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Comparison of Energy Absorptive Capacities of Different Aluminum Alloy Foams Placed Inside the Crash Box

Samet Uslu[1,*], Batuhan Kocaoğlu[1]

[1]*Karabük University, Faculty of Engineering, Karabük, Turkey*

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ABSTRACT

Increasing population worldwide and the resulting increasing number of automobiles increase the risk of traffic accidents. Due to this increasing risk, automobile manufacturers take various safety measures to protect drivers and passengers in case of possible accidents. Crash boxes are one of the passive safety system elements that are the first to absorb the impact in the event of a front or rear impact accident, absorbing the resulting deformation energy and ensuring that it is transmitted into the car at the least possible level. Therefore, increasing the energy absorption ability of crash boxes is an extremely important issue. In this study, it was aimed to increase the energy absorption capabilities by placing aluminum foam based materials produced by using the powder metallurgy method using three different aluminum alloys (Al2024, Al5083, and Al6061) inside the crash boxes, which are normally manufactured as hollow. In addition, the produced aluminum foams were compared in terms of pore sizes with SEM images. It can be said that Al6061 is the most ideal material among the alloys used in terms of pore structure and homogeneity. On the other hand, Al6061 alloys produced the greatest damped energy value within the parameters of the investigation, 221.711 J. This value was 169.556 J for Al2024 alloy and 214.101 J for Al5083 alloy. As a result, it was concluded that the amount of energy absorption can be increased by about 4-5 times by using metallic foams produced using aluminum materials compared to the empty crash box.

Çarpışma Kutusunun İçine Yerleştirilen Farklı Alüminyum Alaşımlı Köpüklerin Enerji Sönümleme Kapasitelerinin Karşılaştırılması

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ÖZET

Dünya çapında artan nüfus ve buna bağlı olarak artan otomobil sayısı trafik kazası riskini artırmaktadır. Artan bu risk nedeniyle otomobil üreticileri olası kazalarda sürücü ve yolcuları korumak için çeşitli güvenlik önlemleri almaktadır. Çarpışma kutuları, önden veya arkadan çarpma durumunda darbeyi ilk absorbe eden, ortaya çıkan deformasyon enerjisini absorbe eden ve araca mümkün olan en az seviyede iletilmesini sağlayan pasif güvenlik sistemi elemanlarından biridir. Bu nedenle çarpışma kutularının enerji absorbe etme yeteneğinin arttırılması son derece önemli bir konudur. Bu çalışmada normalde içi boş olarak üretilen çarpışma kutularının içine alüminyum köpük esaslı malzemeler yerleştirilerek enerji sönümleme yeteneklerinin arttırılması amaçlanmıştır. Bu amaçla üç farklı alüminyum alaşımı (Al2024, Al5083 ve Al6061) seçilmiş ve en iyi enerji sönümleme yeteneğini belirlemek için karşılaştırılmıştır. Al6061 alaşımları, araştırma parametreleri içerisinde en büyük sönümlenmiş enerji değerini (221.711 J) üretmiştir. Bu değer, Al2024 alaşımı için 169.556 J ve Al5083 alaşımı için 214.101 J olarak belirlenmiştir. Boş çarpma kutusuyla karşılaştırıldığında alüminyum köpükler kullanılarak enerji sönümleme kabiliyetinin yaklaşık 4-5 kat arttığı görülmüştür.

1. INTRODUCTION (GİRİŞ)

Day by day, the amount of road transportation grows, and so does traffic density. There are more cars on the road, which leads to more traffic accidents. Automobile manufacturers are working on

**Corresponding author, e-mail: sametuslu@karabuk.edu.tr*
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safety systems and trying to design safe vehicles to reduce the number of accidents that may occur and to prevent drivers and passengers from being harmed in the event of an accident or to minimize the damage that will occur [1]. These security systems are divided into two groups as active and passive security systems. While active safety systems reduce the probability of an accident occurring, passive safety systems are systems that minimize the damage to passengers after the accident occurs. For example, active safety systems; systems such as anti-lock braking system (ABS), anti-skid system (ASR), electronic stability program (ESP), speed control and parking sensor. Passive security systems are elements that come into play when active security systems are not sufficient. For example, vehicle elements such as crash boxes, seat belts and airbags are passive safety systems. While the seat belt restricts the forward movement of the passenger during an accident, airbags reduce the possibility of death and injury by absorbing the impact intensity that will reach the passengers during a possible crash. The purpose of crash boxes is to absorb the impacts that will occur during a crash [2, 3] and ensure that the passengers are affected by these impacts at a minimum level [4]. Crash boxes are located at the front and rear of vehicles and ensure safety in both front and rear collisions [5]. Figure 1 shows the image of the vehicle skeleton structure and crash box.

Figure 1. Skeletal structure and crash boxes of a vehicle (Bir aracın iskelet yapısı ve çarpışma kutuları)

Impact forces occurring during an accident are distributed in different sizes across the car. Most of the impact energy created by these forces is absorbed by the parts at the front of the car. Crash boxes are the parts that first absorb the impact forces with the buffer. Crash boxes absorb approximately 20% of this impact energy. There are different studies on increasing the energy absorption ability of crash boxes [6–8]. To increase the energy absorption capacity of crash boxes, this study aimed to fill them with aluminum foam. The reason why aluminum material is preferred is that it has a high energy absorption capacity and is light [9]. Because ensuring both lightweight and durability at the same time has become one of the most crucial working difficulties in the automotive industry as well as in many engineering sectors in recent years [10]. For this purpose, metallic foam materials have been the focus of extensive research in recent years [11, 12]. It is employed in the rail systems and space industries in addition to the automobile industry [13]. Because of these materials' higher energy absorption capacity, vibration dampening, and thermal insulation, their employment in the automobile sector is expanding. Metallic foams, which are made from a variety of light metals including aluminum, magnesium, nickel, and titanium, are widely used in the automobile sector because they offer resilience, light weight, and fuel efficiency. Aluminum-based metallic foams are the most widely used and chosen among all metallic foams due to their low specific weight, adequate ductility, superior heat conductivity, and low manufacturing cost [14]. Metallic foams produced using aluminum are superior at absorbing energy from many metals by converting impact energy production into plastic energy [15]. Additionally, metallic foams are lightweight; thanks to the void space they have around 75%-90% [16]. Even though the metallic foams placed inside the crash boxes cause some weight increase, they are ignored because they increase the ability to absorb impact energy by 4-5 times. There are some studies in the literature about crash boxes that are tested by filling them with foam material. Rajendran et al. [17]

filled the crash box with the foam material they produced from AlSI 304L material and tested its energy absorption ability. As a result of the tests, they concluded that the energy absorption capacity of the profile filled with foam material is much higher than the hollow profile. Another study, Altın and Yücesu [18] placed aluminum-based metallic foam material inside crash boxes with circular, square, pentagonal and hexagonal cross-sections and examined the changes in energy dissipation capacity with finite element analysis. As a result of the study, they determined that aluminum-based metallic foam materials placed inside hollow crash boxes significantly increased the energy absorption capacity. In another metallic foam study, Wang et al. [19] conducted compression and impact tests on a foam-filled crash box to investigate its energy absorption and shielding capabilities. Their tests indicated that the crash boxes were useful and beneficial for crashworthiness. In a study supported by the finite element method, Valente et al. [20] aimed to improve the crashworthiness behavior by filling a honeycomb crash box with open-cell aluminum foams. For this purpose, they performed optimization with finite element application in addition to experimental studies. The authors reported that successful results were obtained with an error of 1.72% and 0.05% for the breaking force and absorbed energy for the empty structure between the results obtained from the application and the experimental results, respectively. In addition, it was stated that the optimum cell number could be determined with the finite element application and that metallic foams could be used more efficiently. As a result, it was stated by the authors that metallic foams could be used successfully for impact absorption.

In this study, foam materials produced from different aluminums (Al2024, Al5083, and Al6061) were placed inside the crash boxes used in automobiles and their energy absorption capabilities were compared with the hollow crash box. There are a limited number of studies on filling aluminum foam inside crash boxes and these studies were mostly conducted in the form of comparison on a single metallic foam material. The difference of this study from the others is that metallic foam is produced using three different aluminums (Al2024, Al5083 and Al6061), pore size comparison is made through SEM images of the produced foams in cross-sectional form and energy absorption capabilities of the produced foams are compared.

2. MATERIAL AND METHOD (MATERYAL VE YÖNTEM)

2.1. Materials and Production Methods (Materyaller ve Üretim Yöntemleri)

In the laboratory of Gazi University Faculty of Technology, Department of Metallurgical and Materials Engineering, studies were carried out by following the steps of producing metallic foam with the powder metallurgy method. In the first stage, the powders of the substance to be foamed and the foaming agent powders were mixed. Al2024, Al5083 and Al6061 powders with an average grain size of 150 μm and TiH_2 powders with an average grain size of 325 mesh obtained from Aldrich were used as foaming agent powder. Powder mixtures were prepared by calculating the weight of each powder to put the appropriate amount of powder into the volume of the mold designed to press the powders. The dimensions of the mold used are 60x60x10mm and are given in Figure 2.

Figure 2. Compression mold (Sıkıştırma kalıbı)

The powders, whose weights were precisely measured on an electronic scale, were mixed with the turbula shown in Figure 3 for 45 minutes to obtain a homogeneous mixture. The prepared powder samples were pressed under approximately 10 tons of pressure in a hydraulic press with a uniaxial working mechanism in the air environment and turned into semi-finished products. The sintering process was applied to prevent the semi-finished powders from disintegrating in subsequent processes after the pressing process, to form a durable and resistant structure where the powder particles are interconnected, and to prevent foaming gases from escaping from the pores of the structure formed during the foaming stage. The semi-finished products obtained during the sintering process in air were heated for 45 minutes and reached a temperature of 500 °C. The semi-finished products, which reached 500 °C, were sintered under 100 tons of pressure for 35 minutes and left to cool. Visuals of pressing and sintering processes are given in Figure 4.

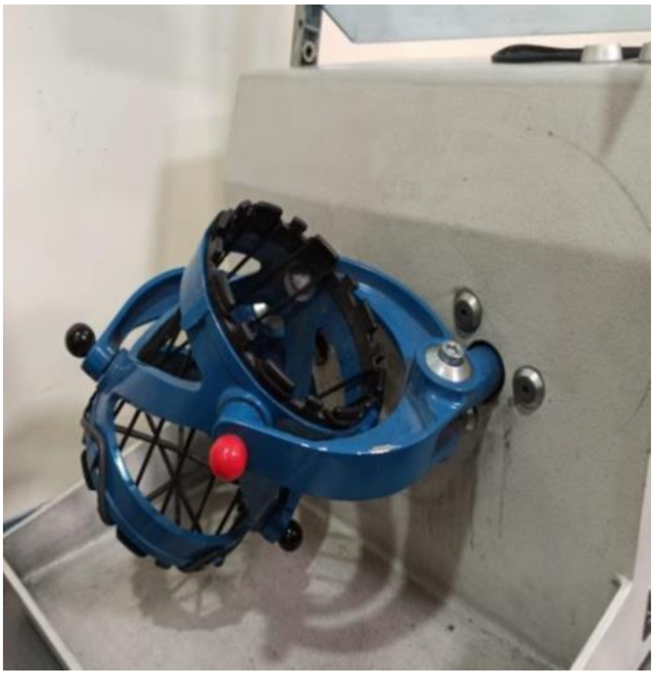

Figure 3. Turbula

Figure 4. (a) Pressing, (b) sintering and (c) final product ((a)Presleme, (b) Sinterleme ve (c) nihai ürün)

The products, whose dimensions were 60x60x10 mm, were prepared for the foaming process, and four pieces of each aluminum alloy were cut in the abrasive grinding device. These materials were prepared to be used in closed mold and foaming at different temperatures. For closed mold foaming processes, aluminum alloys were placed in 30x30x20 mm closed molds shown in **Hata! Başvuru kaynağı bulunamadı.** and three foams from three different alloys were produced.

Figure 5. Foaming in closed mold (Kapalı kalıpta köpürme)

2.2. Compression Tests (Basma Testleri)

Compression tests of rectangular shaped samples were carried out on a computer-controlled 220 V / 50 Hz AC powered Instron 3369 brand universal compression test device with a maximum load capacity of 50 kN. All the samples were deformed with a deformation rate of 1mm/second until they reached 70-80% deformation. Figure 6 gives the visual of the Instron 3369 brand compression-tensile test device, while Figure 7 shows the compression tests of a sample (Al 6061).

Figure 6. Instron 3369 brand compression tester (Instron 3369 marka sıkıştırma test cihazı)

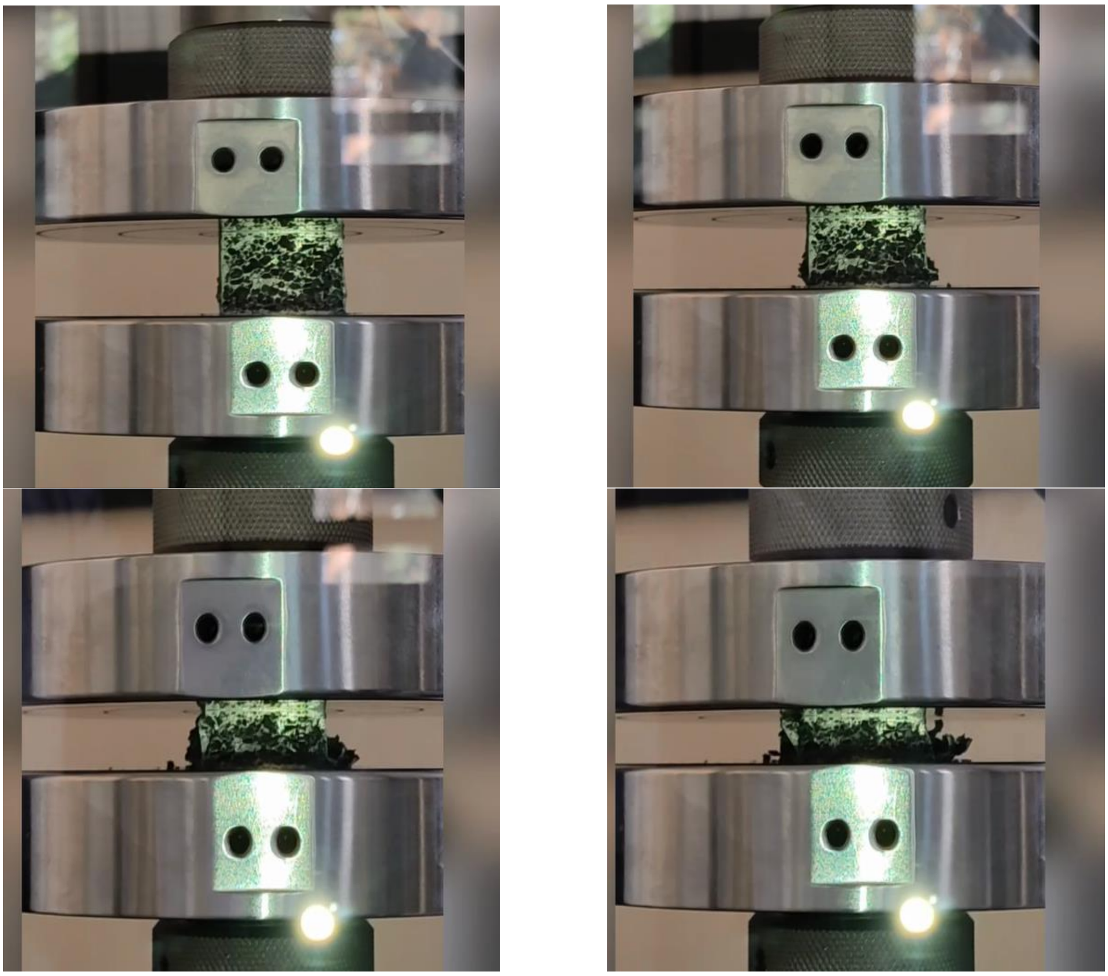

Figure 7. Deformations of Al6061 alloy during the compression test (Al6061 alaşımının basma testi sırasında deformasyonları)

3. RESULTS AND DISCUSSION (SONUÇLAR VE TARTIŞMA)

In Figures 8, 9 and 10, the pore sizes of Al2024, Al5083 and Al6061 alloys are given respectively, and calculations are made based on four points. The results are shown in Table 1. The average spheroidization rate of the Al2024 alloy is 0.525 and the average pore size of four randomly selected pores is 4.69. Similarly, the average spheroidization rate of Al5083 and Al6061 alloys and the average pore sizes of four randomly selected pores are 1-5.125 and 1.1875-2.98, respectively. When the pore structures and dimensions of the aluminum alloys foamed in the closed mold were examined, it was observed that the Al alloy with the lowest spheroidization rate was Al2024, and the highest was the Al5083 Alloy. It can be said that the most ideal alloy in terms of pore structures and homogeneity is Al6061 in terms of foaming pattern and uniform distribution.

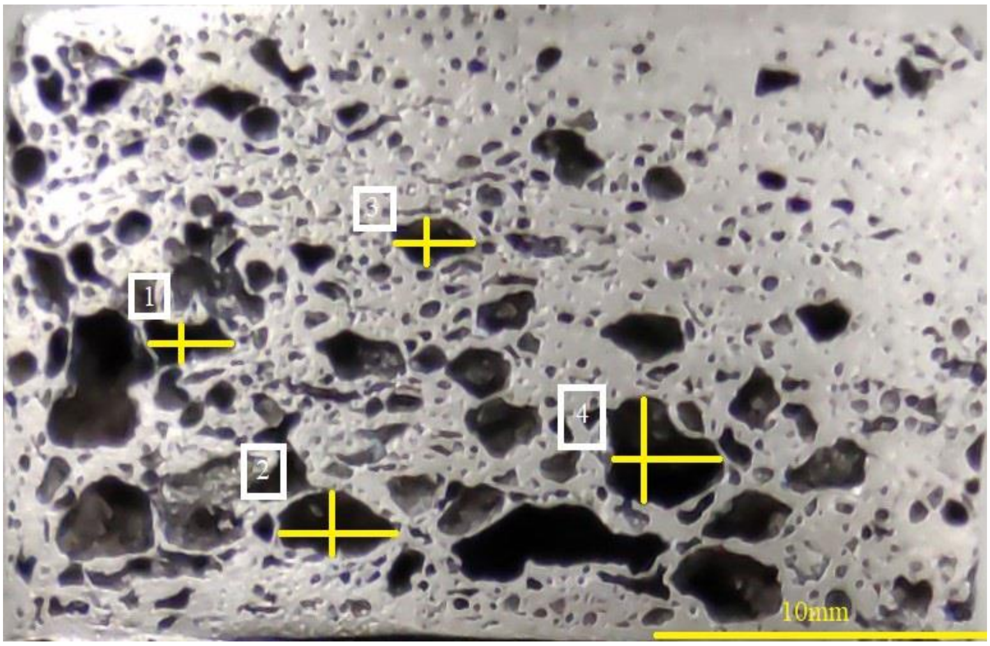

Figure 8. Pore sizes of Al2024 alloy (Al2024 alaşımının gözenek boyutları)

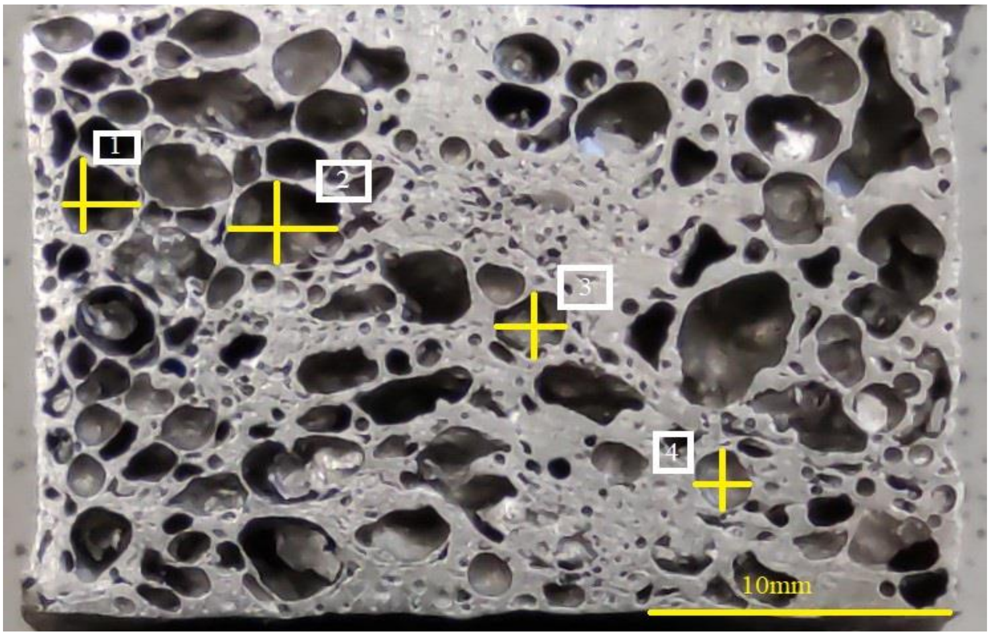

Figure 9. Pore sizes of Al5083 alloy (Al5083 alaşımının gözenek boyutları)

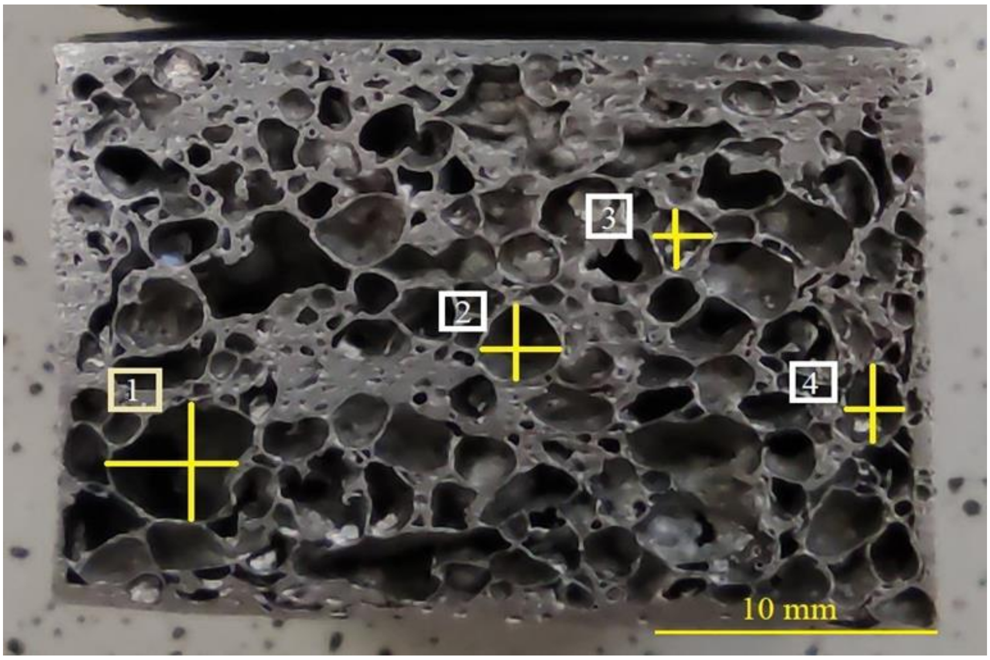

Figure 10. Pore sizes of Al6061 alloy (Al6061 alaşımının gözenek boyutları)

Table 1. Calculation of spheroidization rate and pore size of different alloys (Farklı alaşımların küreselleşme oranının ve gözenek boyutunun hesaplanması)

	Pore	X (mm)	Y (mm)	Spheroidization Rate (Y/X)	Pore Size (X+Y) /2
Al 2024	1^{st} pore	5.27	1.63	0.309	3.45
	2^{nd} pore	7.27	3.63	0.499	5.45
	3^{rd} pore	5	2	0.4	3.5
	4^{th} pore	6.72	6	0.892	6.36
Al 5083	1^{st} pore	5	5.2	1.04	5.1
	2^{nd} pore	7.2	5.8	0.8	6.5
	3^{rd} pore	4.8	4.6	0.95	4.7
	4^{th} pore	3.8	4.6	1.21	4.2
Al 6061	1^{st} pore	4.6	4.4	0.95	4.5
	2^{nd} pore	3	3	1	3
	3^{rd} pore	2	3.2	1.6	2.6
	4^{th} pore	1.66	2	1.20	1.83

Compression tests were applied to examine the mechanical behavior of the obtained samples. Square-section rectangular-shaped samples of equal dimensions with different densities were cut in an abrasive grinding machine to be used in compression tests. Compression test results are shown in Table 2 for each aluminum alloy. Moreover, the physical condition of Al6061 before and after the compression test is shown in Figure 11.

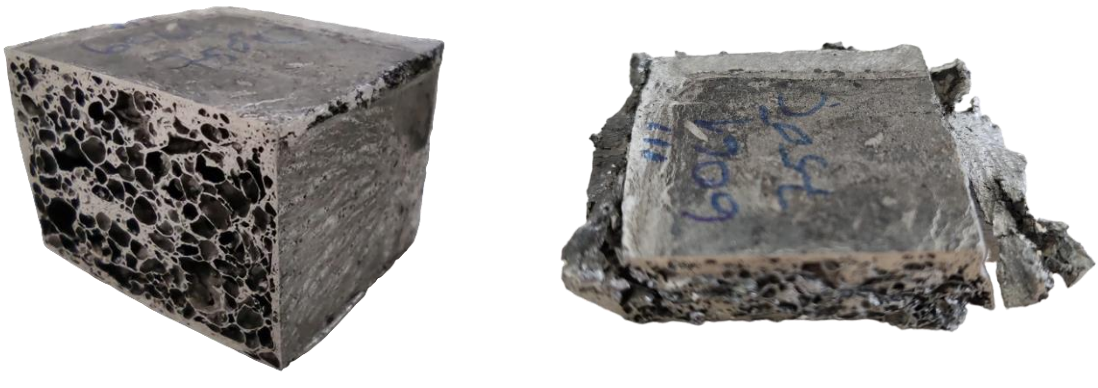

Figure 11. Physical condition of Al6061 before and after compression test (Al6061'in sıkıştırma testinden önceki ve sonraki fiziksel durumu)

Table 2. Compression test results of the samples (Numunelerin basma testi sonuçları)

	Al2024	**Al5083**	**Al6061**
Compressive stress under maximum load (N)	42916.91	35158.43	39829.22
Maximum compressive stress (MPa)	64.391	55.941	63.617
Maximum compression tension (%)	39.49	59.462	52.517
Amount of extension at maximum tension (mm)	8.491	12.754	10.704
Breaking load amount (N)	42916.905	35158.431	39829.221
Width (mm)	31	29.3	30.75
Wall thickness (mm)	21.5	21.45	20.36
Amount of elongation at break (mm)	8.491	12.745	10.704
Compressive stress at break (MPa)	64.391	55.941	63.617
Compressive strain at fracture (mm/mm)	0.39495	0.594	0.525
Fracture energy (J)	169.556	214.101	221.711
Displacement amount at maximum pressure (mm)	8.491	16.103	16.120
Pressure load tension at maximum pressure (N)	42916.905	35158.426	39829.221
Geometry	Rectangle	Rectangle	Rectangle

In the Al2024 aluminum foam material, a maximum compressive stress of 64.391 MPa occurred under a compressive stress of 42.916 kN at maximum load and an elongation of 8.491 mm was achieved in the material. At the moment of fracture, the compressive strain is 0.394 mm/mm and the energy released is 169.556 J. In Al5083 type foam, 55.941 MPa compressive stress occurred under 35.158 kN compressive stress at maximum load and 12.754 mm elongation occurred in the material. At the moment of fracture, the compressive strain was measured as 0.594 mm/mm and the energy released was 214.101 J. Finally, in the data of Al6061 alloy, it was determined that at maximum load, 39.828 kN compressive stress, 63.617 MPa maximum compressive stress occurred and 10.704 mm elongation occurred. The compressive strain at which the fracture occurred was calculated as 0.525 mm/mm and 221.711 J of energy was released. Based on the compression test results of aluminum foams in different alloys, the damped energy values were compared with the empty crash box, and the changes in the damped energy due to displacement are shown in Figure 12. While Al5083 and Al6061 have almost similar energy dissipation abilities, Al2024 remains at lower levels. The amount of energy that the empty crash box can absorb is almost 4-5 times less than Al5083 and Al6061. According to these results, it is clearly seen that improvement is achieved with aluminum foam reinforcement. In addition, the stress-strain diagram is shown in Figure 13. In the stress-strain diagram, one of the most important parameters affecting toughness (the material's capacity to absorb the effect caused by external factors as energy until rupture) is the maximum tensile stress. The true stress (MPa)-true strain (%) curve is shown in order to reveal the maximum stress that the material can carry before rupture. The strain values that reveal the ductility performance of the material are different at the rupture point. It is noticeable that ductility is higher in the 5xxx and 6xxxx series alloys, which have replaced AA2024 in the aviation field in recent years. In order to compare energy absorption, the energy amounts absorbed under a fixed displacement value are consistent with the maximum stress values obtained. Ductility and toughness are the two most important parameters expressing the energy absorption capability of the material. The fact that these two values are high in the 5xxx and 6xxxx series alloys reveals their superiority over the 2xxxx series and the untreated.

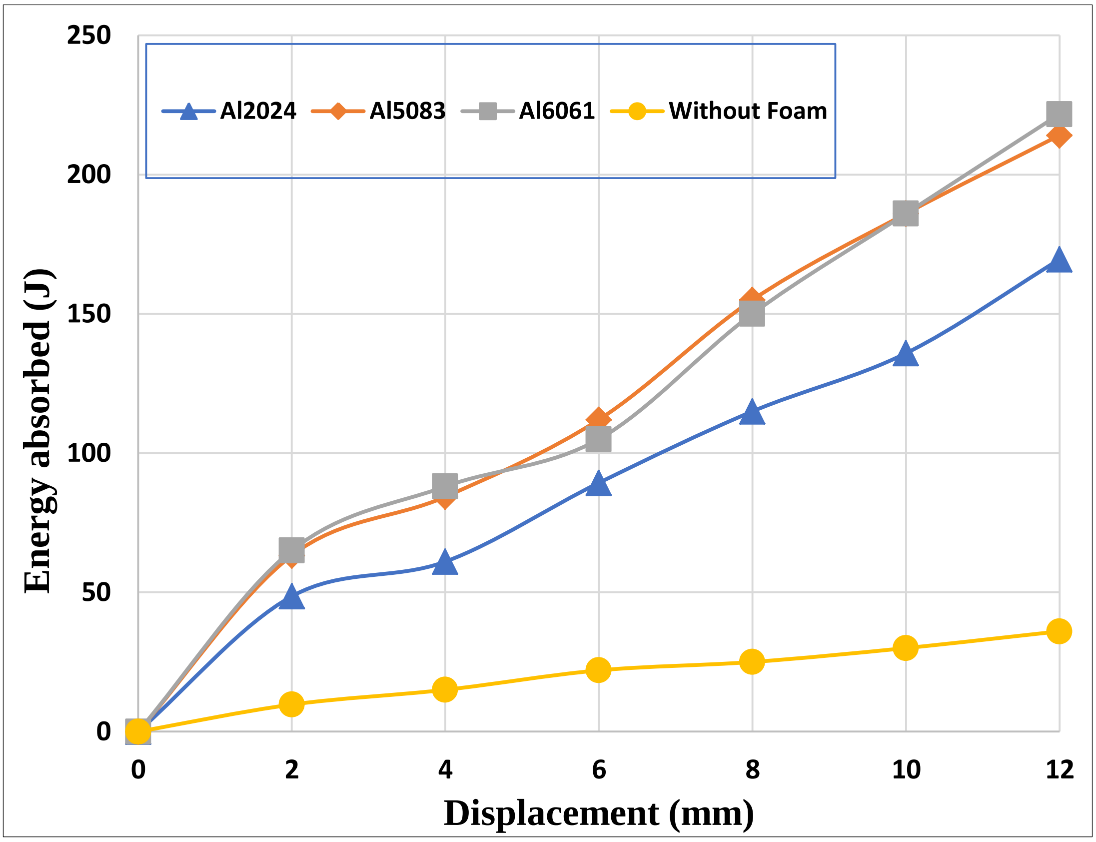

Figure 12. Comparison of the amount of energy absorbed due to displacement (Yer değiştirme nedeniyle emilen enerji miktarının karşılaştırılması)

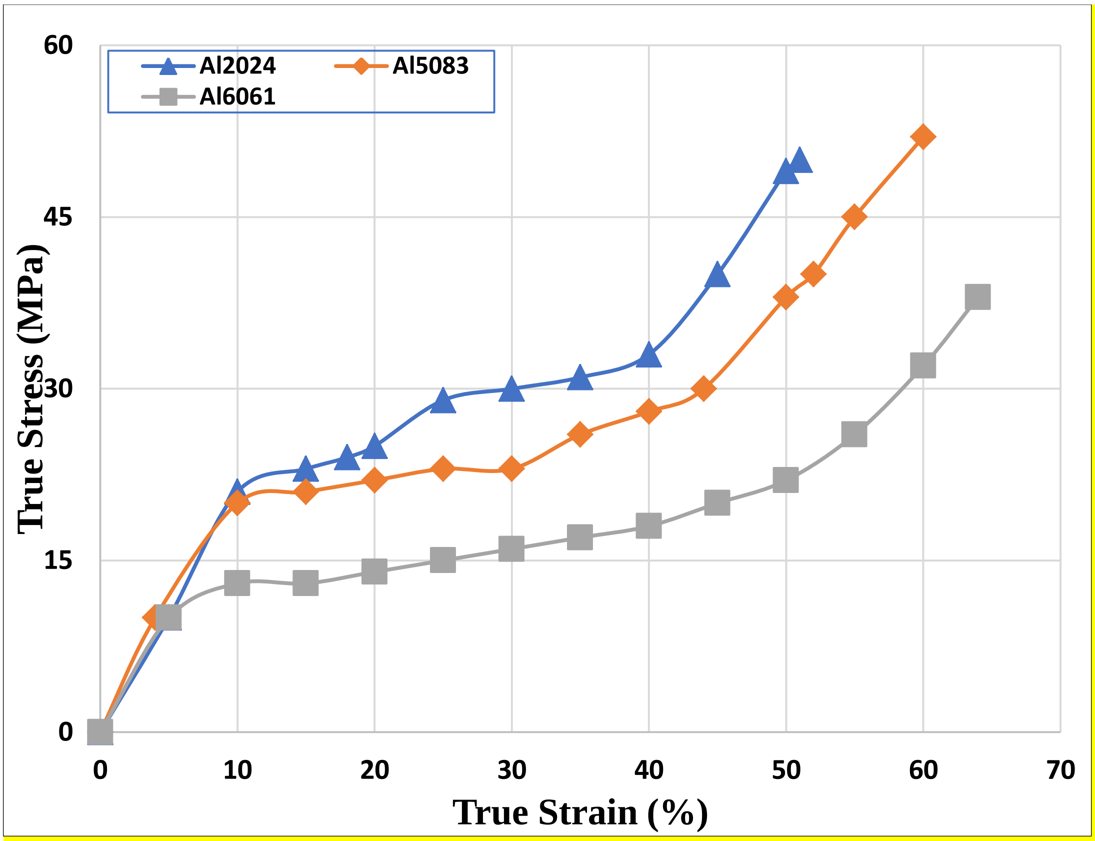

Figure 13. True Stress-Strain graph (Gerçek Gerilim-Gerilme grafiği)

4. CONCLUSIONS (SONUÇLAR)

In this study, aluminum foam materials were produced using three different aluminum alloys, and then the compression test was applied to these foams, their energy dissipation characteristics were experimentally investigated, and an empty crash box was compared. According to research results;

- ✓ It can be said that the most ideal alloy in terms of pore structures and homogeneity is Al6061 in terms of foaming pattern and uniform distribution.
- ✓ In the compression tests of Al2024, Al5083 and Al6061 materials, the compressive stress values under maximum load were 42.916 kN, 35.158 kN and 39.829 kN, respectively, while the maximum compressive stress values were determined as 64.391 MPa, 55.941 MPa and 63.617 MPa, respectively.
- ✓ The displacement amounts under maximum pressure were determined as 8.491, 16.103 and 16.120 mm for Al2024, Al5083 and Al6061, respectively.
- ✓ The highest dissipated energy value was obtained in Al6061 alloys with 221.711 J. In Al2024 and Al5083 alloys, this value was 169.556 J and 214.101, respectively. Compared to the empty crash box, it was observed that the amount of energy absorption increased approximately 4-5 times with aluminum foams.

As a result, it has been concluded that filling the empty crash boxes with aluminum foam material increases the energy absorption ability and thus its use in automobiles can be used as an effective method to reduce the rate of injury and death in traffic accidents.

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