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Effect of Heating Temperature, Holding Time, and Stabilization Temperature on the Al-Foam Properties

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ABSTRACT

The interest in metallic foam is increasing since their cellular structures have a unique combination of properties such as high stiffness, low density, lightweight, high specific strength, and thermal insulation. Commonly, the performance of metallic foam can be improved by the heat treatment process. However, the previous heat treatment methods still present the brittle crack path and the research on heat treatments of the metal foam properties is very limited. In this study, individual parameters in stress relieving treatment that contribute to Al-Foam properties were investigated. The stress-relieving process of the samples was performed using a vacuum furnace. The composition of aluminium foam was determined by X-Ray Fluorescence (XRF). The hardness test was conducted using a microhardness tester. Quasi-static compression test was conducted by a universal testing machine. From the SEM-EDX elemental images, it can be observed that traces of Ca, Fe, Ti, and Si have a homogeneous distribution in the Al-matrix. In the result obtained, the mechanical properties of aluminium alloy foam decrease when the heating temperature is enhanced. The mechanical properties of closed-cell aluminium alloy increase with the reduction of the holding temperature. This was due to the recovery and recrystallization process which depended on time and temperature during the heat treatment process. The mechanical properties of aluminium foam were raised after increasing the stabilization temperature. This finding was due to the vibrational atomic motion in the recovery process.

Keywords: *Al-foam, heating temperature, holding time, mechanical properties, stabilization temperature*

I. Introduction

The biggest challenges on fuel economy advancement and greenhouse gas emission control have become impulses for automobile industry to build a lightweight automobile [1]. During the manufacture of vehicle, vehicle planner repeatedly attempts to reduce the weight of vehicle by which the performance and efficiency of vehicle upward [2]. In order to achieve this goal, metallic foam is developed [3]. Metallic foam is one of the novel materials that has a unique combination property, such as high stiffness, low specific weight, high gas permeability, low thermal conductivity, high impact absorption capacity, and electrical

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insulation properties [2]. The metal foam such as aluminium foam is utilized in the fields of automotive, railway, aerospace, and chemical applications where lightweight materials, improvement in comfort and safety are required [4]–[6]. Aluminium foam has presented the expansive development in the scope of automobile industry industrial [2], [7]. According to the global aluminium foam market, the size valued at USD 40 million in 2022 and is to register CAGR of around 4.6 % from 2023 to 2032 [8].

A metallic foam structures have a strength to withstand an enormous plastic deformation when stress is applied, and their energy absorbers have the capability to resist strong loads towards changes in term of geometry and strain effects. In order to increase the energy absorption capability to improved safety, the enhanced of mechanical and physical properties of metal foam is needed [9]. The mechanical and physical properties of metal foam can be refined by heat treatments process [10]. There are many investigations in the heat treatment of metal foam such as Lehmus and Banhart [11] found that heat treatment process has resulted on increasing in hardness and compressive strength of closed-cell aluminium foam by 60-70% compared with an untreated sample. Feng et al. [12] investigated the aging treatment towards the compressive properties on the alloy foam. They concluded that the absorption energy per unit of the aging treatment is 34%-64% higher than the as-received foam.

In the previous study, the effect of heat treatment on the metal foam properties still has a limitation. Such as a crack progression was formed during aging treatment, brittle behavior presented, foam instability and grain size increase. Therefore, the effect of heating temperature, holding time and stabilization temperature on the Al-foam properties is investigated.

II. Material and Methods

1. Materials

In this study aluminium foam called Alporas is used, produced by Zopin- China with a ZOPIN-Al Foam2 model. The Alporas is material that has closed structure and an ultra-light material [13]. It is produced by casting process, start with molten aluminum by maintain bubbles in the melt with a blowing agent [13], [14]. The composition of aluminium foam was determined by X-Ray Fluorescence (XRF).

2. Experimental Procedure

The experimental procedure involves the preparation of a standard test specimen and stress relieving method. The specimen was cut using an abrasive cutting machine. The stress relieving method was applied in this study, the diagram of stress relieving method presents in Figure 1.

The settings of heating temperature (C 04 – C 05) is presented in Table 1, holding time (t 04) is tabulated in Table 2, and stabilization temperature (C 02 – C 03) are presented in Table 3. The design of heating temperature, holding time and stabilization temperature are using response surface methodology. The stress relieving process of the samples was performed using a vacuum furnace. The heating rate of the stress relieving process was fixed at 10°C/min and the vacuum level of the furnace was fixed at 114 mTor.

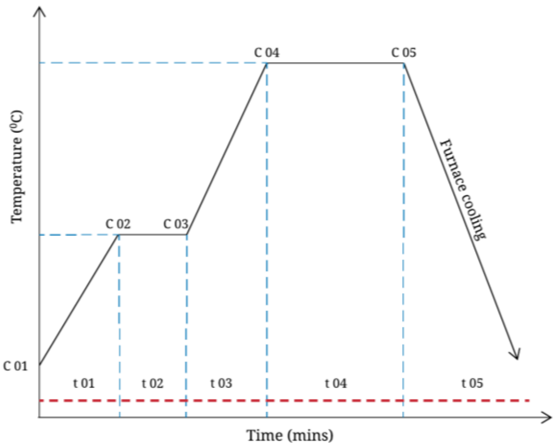


Fig. 1. Temperature profile for stress relieving method
(Source: The figure has been adapted from the study done by Puspitasari et.al [14])

Table 1. The parameters setting of heating temperature

Run	Heating Temperature (℃)	Holding Time (min)	Stabilization Temperature (℃)
1	460		
2	480		
3	500		
4	520		
5	540		
6	560	60	450
7	580		
8	600		
9	620		
10	640		

Table 2. The parameters setting of holding time

Run	Heating Temperature (℃)	Holding Time (min)	Stabilization Temperature (℃)
1		20	
2		40	
3		60	
4		80	
5		100	
6	500	120	450
7		160	
8		180	
9		200	
10		220	

Table 3. The parameters setting of stabilization temperature

Run	Heating Temperature (℃)	Holding Time (min)	Stabilization Temperature (℃)
1	500	60	345
2			360
3			375
4			390
5			405
6			420
7			435
8			450
9			465
10			480

3. Characterizations Procedure for Test Specimen

Several characterization techniques were applied to the samples after each process. Mechanical properties of Alporas foam were determined by hardness and compressive testing. The Vickers hardness test is conducted to measure the hardness value of the aluminium foam specimens. Universal testing machine is used in this study to determine the energy absorption of aluminium foam. Microhardness test on cell wall nodes was conducted in according to ASTM E 92 using microhardness tester LM24AT with 150 mN load and 15s loading time. Five hardness readings were taken on each node [15].

III. Results and Discussions

1. Elemental Mapping Analysis by EDX (Energy Dispersive X-ray)

In order to identify the different elements in the sample, SEM and energy-dispersive x-ray (EDX) spectrometry were applied. The analysis was conducted at three different random spots shown in Figure 2. The interface layer consisted of grey and dark regions. Although the accuracy of this technique was not 100%, it provides general information on the compounds or phase at the specified spot of the cell wall surface. The concentration was in weight% and varied based on the location of the spectrum. The result is tabulated in Table 4. In spectrum 1, the carbon (C) and oxygen (O) contributed large concentration of the element. It was believed that carbon (C) element that appeared on the specimen was coming from $CaCO_3$ phase while oxygen (O) was obtained from the SiO_2 phase. For spectrum 2 and 3, the element of Al was the dominant as compared to the elements that are present in the gray region.

Table 4. The concentration of elements in as-received aluminium alloy foam shown on Figure 2

Spectrum No	Concentration of Element (Weight %)					
	C	O	Al	Si	Ca	Ti
1	73.35	21.56	1.59	1.88	1.62	0
2	10.73	5.79	69.23	13.73	0.22	0.3
3	6.24	17.29	67.33	2.19	6.94	0

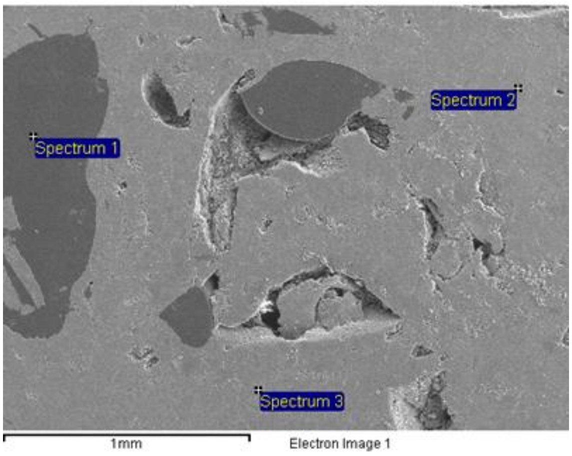
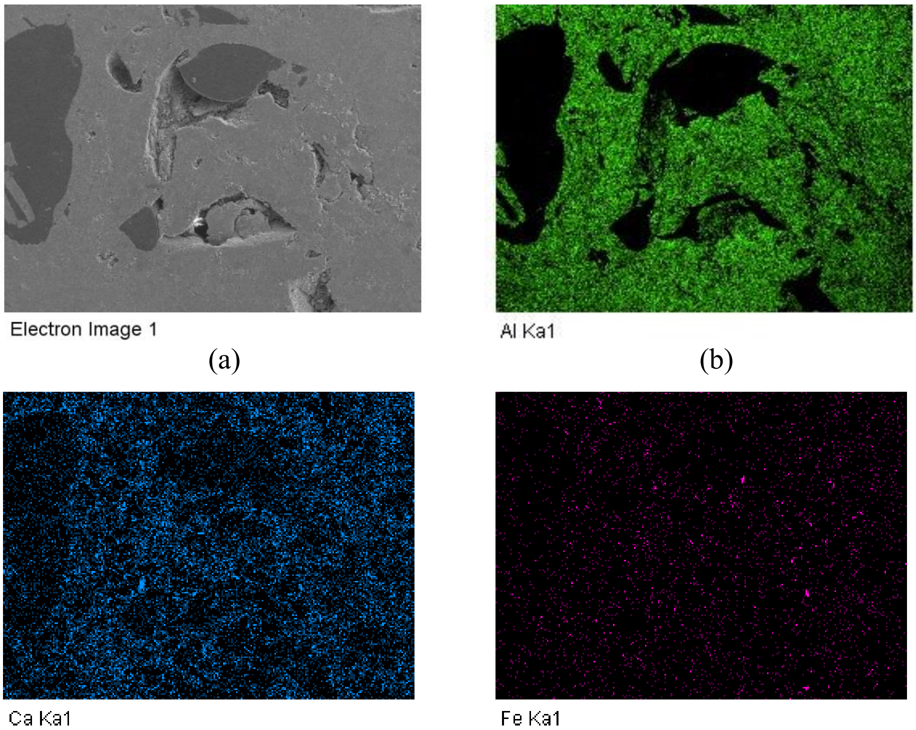


Fig. 2. Map of EDX spot analysis of the as-received aluminium alloy foam

In order to investigate the chemical composition of the closed-cell aluminium alloy foam, energy dispersive x-ray (EDX) measurements were conducted at several locations and representative area. The results are presented in Figure 3. From the SEM-EDX elemental images, it can be observed that traces of Ca, Fe, Ti and Si have a homogeneous distribution in the Al-matrix. Al and Ca were detected from the dendritic and eutectic regions. Fe and Ti were scattered in the particle region while Si was detected at particle and eutectic regions. As shown in Table 1, the concentration of Carbon was dominated in the dark region and it was believed to be epoxy resins. The oxygen element revealed that the oxide layer had appeared in the as-received sample.



(a) (b)

(c) (d)

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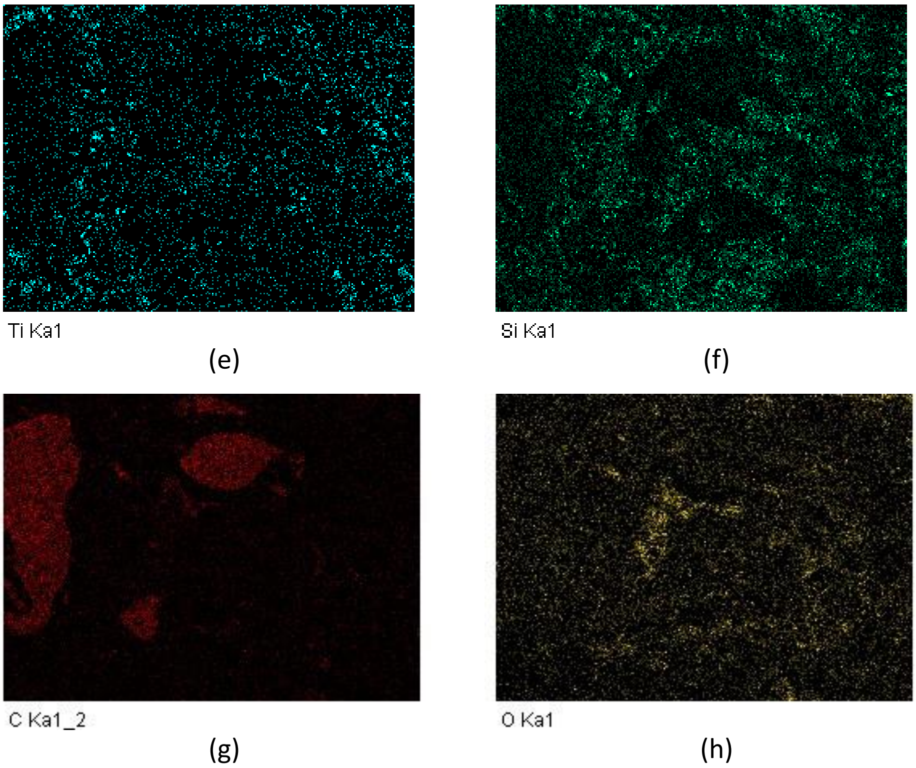


Fig. 3. EDX image of an area showing the distribution of element within the cell wall of as-received sample: (a) different intermetallic phase, (b) Aluminium (Al), (c) Calcium (Ca), (d) Iron (Fe), (e) Titanium (Ti), (f) Silicon (Si), Carbon (C), and (h) Oxygen (O)

2. The Effect of Heating Temperature

In Figure 4, the heating temperature showed a significant influence on the mechanical properties of closed-cell aluminium foam. In the result obtained, the mechanical properties of aluminium alloy foam decrease when the heating temperature is enhanced. It because of the grain growth process as illustrated in Figure 5. The grain boundary will develop into a new grain, followed by the establishment of the nuclei and then develop to become larger nuclei when the heating temperature was increased [15]. Therefore, lower temperature of stress relieving process was required to improve the microstructure of the material. As ascertained by Callister and Rethwisch [16], the mechanical properties of the metal become softer and weaker when the heating temperature during the treatment was raised. The results obtained also comparable with the previous work carried out by Jones and Humaphreys [17], whereby the precipitation growth becomes larger when the heating temperature was enhanced. The result obtained agreed with previous work done by Lázaro et.al [18], the precursor was pre-heated furnace at 710 ºC and the result present large and elongated pores and missing cell walls. After heating at 500 ºC during 8h the smaller pores with similar irregular shape were presented.

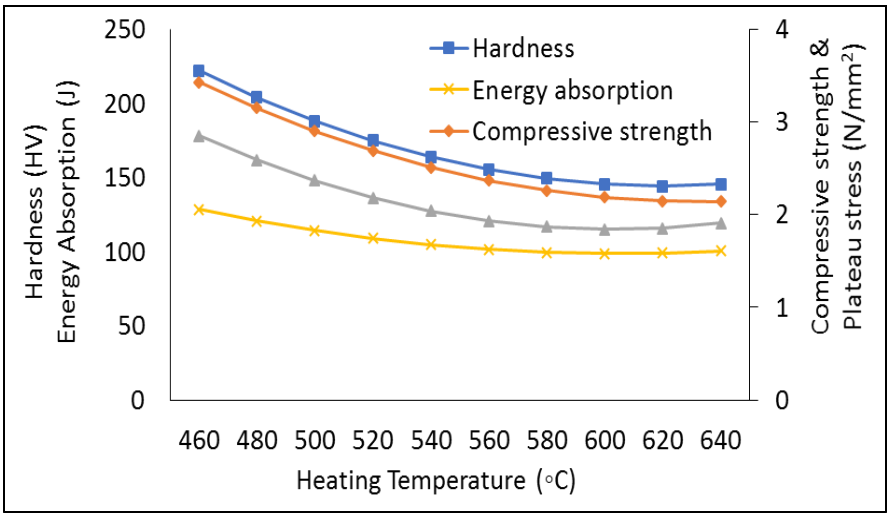


Fig. 4. The effect heating temperature

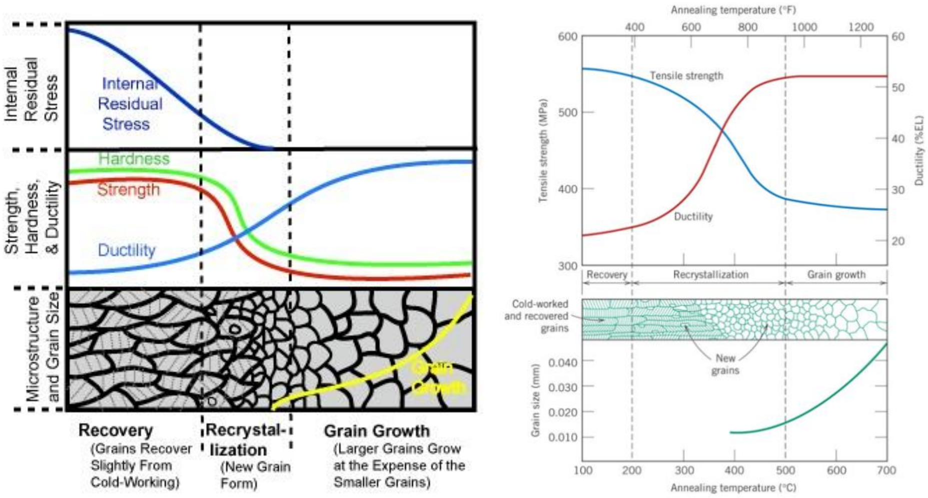


Fig. 5. Effect of recovery and recrystallization on grain structure
(Source: The figure has been adapted from Rethwisch and Herring [15], [19])

3. *The Effect of Holding Time*

The effect of holding time on the mechanical properties of closed-cell aluminium foam can be seen in Figure 6. To examine the effect of holding temperature parameter on the mechanical properties of aluminium foam, the other parameters such as heating time and stabilization temperature were set at a constant value. Generally, the mechanical properties of closed-cell aluminium alloy are increasing with the reduction of the holding temperature. This was due to the recovery and recrystallization process which depended on time and temperature during the heat treatment process. The poor microstructure was formed when both holding time and temperature were enhanced and the grain becomes larger as given in Figure 7(b) if compare with Figure 7(a). This is in agreement with the work reported by Olorunniwo et al. [20], in which the increase in holding time would generate a reduction in the number of grains size. This result was also proved by statistical analysis [21].

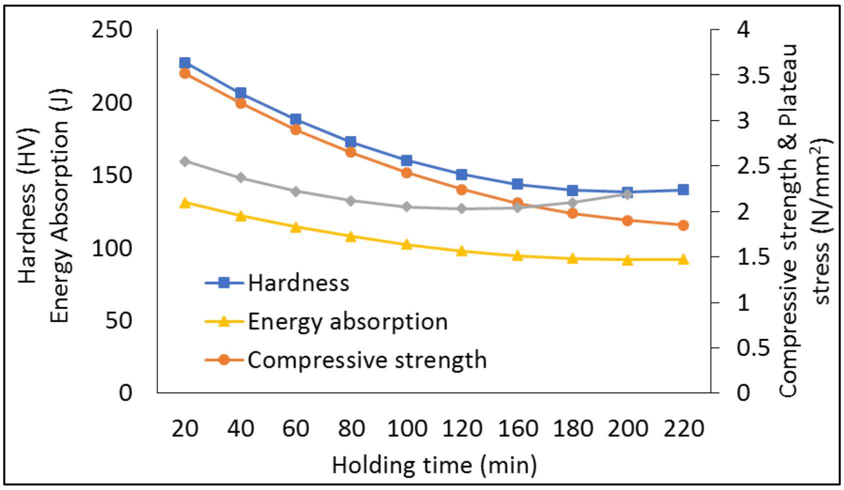
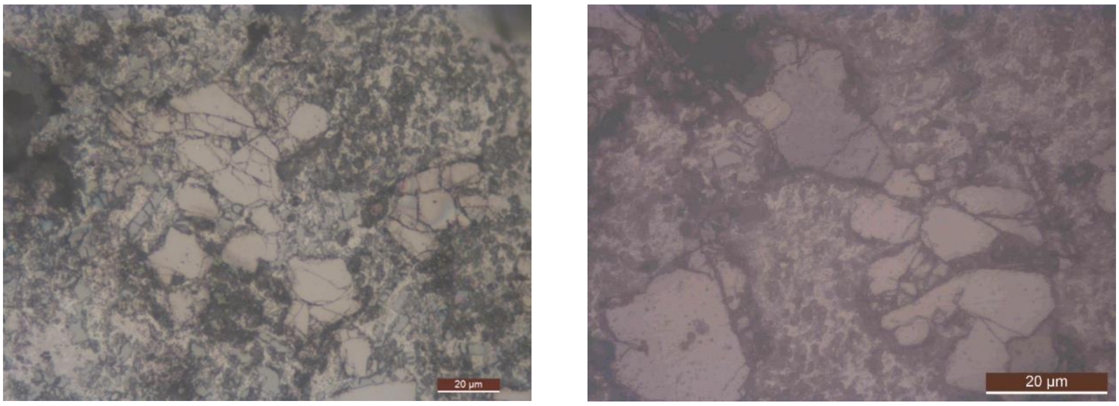


Fig. 6. Effect of holding time



(a) (b)

Fig. 7. Microstructure for a sample (a) microstructure of the sample of control (b) that undergone hold in the longest time

4. The Effect of Stabilization Temperature

The influence of stabilization temperature on the mechanical properties of aluminium foam can be seen graphically in Figure 8. The mechanical properties result comprised hardness properties, compressive strength, plateau stress and energy absorption. In order to study the influence of mechanical properties with stabilization temperature, the aluminium foam undergone the stress relieving process at a constant heating temperature and holding time. Based on the data from figure 8, it can be observed that the mechanical properties of aluminium foam were raised after increasing the stabilization temperature. This finding was due to the vibrational atomic motion in the recovery process. At any instant of time, not all atoms vibrate at the same frequency and amplitude. This will affect the microstructure of the material as ascertained by Callister and Rethwisch [15]. Therefore, the stabilization temperature was applied to stabilize the microstructure from the subsequent softening process at higher temperatures.

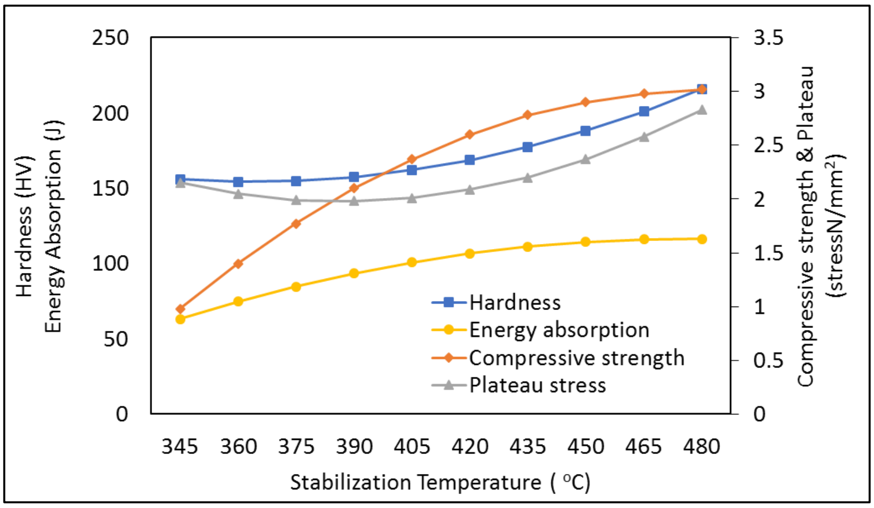


Fig. 8. The influence of stabilization temperature on the mechanical properties

IV. Conclusions

Three stress relieving parameters such as heating temperature, holding time and stabilization temperature have an influential effect on the physical and mechanical properties of closed-cell aluminium alloy foam. For the effect of heating temperature on the mechanical properties of closed-cell aluminium alloy foam, the mechanical properties namely hardness, compressive strength, plateau stress and energy absorption were increased with decreasing of heating temperatures. For the effect of holding time on mechanical properties, it was found that the mechanical properties diminished with the rising of the holding time. Afterward, the mechanical properties of closed-cell aluminium alloy foam were enhanced with the increase in the stabilization temperature. The aluminium foam after treatment can be used as material applied in the bumper and other shock absorbing elements.

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References

[1] W. Zhang and J. Xu, “Advanced lightweight materials for Automobiles: A review,” *Mater. Des.*, vol. 221, 2022, doi: 10.1016/j.matdes.2022.110994.
[2] S. Sunder Sharma, S. Yadav, A. Joshi, A. Goyal, and R. Khatri, “Application of metallic foam in vehicle structure: A review,” *Mater. Today Proc.*, vol. 63, pp. 347–353, 2022, doi: https://doi.org/10.1016/j.matpr.2022.03.201.
[3] B. Bauer, S. Kralj, and M. Bušić, “Production and application of metal foams in casting technology,” *Teh. Vjesn.*, vol. 20, no. 6, pp. 1095–1102, 2013.
[4] J. Banhart, “Manufacture, characterization and application of cellular metals and metal foams,” *Prog. Mater. Sci.*, vol. 46, pp. 559–632, 2001.
[5] Z. Wang, J. Shen, G. Lu, and L. Zhao, “Compressive behavior of closed-cell aluminum alloy foams at medium strain rates,” *Mater. Sci. Eng. A*, vol. 528, no. 6, pp. 2326–2330, 2011, doi: 10.1016/j.msea.2010.12.059.
[6] Y. Chen, R. Das, and M. Battley, “Effects of cell size and cell wall thickness

variations on the stiffness of closed-cell foams," *Int. J. Solids Struct.*, vol. 52, pp. 150–164, 2015, doi: 10.1016/j.ijsolstr.2014.09.022.

[7] E. P. Becker, "Trends in tribological materials and engine technology," *Tribol. Int.*, vol. 37, no. 7, pp. 569–575, 2004, doi: https://doi.org/10.1016/j.triboint.2003.12.006.

[8] M. G. Insights, "Aluminium Foam Market." https://www.gminsights.com/industry-analysis/aluminum-foam-market

[9] V. K. Jeenager, V. Pancholi, and B. S. S. Daniel, "The Effect of Aging on Energy Absorption Capability of Closed Cell Aluminum Foam," *Adv. Mater. Res.*, vol. 585, pp. 327–331, 2012, doi: 10.4028/www.scientific.net/AMR.585.327.

[10] Z. Wang, Z. Li, J. Ning, and L. Zhao, "Effect of heat treatments on the crushing behaviour and energy absorbing performance of aluminium alloy foams," *Mater. Des.*, vol. 30, no. 4, pp. 977–982, 2009, doi: 10.1016/j.matdes.2008.06.058.

[11] D. Lehmhus and J. Banhart, "Properties of heat-treated aluminium foams," *Mater. Sci. Eng. A*, vol. 349, no. 1–2, pp. 98–110, 2003, doi: 10.1016/S0921-5093(02)00582-8.

[12] Y. Feng, N. Tao, Z. Zhu, S. Hu, and Y. Pan, "Effect of aging treatment on the quasi-static and dynamic compressive properties of aluminum alloy foams," *Mater. Lett.*, vol. 57, no. 24–25, pp. 4058–4063, 2003, doi: 10.1016/S0167-577X(03)00265-9.

[13] T. Miyoshi, M. Itoh, S. Akiyama, and A. Kitahara, "ALPORAS aluminum foam: Production process, properties, and applications," *Adv. Eng. Mater.*, vol. 2, no. 4, pp. 179–183, 2000, doi: 10.1002/(SICI)1527-2648(200004)2:4<179::AID-ADEM179>3.0.CO;2-G.

[14] D. Puspitasari, T. L. Ginta, P. Puspitasari, and M. Mustapha, "The effect of thermal processing parameters on the mechanical properties of aluminium alloy foam," *J. Achiev. Mater. Manuf. Eng.*, vol. 91, no. 1, pp. 12–17, 2018, doi: 10.5604/01.3001.0012.9652.

[15] W. D. C. and . D. G. Rethwisch, *Materials Science and Engineering*. New Jersey: John Wiley &Sons, Inc., 2010.

[16] W. D. Callister Jr and D. G. Rethwisch, Characteristics, Application, and Processing of Polymers in *Materials Science and Engineering*, New Jersey: ohn Wiley &Sons, Inc., 2018.

[17] M. J. Jones and F. J. Humphreys, "Interaction of recrystallization and precipitation: The effect of Al3Sc on the recrystallization behaviour of deformed aluminium," *Acta Mater.*, vol. 51, no. 8, pp. 2149–2159, 2003, doi: 10.1016/S1359-6454(03)00002-8.

[18] J. Lázaro, E. Solórzano, M. A. Rodríguez-Pérez, O. Rämer, F. García-Moreno, and J. Banhart, "Heat Treatment of Aluminium Foam Precursors: Effects on Foam Expansion and Final Cellular Structure," *Procedia Mater. Sci.*, vol. 4, pp. 287–292, 2014, doi: 10.1016/j.mspro.2014.07.559.

[19] D. H. Herring, "Stress Relief," *Wire Form. Technol. Int.*, vol. 13, no. 3, pp. 26–28, 2010.

[20] O. E. Olorunniwo, P. O. Atanda, and K. J. Akinluwade, "Effects of Variation of Some Process Variables on Recrystallization Rate of Aluminium Alloy (6063)," *Mater. Charact.*, vol. 8, no. 1, pp. 1–14, 2009.

[21] D. Puspitasari, T. L. Ginta, M. Mustapha, N. Sallih, and P. Puspitasari, "Statistical optimization of stress relieving parameters on closed cell aluminium foam using central composite design," *Arch. Mater. Sci. Eng.*, vol. 89, no. 2, pp. 55–63, 2018, doi: 10.5604/01.3001.0011.7172.