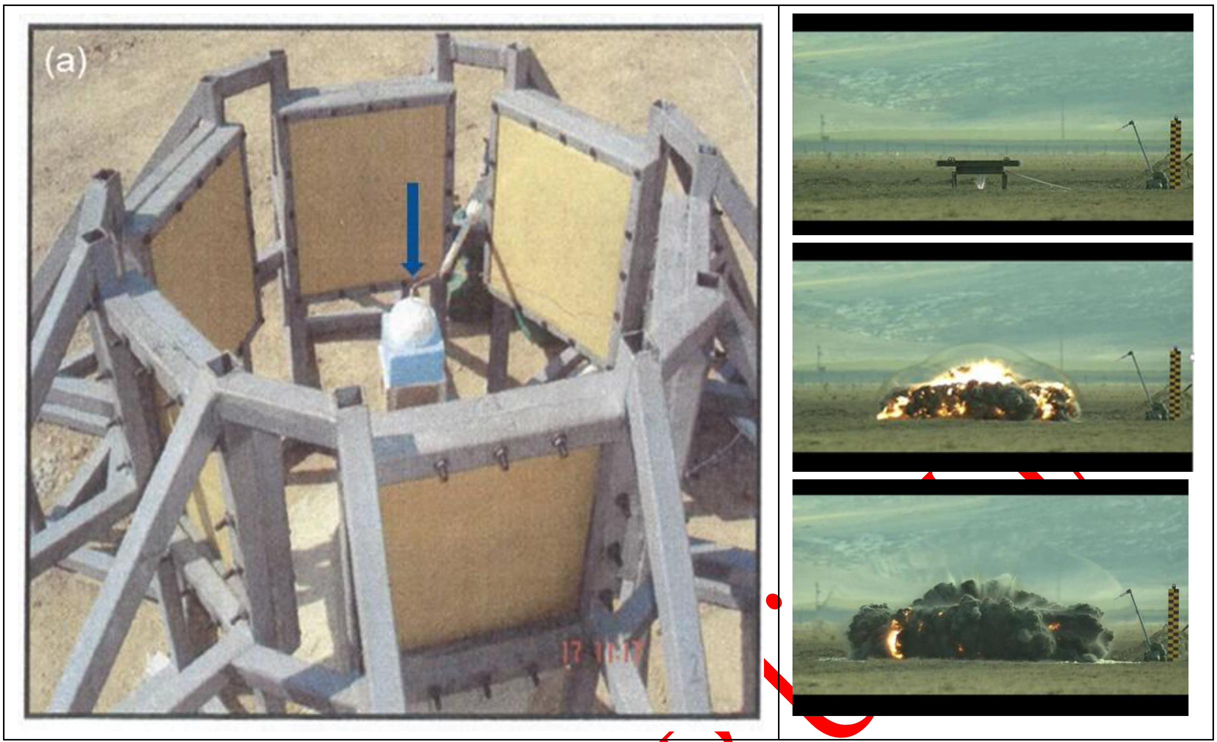

Figure 32. Blast test setup (a), prepared according to NATO Stanag standard (TNT is shown with arrow) and images of certain durations of the explosion [1, 33, 180]. (NATO Stanag standardına göre hazırlanmış patlama testi düzeneği (TNT okla gösterilmiştir) ve patlamanın belirli sürelerine ait görüntüler.)

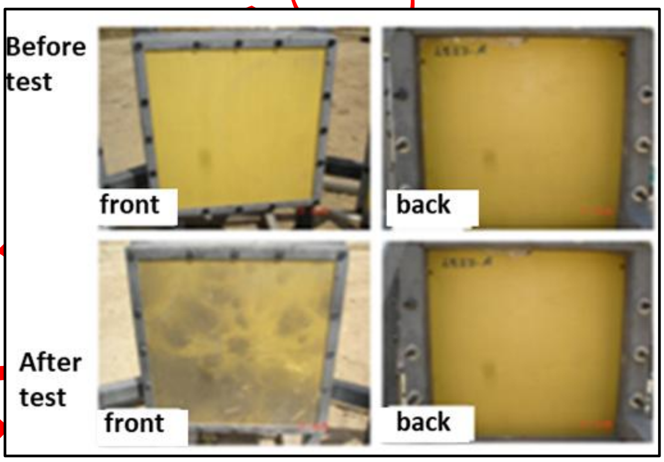

Figure 33. Condition of the armor plate before and after the explosion test. From the condition of the armor plates, it can be seen that there was no significant damage to the armor plate after the explosion [1, 34]. (Patlama testinden önce ve sonra zırh plakasının durumu. Zırh plakalarının durumuna bakıldığında, patlamadan sonra zırh plakasında önemli bir hasar olmadığı görülmektedir.)

5. CONCLUSIONS (SONUÇLAR)

In this study, information is given about different production methods of Al foams with PM methods and the areas where these materials can be used are focused. It is seen that Al foams provide advantages in various industries such as automotive, aircraft manufacturing, construction and defense thanks to their excellent impact and high energy absorption capacity and lightweight structure. In addition, research on foam formation parameters and production techniques of the material have been determined as important factors affecting the mechanical and physical properties of the foam structure. Within the framework of this information, it is seen that it is possible to produce foams with fine pore structure and high mechanical properties, as well as foams with coarser pore structure, low density but good insulation.

In addition to the above properties, it has been determined that the sandwich structure formed by placing the reinforced Al-based composite foams between the polymer-based armor material makes a significant contribution to the blast properties at the time of explosion.

ACKNOWLEDGEMENT (TEŞEKKÜR)

This study was prepared using experimental results and general literature information obtained within the scope of the following three projects:

- "Development of Protective Armor Against Explosion Effects, TUBITAK 1007 Project (Scientific and Technological Research Council of Türkiye) (supported by the Ministry of National Defence of TÜRKİYE), 107A014 (Subproject No: 107A015 and 107A016),
- Production of Al based boron carbide and ceramic particle reinforced metallic foam by PM method and evaluation of its performance as integral armor material, 106M513, TUBITAK (Scientific and Technological Research Council of Türkiye) Project 2009,
- Based B_4C Reinforced Sandwich Metallic Foam by PM Method, Investigation of Its Ballistic and Mechanical Properties; Supported by Gazi University, Scientific Research Projects Unit.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Mehmet TÜRKER*:** He conducted the experiments, analyzed the results and performed the writing process.

Deneyleri yapmış, sonuçlarını analiz etmiş ve maklenin yazım işlemini gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

REFERENCES (KAYNAKLAR)

[1] Türker, M. Toz Metal Al Köpükler: Üretimi, Çeşitleri ve Kullanım Alanları. Politeknik Dergisi. 2024; 27: 2335–2356.

[2] Sharma, S.S., et al. Application of metallic foam in vehicle structure: A review. Materials Today: Proceedings. 2022; 63: 347–353.

[3] Koza, E., et al. Compressive strength of aluminium foams. Materials letters. 2004; 58: 132–135.

[4] Madgule, M., Sreenivasa, C. and Borgaonkar, A.V. Aluminium metal foam production methods, properties and applications-a review. Materials Today: Proceedings. 2023; 77: 673–679.

[5] Atwater, M.A., et al. Solid state porous metal production: A review of the capabilities, characteristics, and challenges. Advanced Engineering Materials. 2018; 20: 1700766.

[6] Gibson, L.J. Mechanical behavior of metallic foams. Annual Review of Materials Science. 2000; 30: 191–227.

[7] Hanssen, A.G., Langseth, M. and Hopperstad, O.S. Static and dynamic crushing of circular aluminium extrusions with aluminium foam filler. International journal of impact engineering. 2000; 24: 475–507.

[8] Schwingel, D.D., et al. Aluminium foam sandwich structures for space applications. in 57th International Astronautical Congress. 2007.

[9] YU, H.-j., et al. Sound insulation property of Al-Si closed-cell aluminum foam bare board material. Transactions of nonferrous metals society of China. 2007; 17: 93–98.

[10] Peroni, L., Avalle, M. and Peroni, M. The mechanical behaviour of aluminium foam structures in different loading conditions. International journal of impact engineering. 2008; 35: 644–658.

[11] Sha, J. and Yip, T. In situ surface displacement analysis on sandwich and multilayer beams composed of aluminum foam core and metallic face sheets under bending loading. Materials Science and Engineering: A. 2004; 386: 91–103.

[12] Schwingela, D., et al. Aluminium foam sandwich structures for space applications. Acta Astronautica 2007; 61 326–330.

[13] Michailidis, N., Stergioudi, F. and Tsouknidas, A. Deformation and energy absorption

properties of powder-metallurgy produced Al foams. Materials Science and Engineering: A. 2011; 528: 7222–7227.
[14] Hangai, Y., et al. Drop weight impact behavior of functionally graded aluminum foam consisting of A1050 and A6061 aluminum alloys. Materials Science and Engineering: A. 2015; 639: 597–603.
[15] Peroni, M., Solomos, G. and Pizzinato, V. Impact behaviour testing of aluminium foam. International Journal of Impact Engineering. 2013; 53: 74–83.
[16] Ghazi, A., et al. Computed tomography based modelling of the behaviour of closed cell metallic foams using a shell approximation. Materials & Design. 2020; 194: 108866.
[17] Naeem, M.A., Gábora, A. and Mankovits, T. Influence of the manufacturing parameters on the compressive properties of closed cell aluminum foams. Periodica Polytechnica Mechanical Engineering. 2020; 64: 172–178.
[18] Vesenjak, M. and Ren, Z. Geometrical and mechanical analysis of various types of cellular metals. Ciência & Tecnologia dos Materiais. 2016; 28: 9–13.
[19] Singh, S. and Bhatnagar, N. A survey of fabrication and application of metallic foams (1925–2017). Journal of Porous Materials. 2018; 25: 537–554.
[20] Gauthier, M., et al. Production of metallic foams having open porosity using a powder metallurgy approach. Materials and manufacturing processes. 2004; 19: 793–811.
[21] Yalçın, N. and Ercil, A. Döküm yöntemi ile açık gözenekli parça üretiminde gözenek boyutunun mekanik özelliklere etkisi. in 2nd International Turkish World Engineering and Science Congress. 2019. Antalya, Türkiye
[22] Dannemann, K.A. and Lankford Jr, J. High strain rate compression of closed-cell aluminium foams. Materials Science and Engineering: A. 2000; 293: 157–164.
[23] Menç, B. and Özçatalbaş, Y. Manufacturing and characterization of open-cell aluminum foam by powder metallurgy. Materials Science and Technology. 2024; 02670836241291267.
[24] Fu, W. and Li, Y. Fabrication, processing, properties, and applications of closed-cell aluminum foams: a review. Materials. 2024; 17: 560.
[25] Uzun, A. and Turker, M. The investigation of mechanical properties of B4C-reinforced AlSi7 foams. International Journal of Materials Research. 2015; 106: 970–977.
[26] Kırmızı, G., Arık, H. and Çinici, H. Experimental study on mechanical and ballistic behaviours of silicon carbide reinforced functionally graded aluminum foam composites. Composites Part B: Engineering. 2019; 164: 345–357.
[27] Zare, J. and Manesh, H.D. A novel method for producing of steel tubes with Al foam core. Materials & Design. 2011; 32: 1325–1330.
[28] Miyoshi, T., et al. ALPORAS aluminum foam: production process, properties, and applications. Advanced engineering materials. 2000; 2: 179–183.
[29] Mu, Y., et al. Deformation mechanisms of closed-cell aluminum foam in compression. Scripta Materialia. 2010; 63: 629–632.
[30] Paul, A. and Ramamurty, U. Strain rate sensitivity of a closed-cell aluminum foam. Materials Science and Engineering: A. 2000; 281: 1–7.
[31] Yousefi, M.K., Kianirad, A. and Vaseghi, M. Simulation and investigation to the behavior of metallic foam as a bumper in automobile under impact loadings. in The First International Conference on Mechanics of Advanced Materials and Equipment. 2018.
[32] Uzun, A., et al. Investigation of modal properties of AlSi7 foam produced by powder metallurgy technique. Materials Testing. 2013; 55: 598–601.
[33] Türker, M. Production of closed cell aluminum foam as armor support material. in International Congress on Engineerıng Sciences and Multidisciplinary Approaches. 2021. İstanbul, Türkiye.
[34] Türker, M. Aluminum based metallic foams produced via powder metallurgy process in International Porous and Powder Materials Symposium and Exhibition. 2015. Çeşme, İzmir- Türkiye.
[35] Han, M.S. and Cho, J.U. Impact damage behavior of sandwich composite with aluminum foam core. Transactions of Nonferrous Metals Society of China. 2014; 24: s42–s46.
[36] Santosa, S. and Wierzbicki, T. On the modeling of crush behavior of a closed-cell aluminum foam structure. Journal of the Mechanics and Physics of Solids. 1998; 46: 645–669.
[37] Weise, J., Lehmhus, D. and Baumeister, J. Lightweight Structures Based on Aluminium Foam Granules. Lightweight Design worldwide. 2017; 10: 6–11.
[38] Babcsán, N., Banhart, J. and Leitlmeier, D. Metal foams–manufacture and physics of foaming. in Proceedings of the International Conference Advanced Metallic Materials. 2003.
[39] Andrews, E., Huang, J.-S. and Gibson, L. Creep behavior of a closed-cell aluminum foam. Acta Materialia. 1999; 47: 2927–2935.

[40] Uzun, A. Compressive Crush Performance of Square Tubes Filled with Spheres of Closed-Cell Aluminum Foams. Archives of Metallurgy and Materials. 2017;

[41] Uzun, G., et al. Effect of cutting parameters on the drilling of AlSi metallic foams. Material in Tehnologie/Materials and Technology. 2017; 51: 19–24.

[42] Banhart, J. Manufacture, characterisation and application of cellular metals and metal foams. Progress in materials science. 2001; 46: 559–632.

[43] Gülenç, İ.T. Patlama kaynağı ile kaynaklanmış sandviç yapıların köpürebilirliğinin araştırılması. Fen Bilimleri Enstitüsü, Metalurji ve Malzeme Mühendisliği. Yüksek Lisans Tezi. Gazi Üniversitesi 2014.

[44] Uzun, A. and Turker, M. Friction stir welding of foamable AlSi7 reinforced by B4C. International Journal of Materials Research. 2016; 107: 558–565.

[45] Bernard, T., Burzer, J. and Bergmann, H. Mechanical properties of structures of semifinished products joined to aluminium foams. Journal of Materials Processing Technology. 2001; 115: 20–24.

[46] Cambronero, L., et al. Weld structure of joined aluminium foams with concentrated solar energy. Journal of Materials Processing Technology. 2014; 214: 2637–2643.

[47] Pelit, Y., et al. Toz metal Al malzemelerin köpürtme öncesi saplama kaynağı ile birleştirilmesi. in 6th International Advanced Technologies Symposium (IATS11). 2011. Elazığ, Türkiye.

[48] Ersoy, E. and Özçatalbaş, Y. Deformation of metallic foams with closed cell at high temperatures. Int J Mater Metall Eng. 2015; 9: 789–792.

[49] POTOČNIK, D., RAZBORŠEK, B. and FICKO, M. Overview of aluminum foam machining. EXPRES 2020. 2020; 52.

[50] Yan, L., et al. Three-point bending of sandwich beams with aluminum foam-filled corrugated cores. Materials & Design. 2014; 60: 510–519.

[51] Changdar, A. and Chakraborty, S.S. Laser processing of metal foam-A review. Journal of Manufacturing Processes. 2021; 61: 208–225.

[52] Cambronero, L., et al. Manufacturing of Al–Mg–Si alloy foam using calcium carbonate as foaming agent. Journal of materials processing technology. 2009; 209: 1803–1809.

[53] Orłowicz, A., et al. Materials used in the automotive industry. Archives of foundry engineering. 2015; 15:

[54] Onck, P., et al. Fracture of Metal Foams: In-situ Testing and Numerical Modeling. Advanced Engineering Materials. 2004; 6: 429–431.

[55] Lehmhus, D., et al., From stochastic foam to designed structure: Balancing cost and performance of cellular metals. 2017, Materials. p. 922.

[56] Turker, M. Production of Ceramics Reinforced Al Foams by Powder Metallurgy Techniques. in Materials Science Forum. 2011.

[57] Güden, M., Elbir, S. and Yılmaz, S. Kompozit alüminyum köpüklerin hazırlanması ve mekanik özelliklerinin belirlenmesi. II. Makine Malzemesi ve İmalat Teknolojisi Sempozyumu. 2015;

[58] Wang, Z., et al. Effect of copper metal foam proportion on heat transfer enhancement in the melting process of phase change materials. Applied Thermal Engineering. 2022; 201: 117778.

[59] Gao, H., et al. 3D porous nickel metal foam/polyaniline heterostructure with excellent electromagnetic interference shielding capability and superior absorption based on pre-constructed macroscopic conductive framework. Composites Science and Technology. 2021; 213: 108896.

[60] Sreenivasa, C. and Shivakumar, K. A review on prodution of aluminium metal foams. in IOP Conference Series: Materials Science and Engineering. 2018.

[61] Aida, S., Zuhailawati, H. and Anasyida, A. The effect of space holder content and sintering temperature of magnesium foam on microstructural and properties prepared by sintering dissolution process (SDP) using carbamide space holder. Procedia Engineering. 2017; 184: 290–297.

[62] Kovacik, J. and Simancik, F. Comparison of zinc and aluminium foam behaviour. Translations-Ve Riecansky. 2004;

[63] Tianjian, L. Ultralight porous metals: from fundamentals to applications. Acta Mechanica Sinica. 2002; 18: 457–479.

[64] Liu, J., et al. The compressive properties of closed-cell Zn-22Al foams. Materials Letters. 2008; 62: 683–685.

[65] Banhart, J. Light-metal foams—history of innovation and technological challenges. Advanced Engineering Materials. 2013; 15: 82–111.

[66] Liu, P. and Liang, K. Review Functional materials of porous metals made by P/M, electroplating and some other techniques. Journal of materials science. 2001; 36: 5059–5072.

[67] Türker, M., et al. Effects of foaming agent and boron carbide additions on the foamability

behaviour of al based metallic foam produced by powder metallurg. in Advances in Powder Metallurgy and Particulate Materials-2008, Proceedings of the 2008 World Congress on Powder Metallurgy and Particulate Materials, PowderMet 2008. 2008.

[68] Türker, M., et al. TM ile üretilen al esaslı metalik köpükte bor oksit ilavesinin köpürmeye etkisinin araştırılması. in 13. Uluslararası Metalurji ve Malzeme Kongresi. 2006. İstanbul, Türkiye.

[69] Uzun, A. Production of aluminium foams reinforced with silicon carbide and carbon nanotubes prepared by powder metallurgy method. Composites Part B: Engineering. 2019; 172: 206–217.

[70] Çinici, H., et al. Toz metalurjisi yöntemiyle üretilen AlSi7 köpüklerin düşük hızlı darbe enerjileri altında penetrasyon davranışının incelenmesi. Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi. 2014; 29: 395–400.

[71] Esmaeelzadeh, S., Simchi, A. and Lehmhus, D. Effect of ceramic particle addition on the foaming behavior, cell structure and mechanical properties of P/M AlSi7 foam. Materials Science and Engineering: A. 2006; 424: 290–299.

[72] Kennedy, A. and Asavavisitchai, S. Effects of TiB2 particle addition on the expansion, structure and mechanical properties of PM Al foams. Scripta Materialia. 2004; 50: 115–119.

[73] Kováčik, J., et al. Reinforced aluminium foams. in International Conference in Advanced Metallic Materials. 2003.

[74] Gergely, V. and Clyne, B. The FORMGRIP process: foaming of reinforced metals by gas release in precursors. Advanced Engineering Materials. 2000; 2: 175–178.

[75] Gergely, V., Degischer, H. and Clyne, T. Recycling of MMCs and production of metallic foams. Comprehensive composite materials. 2000; 797–820.

[76] Wang, C., et al. Fabrication and characterization of layered structure reinforced composite metal foam. Journal of Alloys and Compounds. 2022; 895: 162658.

[77] Gökmen, U. and Türker, M. Al2O3 ilavesinin alüminyum ve alumix 231 esasli metalik köpüğün köpürme özelliklerine etkisi. Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi. 2012; 27:

[78] Gergely, V. and Clyne, T. Drainage in standing liquid metal foams: modelling and experimental observations. Acta Materialia. 2004; 52: 3047–3058.

[79] Deqing, W. and Ziyuan, S. Effect of ceramic particles on cell size and wall thickness of aluminum foam. Materials Science and Engineering: A. 2003; 361: 45–49.

[80] Brunke, O., et al. Experimental and numerical analysis of the drainage of aluminium foams. Journal of Physics: Condensed Matter. 2005; 17: 6353.

[81] Markaki, A. and Clyne, T. The effect of cell wall microstructure on the deformation and fracture of aluminium-based foams. Acta Materialia. 2001; 49: 1677–1686.

[82] Temiz, A., et al. Rapid casting of biodegradable porous magnesium scaffolds and electrophoretic deposition of 45S5 bioactive glass nanoparticles coatings on porous scaffolds: characterization and in vitro bioactivity analysis. International Journal of Metalcasting. 2023; 17: 1871–1882.

[83] Ersoy, E., Özçatalbaş, Y. and Bahçeci, E. An experimental study on hot formability of closed cell metallic foams. in International Porous and Powder Materials Symposium. 2013. İzmir, Türkiye.

[84] Arif, U. Sıcak Presleme Yöntemi ile Üretilmiş Al Köpüğün Gözenek Yapısı ve Köpürme Davranışı Üzerine MgO İlavesinin Etkisi. Honor Committee. 613.

[85] Steen, W.M. and Mazumder, J. Laser Material Processing. Springer-Verlag Ltd. London. 2010.

[86] Ozan, S., et al. Application of ANN in the prediction of the pore concentration of aluminum metal foams manufactured by powder metallurgy methods. The International Journal of Advanced Manufacturing Technology. 2008; 39: 251–256.

[87] Yu, C.-J., et al. Metal foaming by a powder metallurgy method: Production, properties and applications. Materials Research Innovations. 1998; 2: 181–188.

[88] Onck, P., et al. Fracture of open-and closed-cell metal foams. Journal of materials science. 2005; 40: 5821–5828.

[89] Parveez, B., et al. Microstructure and mechanical properties of metal foams fabricated via melt foaming and powder metallurgy technique: a review. Materials. 2022; 15: 5302.

[90] Madgule, M., et al. Influence of foaming agents on mechanical and microstructure characterization of AA6061 metal foams. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering. 2024; 238: 520–532.

[91] Ali, H., et al. Effect of the manufacturing parameters on the pore size and porosity of closed-cell hybrid aluminum foams. International Review of Applied Sciences and Engineering. 2021; 12: 230–237.

[92] Banhart, J. Manufacturing routes for metallic foams. Jom. 2000; 52: 22–27.
[93] Kennedy, A. and Asavavisithchai, S. Effect of Ceramic Particle Additions on Foam Expansion and Stability in Compacted Al-TiH2 Powder Precursors. Advanced Engineering Materials. 2004; 6: 400–402.
[94] Elbir, S., et al. SiC-particulate aluminum composite foams produced by powder compacts: Foaming and compression behavior. Journal of materials science. 2003; 38: 4745–4755.
[95] Asavavisithchai, S. and Kennedy, A. Effect of powder oxide content on the expansion and stability of PM-route Al foams. Journal of Colloid and Interface Science. 2006; 297: 715–723.
[96] Styles, M., Compston, P. and Kalyanasundaram, S. The effect of core thickness on the flexural behaviour of aluminium foam sandwich structures. Composite Structures. 2007; 80: 532–538.
[97] speaker), M.T.I. Toz Metalurjisi Yöntemi İle Üretilen Alüminyum Esaslı Metalik Köpükte Si İlavesinin Köpürmeye Etkisi in Uluslararası İleri Teknolojiler Sempozyumu (IATS'09), . 13–15 Mayıs 2009. Karabük, Türkiye,pp1-6, .
[98] Banhart, J. and Baumeister, J. Deformation characteristics of metal foams. Journal of materials science. 1998; 33: 1431–1440.
[99] Ashby, M.F., et al. Metal foams: a design guide. Elsevier. 2000.
[100] Guden, M. and Yüksel, S. SiC-particulate aluminum composite foams produced from powder compacts: foaming and compression behavior. Journal of Materials Science. 2006; 41: 4075–4084.
[101] Wadley, H.N. Cellular metals manufacturing. Advanced engineering materials. 2002; 4: 726–733.
[102] Montanini, R. Measurement of strain rate sensitivity of aluminium foams for energy dissipation. International Journal of Mechanical Sciences. 2005; 47: 26–42.
[103] Körner, C. and Singer, R.F. Processing of metal foams—challenges and opportunities. Advanced Engineering Materials. 2000; 2: 159–165.
[104] Banhart, J. and Weaire, D. On the road again: metal foams find favor. Physics Today. 2002; 55: 37–42.
[105] Pelit, Y. and Türker, M. Mekanik Alaşımlanmış Al2O3 Takviyeli AlSi7Mg0,6 Esaslı Tozlardan Metalik Köpük Üretimi ve Özelliklerinin İncelenmesi,. in 6th Internatıonal Powder Metallurgy Conference & Exhibition. October 05–09, 2011. Ankara
[106] Proa-Flores, P., Mendoza-Suarez, G. and Drew, R. Effect of TiH 2 particle size distribution on aluminum foaming using the powder metallurgy method. Journal of Materials Science. 2012; 47: 455–464.
[107] Kriszt, B. and Degischer, H. Handbook of cellular metals: Production, processing, applications. Weinheim: Wiley-VCH. 2002; 2002.
[108] Yu, S., Luo, Y. and Liu, J. Effects of strain rate and SiC particle on the compressive property of SiCp/AlSi9Mg composite foams. Materials Science and Engineering: A. 2008; 487: 394–399.
[109] Hassan, A. and Alnaser, I.A. A review of different manufacturing methods of metallic foams. ACS omega. 2024; 9: 6280–6295.
[110] Bahçeci, E., Özçatalbaş, Y. and Türker, M. TM yöntemiyle AlSiMg alaşımı metalik köpük üretimi için geliştirilen preform malzeme üretim sürecinin karekterizasyonu. in 6th International Powder Metallurgy Conference Exhibition. 2011. Ankara, Türkiye.
[111] Matijasevic, B. and Banhart, J. Improvement of aluminium foam technology by tailoring of blowing agent. Scripta Materialia. 2006; 54: 503–508.
[112] Kim, A., et al. Time–temperature superposition for foaming kinetics of Al-alloy foams. Journal of Materials Processing Technology. 2008; 202: 450–456.
[113] Turker, M., et al. Effect of Foaming Agent on The Structure and Morphology of Al and Alumix 231 Foams Produced by Powder Metallurgy. in Materials Science Forum. 2011.
[114] Banhart, J. Manufacturing routes for metallic foams. The journal of the Minerals, Metals & Materials Society 2012; 52(12):22-27
[115] Baumgärtner, F., Duarte, I. and Banhart, J. Industrialization of powder compact toaming process. Advanced Engineering Materials. 2000; 2: 168–174.
[116] Mudge, A. and Morsi, K. Fabrication of Uniform and Rounded Closed-Cell Aluminum Foams Using Novel Foamable Precursor Particles (FPPs). Metals. 2024; 14: 120.
[117] Banhart, J. Metallic foams: challenges and opportunities. Eurofoam. 2000; 2000: 13–20.
[118] Shiomi, M., et al. Fabrication of aluminium foams from powder by hot extrusion and foaming. Journal of Materials Processing Technology. 2010; 210: 1203–1208.
[119] Wang, L., et al. Achieving metallurgical bonding in steel faceplate/aluminum foam sandwich via hot pressing and foaming

processes: interfacial microstructure evolution and tensile behavior. Journal of Materials Processing Technology. 2024; 334: 118636.

[120] KARAKOÇ, H., et al. Sıcak presleme yöntemi ile B4C takviyeli Alumix 231 köpüklerin üretimi ve gözenek morfolojisinin incelenmesi.

[121] Uzun, A., et al. Vickers Microhardness Studies on B 4 C Reinforced/Unreinforced Foamable Aluminium Composites. Transactions of the Indian Institute of Metals. 2018; 71: 327–337.

[122] Pen, S.I., et al. Synthesis and characterization of Al foams produced by powder metallurgy route using dolomite and titanium hydride as a foaming agents. Materiali in tehnologije. 2014; 48: 943–947.

[123] Schaeffler, P., et al. Production, properties, and applications of Alulight® closed-cell aluminum foams. in Proceedings of the Fifth International Workshop on Advanced Manufacturing Technologies. 2005.

[124] Stanzick, H., et al. Process Control in Aluminum Foam Production Using Real-Time X-ray Radioscopy. Advanced Engineering Materials. 2002; 4: 814–823.

[125] Babcsán, N., Moreno, F.G. and Banhart, J. Metal foams—high temperature colloids: part II: in situ analysis of metal foams. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2007; 309: 254–263.

[126] Yang, D., et al. Effect of decomposition kinetics of titanium hydride on the Al alloy melt foaming process. Journal of Materials Science & Technology. 2015; 31: 361–368.

[127] Abo sbia, A.E.S. and Uzun, A. Production of MWCNT-Reinforced Aluminum Foams Via Powder Space-Holder Technique and Investigation of their Mechanical Properties. Transactions of the Indian Institute of Metals. 2022; 75: 2241–2253.

[128] Gökmen, U., Özçatalbaş, Y. and Türker, M. Al2O3 Takviyeli Metalik Köpüğe Köpürme Sıcaklığı ve Köpürtücü Madde Miktarının Etkisinin Araştırılması. in 5. Uluslararası Toz Metalurjisi Konferansı. 2008. Ankara.

[129] Banhart, J. and Seeliger, H.W. Aluminium foam sandwich panels: manufacture, metallurgy and applications. Advanced Engineering Materials. 2008; 10: 793–802.

[130] Banhart, J., et al. Real-time x-ray investigation of aluminium foam sandwich production Advanced Engineering Materials. 2001; 3: 1–10.

[131] Magnucka-Blandzi, E. and Magnucki, K. Effective design of a sandwich beam with a metal foam core. Thin-Walled Structures. 2007; 45: 432–438.

[132] Contorno, D., et al. Forming of aluminum foam sandwich panels: Numerical simulations and experimental tests. Journal of Materials Processing Technology. 2006; 177: 364–367.

[133] Simancik, F. Metallic foams-ultra light materials for structural applications. Inżynieria Materiałowa. 2001; 22: 823–828.

[134] Liu, S., et al. Fatigue of an Aluminum Foam Sandwich Formed by Powder Metallurgy. Materials. 2023; 16: 1226.

[135] Stöbener, K., et al. Composites based on metallic foams: phenomenology, production; properties and principles. in Proc (Nov. 2003), International Conference "Advanced Metallic Materials. 2003.

[136] Mohan, K., et al. Failure of sandwich beams consisting of alumina face sheet and aluminum foam core in bending. Materials Science and Engineering: A. 2005; 409: 292–301.

[137] Çinici, H. and Türker, M. Effect of Foaming Duration and Temperature on the Foamability Behaviour of AlSi7Mg0. 6 Sandwich. in PM2010 World Congress – Foams Porous Materials. 2010. Italy.

[138] Bucher, T., et al. Laser forming of sandwich panels with metal foam cores. Journal of Manufacturing Science and Engineering. 2018; 140: 111015.

[139] Hanssen, A., et al. A numerical model for bird strike of aluminium foam-based sandwich panels. International journal of impact engineering. 2006; 32: 1127–1144.

[140] Uzun, A. and Turker, M. The effect of production parameters on the foaming behavior of spherical-shaped aluminum foam. Materials Research. 2014; 17: 311–315.

[141] Vesenjak, M., et al. Structural characterisation of advanced pore morphology (APM) foam elements. Materials letters. 2013; 110: 201–203.

[142] Ulbin, M., et al. Internal structure characterization of AlSi7 and AlSi10 advanced pore morphology (APM) foam elements. Materials Letters. 2014; 136: 416–419.

[143] Stöbener, K., et al. Forming metal foams by simpler methods for cheaper solutions. Metal Powder Report. 2005; 60: 12–16.

[144] Patel, N., et al. Aluminum foam production, properties, and applications: a review. International Journal of Metalcasting. 2024; 18: 2181–2198.

[145] Kovačič, A. and Ren, Z. On the porosity of advanced pore morphology structures. Composite Structures. 2016; 158: 235–244.

[146] Wang, F., et al. Foaming Behavior of Microsized Aluminum Foam Using Hot Rolling Precursor. Metals. 2023; 13: 928.

[147] Kovačič, A., et al. Geometrical and mechanical properties of polyamide PA 12 bonds in composite advanced pore morphology (APM) foam structures. Archives of Civil and Mechanical Engineering. 2018; 18: 1198–1206.

[148] Sulong, M., et al. Compressive properties of Advanced Pore Morphology (APM) foam elements. Materials Science and Engineering: A. 2014; 607: 498–504.

[149] Sun, K., et al. Recent advances and future trends in enhancing the compressive strength of aluminum matrix foam composites reinforced with ceramic hollow spheres: A review. Composite Structures. 2024; 331: 117918.

[150] Rausch, G., Stöbener, K. and Bassan, D. Improving structural crashworthiness using metallic and organic foams. 2006;

[151] Arif, U. Investigation of Crushing Behavior of Polystyrene Coated Spherical Shaped Aluminum Foams. Bitlis Eren Üniversitesi Fen Bilimleri Dergisi. 2020; 9: 1273–1281.

[152] Wang, E., et al. Lightweight metallic cellular materials: a systematic review on mechanical characteristics and engineering applications. International Journal of Mechanical Sciences. 2023; 108795.

[153] Sánchez de la Muela, A., Cambronero, L. and Ruiz-Bustinza, I. Quasi-static and dynamic analysis of single-layer sandwich structures of APM foam spheroid elements in-situ foamed with marble". Rev. Metal. 2020; 56: e159.

[154] Weise, J., et al. Mechanical Behavior of Particulate Aluminium-Epoxy Hybrid Foams Based on Cold-Setting Polymers. Advanced Engineering Materials. 2017; 19: 1700090.

[155] Borovinsek, M., et al. Analysis of advanced pore morphology (APM) foam elements using compressive testing and time-lapse computed microtomography. Materials. 2021; 14: 5897.

[156] Vopalensky, M., et al. Fast 4D On-the-Fly Tomography for Observation of Advanced Pore Morphology (APM) Foam Elements Subjected to Compressive Loading. Materials. 2021; 14: 7256.

[157] Salehi, M., Mirbagheri, S. and Ramiani, A.J. Efficient energy absorption of functionally-graded metallic foam-filled tubes under impact loading. Transactions of Nonferrous Metals Society of China. 2021; 31: 92–110.

[158] Uzun, A., et al. Investigation of mechanical properties of tubular aluminum foams. International Journal of Materials Research. 2016; 107: 996–1004.

[159] Crupi, V. and Montanini, R. Aluminium foam sandwiches collapse modes under static and dynamic three-point bending. International Journal of Impact Engineering. 2007; 34: 509–521.

[160] Banhart, J. Metal foams-from fundamental research to applications. Frontiers in the Design of Materials. 2007; 279:

[161] Lefebvre, L.P., Banhart, J. and Dunand, D.C. Porous metals and metallic foams: current status and recent developments. Advanced engineering materials. 2008; 10: 775–787.

[162] Seitzberger, M., et al. Experimental studies on the quasi-static axial crushing of steel columns filled with aluminium foam. International Journal of Solids and Structures. 2000; 37: 4125–4147.

[163] Olurin, O., Fleck, N.A. and Ashby, M.F. Deformation and fracture of aluminium foams. Materials Science and Engineering: A. 2000; 291: 136–146.

[164] Davies, G. and Zhen, S. Metallic foams: their production, properties and applications. Journal of Materials science. 1983; 18: 1899–1911.

[165] Yao, R., et al. On the crashworthiness of thin-walled multi-cell structures and materials: State of the art and prospects. Thin-Walled Structures. 2023; 189: 110734.

[166] Banhart, J. Aluminium foams for lighter vehicles. International Journal of vehicle design. 2005; 37: 114–125.

[167] Claar, T.D., et al. Ultra-lightweight aluminum foam materials for automotive applications. SAE transactions. 2000; 98–106.

[168] Wang, D., et al. Structure-material-performance integration lightweight optimisation design for frontal bumper system. International journal of crashworthiness. 2018; 23: 311–327.

[169] Baumeister, J., et al. Applications of aluminium hybrid foam sandwiches in battery housings for electric vehicles: Anwendung von Aluminium-Hybridschaum-Sandwichen in Batteriegehäusen von Elektrofahrzeugen. Materialwissenschaft und Werkstofftechnik. 2014; 45: 1099–1107.

[170] Heyhat, M.M., Mousavi, S. and Siavashi, M. Battery thermal management with thermal energy storage composites of PCM, metal foam, fin and nanoparticle. Journal of Energy Storage. 2020; 28: 101235.

[171] Banhart, J. Industrialisation of aluminium foam technology. in Proceedings of the ninth International Conference on aluminium alloys. 2004.

[172] Banhart, J. and Seeliger, H. Aluminium Foam Sandwich Panels: Metallurgy, Manufacture and

Applications, Porous Metals and Metallic Foams. in Proceedings of the Fifth International Conference on Porous Metals and Metallic Foams. 2007.
[173] Seeliger, H.W. Aluminium foam sandwich (AFS) ready for market introduction. Advanced Engineering Materials. 2004; 6: 448–451.
[174] Pinnoji, P.K., et al. New motorcycle helmets with metal foam shell. in 2008 IRCOBI Conference Proceedings, Bern, Switzerland. 2008.
[175] Pinnoji, P.K., et al. Impact dynamics of metal foam shells for motorcycle helmets: Experiments & numerical modeling. International Journal of Impact Engineering. 2010; 37: 274–284.
[176] Carruthers, J., et al. The design and prototyping of a lightweight crashworthy rail vehicle driver's cab. in 9th World Congress on Railway Research. 2011.
[177] Neugebauer, R. and Hipke, T. Machine tools with metal foams. Advanced Engineering Materials. 2006; 8: 858–863.
[178] Gökmen, U. Toz metalurjisi yöntemi ile Al esaslı parçacık takviyeli metalik köpük üretimi. Yüksek Lisans Tezi, Gazi Üniversitesi, Ankara. 2009.
[179] Ersin BAHÇECİ, Y.Ö., Mehmet TÜRKER, PM YÖNTEMİYLE BÜYÜK YÜZEY ALANLI METALİK KÖPÜK ÜRE TİMİNDE KÖPÜREBİLİRLİK PROBLEMLERİ, in 6. ULUSLARARASI TOZ METALURJİSİ KONFERANSI ve SERGİSİ, M.T.v. ediğerleri, Editor. 05–09 Ekim 2011 Mina Ajans: Orta Doğu Teknik Üniversitesi Ankara, Türkiye. p. 253–260.
[180] Türker, M. Al Foams Reinforced With B4C And SiC Particles: Production Process, Characterization, Properties and Applications. in International Conference on Advanced Materials Science & Engineering and High Tech Devices Applications; Exhibition (ICMATSE 2020). 2020. Gazi University, Ankara, Türkiye.