SAINSTECH NUSANTARA

Jurnal Sainstech Nusantara
https://nusantarajournal.id/sainstech
Vol.1 No.3 (2024) 49-61
ISSN: 3063-0657

Effect of Heat Treatment and 1,5% Magnesium Addition on Density, Hardness, and Tensile Strength of Al-Cu-Mg Alloys

Bambang Junipitoyo[1], Djamaaludin Said[1], Dwiyanto[1]

[1]Aircraft Engineering, Politeknik Penerbangan Surabaya, Jalan Jemur Andayani I No 73 Surabaya 60236, INDONESIA

Article Info

Article history:

Received 07 June, 2024
Revised 06 July, 2024
Accepted 31 August, 2024

Abstract

This research focuses on adding aluminum 1100 combinations by adding magnesium (Mg) as much as 1.5% and varying the percentage of copper (Cu). 3.9%, 4.1%, 4.3%/ with heat treatment at temperatures of 100^{0}C, 200^{0}C, 300^{0}C, and 4000C with a holding time at each temperature of 120 minutes, then tested the aluminum combination's density, Vickers hardness, and tensile strength. The final results of this study showed that in the density test, the highest density value obtained was 4.24 gr/cm3 in a mixture of 1.5% magnesium and 4.3% copper (Cu) with a temperature of 200^{0}C. In the Vickers hardness test, the highest hardness value was 83.9 HVN in a mixture of 1.5% magnesium and 4.3% copper with a temperature of 400^{0}C. The final result of the research conducted was to obtain the tensile strength results of each specimen by obtaining the maximum tensile strength of the 4.1% Cu mixture specimen with a temperature of 400^{0}C of 163.2698 Mpa and the highest strain value in the 4.3% Cu mixture specimen with a temperature of 400^{0}C of 0.0472 %, for the results of the lowest elastic modulus value in the 4.3% Cu mixture specimen with a temperature of 200^{0}C of 3147.319 Mpa and the highest value of the 4.1 % Cu mixture specimen with a temperature of 400^{0}C of 5947.898 Mpa.

Keywords: Aluminium 1100, Heat Treatment, Vickers hardness test, Tensile test, Density Test

Corresponding Author:

Name: Bambang Junipitoyo
Email: bambang.junipitoyo@poltekbangsby.ac.id

1. Introduction

Aluminium is the primary material currently used in the commercial aircraft industry. The advantages of aluminum lie in its lightweight nature and its ability to be strengthened by adding other elements. Initially, aluminum alloys were developed to obtain solid and lightweight materials. However, with the increasing size and complexity of commercial aircraft structures, the need for materials includes strength and lightness, durability, low manufacturing cost, high failure tolerance, and corrosion resistance. Therefore, aluminum alloys are continuously developed to meet these demands [1].

DOI: https://doi.org/10.71225/jstn.v1i3.61

Lightweight aircraft structural materials are essential for the aviation industry. Although aluminum is commonly used, its too-soft nature and low strength require alloying with other metals to improve its quality. Among the metals often alloyed with aluminum are copper (Cu), silicon (Si), magnesium (Mg), manganese (Mn), zinc (Zn), and iron (Fe) [2]. Mixing these metals can produce chemical compounds that increase the mechanical strength of aluminum. The composition of aluminum alloys can be adjusted for specific applications, such as making aircraft or machine parts that require strength, hardness, corrosion resistance, and low weight. Therefore, adding a certain percentage of copper can improve aluminum alloys' mechanical properties and microstructure [3].

Before being developed into 2XXX series aluminum or other series, aluminum alloys are usually based on pure aluminum of the 1100 series. The AA 1100 aluminum series is widely used in industry for heat exchangers, pressure containers, and pipe applications. Although 1100 aluminum has low potency and is rarely used in structural applications, its properties can be improved by mixing it with other metals [4]. For a long time, the aviation industry has used combinations of the three aluminum groups. They are still essential when manufacturing aircraft [5]. The first aluminum alloy consists of copper, silicon, manganese, and iron. It has a chemical composition of about 4 percent copper, 0.5 percent magnesium, 0.5 percent manganese, 0.3 percent silicon, and 0.2 percent iron. This alloy is commonly used to make aircraft wing skins. The second group is aluminum alloys containing 1-2% nickel and higher contents of iron, copper, silicon, and more.[6]. These alloys are well suited for tasks that require strength at high temperatures, such as making aircraft engines and frames. Aluminum alloys from the third group consist of 2.5% copper, 5% zinc, 3% magnesium, and 1% nickel. Their strength depends on the amount of zinc added [7].

Adding an element to aluminum alloys will significantly affect the microstructure and characteristics of an alloy metal, as well as the grain size, which will determine the mechanical strength of the alloy metal. The re-casting process on aluminum will change its physical and mechanical properties.[8]. To obtain good physical and mechanical properties, aluminum components will generally be added with reinforcing alloying elements to complement the basic properties of the component and produce aluminum alloys that meet the needs [9].

Aluminum alloys are classified by various standards by several countries. In general, aluminum alloys are classified into two groups: cast aluminum alloys and wrought aluminum alloys [6]. Each group is further divided into two categories: heat-treatable and non-heat-treatable [10].

2. Research Method

2.1 Specimen Test

Prepare Aluminum, Copper, and Magnesium materials. Aluminum is put into the mold before mixing with magnesium and copper according to the dosage in Table 1 Research Design. The heating furnace is switched on, and the aluminum mold is inserted. Aluminum is put into the heating furnace and heated at 900°C [11]. Once the molten aluminum is ready, magnesium and copper are put into the mold containing molten aluminum [9]. The mixture was stirred after the Al-Mg-Cu composite mixing process was complete; the mixture was poured into a mold and cooled at room temperature. The finished Al-Mg-Cu composite was from the furnace. Then, test whether the casting results are successful by inserting them into the water [12] If the specimen sinks and there are no bubbles, then the specimen is said to be successful.

DOI: https://doi.org/10.71225/jstn.v1i3.61

Table 1. Research Design

Materials			Heat Treatment		Results test		
Mg	Cu	Al-1100	Temperature (ºC)	Aging (Hours)	Hardnes test	Tensile Strength	Density
1,5%	3,9%	94,6%	100	2			
			200	2			
			300	2			
			400	2			
	4,1%	98,4%	100	2			
			200	2			
			300	2			
			400	2			
	4,3%	94,2%	100	2			
			200	2			
			300	2			
			400	2			

2.2 Tensile Testing Specimen

The test material used in this research is 1100 aluminum mixed with magnesium and copper. This material is a slab, which is then cut into test specimens using sheet metal cutting tools at Sheet Metal Shop Hangar AMTO 147D/010 Aviation Polytechnic Surabaya. The size of the test specimen is adjusted to the ASTM E8/E8M standard applicable for tensile testing. Sketches and sizes of materials to be used for tensile testing are:

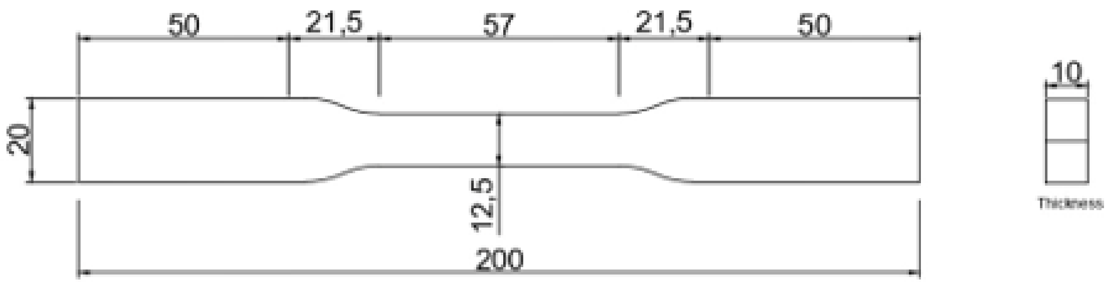

Figure 1. Sketch of Tensile Testing Test Specimen

Gauge Length	= 57 mm
Thickness	= 10 mm
Width	= 12.5 mm
Grip Section Length	= 50 mm
Grip Section Width	= 20 mm
Fillet Radius	= 21.5 mm
Overall Length	= 200 mm

2.3 Vickers Hardness Test Specimen

The test material used in this research is 1100 aluminum, added with magnesium as a reinforcing agent through melting and heating [13]. The slab is then cut into three specimens using a sheet metal cutting tool at Sheet Metal Shop Hangar AMTO 147D/010 Aviation Polytechnic Surabaya. A sketch of the hardness test specimen can be seen in the figure (based on ASTM International E384,

DOI: https://doi.org/10.71225/jstn.v1i3.61

Standard Vickers Hardness Test Method for Metallic Materials). The size of the material to be formed into a specimen for the Vickers hardness test is:

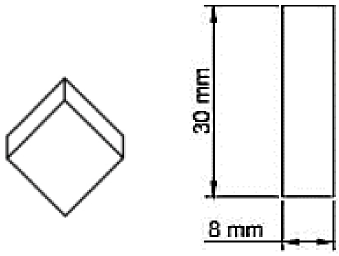

Figure 2. Vickers Test Specimen

2.4 Heat Treatment

The first step after forming the samples according to each test is to perform the solution annealing process on all samples at temperatures of 1000°C, 2000°C, 3000°C, 4000°C and a holding time of 2 hours. After solution treatment of all samples, the next step is rapid cooling (quenching) of oil media for 3 minutes. The following are the test steps:

The workpiece is put into the heating kitchen with a temperature of 100^0 C, 200^0 C, 300^0 C, 400^0 C and given a holding time of 2 hours. After the holding time reaches 2 hours, clamping pliers remove the workpiece from the heating kitchen [14]. The next stage is *quenching* with a cooling medium in the form of water for 3 minutes at a temperature of 26-27°C [4]. The workpiece is allowed to come to room temperature in the oil. After the workpiece has passed through the *solution heat treatment* and *quenching* stages, the next step is to perform processes suitable for the research or application, such as mechanical properties testing, microstructure checking, or other advanced treatments. After the workpiece has received quenching treatment, it is ready for the next stage [15].

2.5 Density Test

The aim was to find the difference in density in each sample and estimate the purity of the aluminum metal used. Here are the steps of the test: First, put the cut specimen into a measuring cup filled with water to a predetermined volume. Then, the weighted casting pieces are added to a measuring cup containing water. After the casting pieces are added, pay attention to the volume change in the measuring cup.[12]. After data is obtained from weighing castings and volume changes, the next step is calculating the density using the following equation.

$$\text{Density of castings } (\rho) = \frac{\text{Weight Of Castings (W)}}{\text{Volume Of Addition(V)}}$$

2.6 Tensile Strength Test

Is carried out to determine the safety of using the material for the need so that this test will know the maximum weight and maximum strain on the beverage. The dance testing process is as follows: ASTM E8 made specimens. The specimen is fixed at the upper and lower corners of the test apparatus. The lower handle is raised and lowered at a slow speed so that the test apparatus handle is folded, the holder is kept upright, and the handle is adjusted. The specimen is injected at a speed of 10 mm/sec so that the test bead will increase in length until the test bead breaks [8]. Fracture is expected to occur at the gauge length or gauge length of the test bead. The data obtained is recorded during the dance testing

DOI: https://doi.org/10.71225/jstn.v1i3.61

process (weight gain (P) and length gain (ε)) on the handrail in up [16]. Record the results of the broken test piece's maximum tensile load and tensile strength. Release the handle slowly. Do not lower the handle abruptly; let the handle descend slowly. The needle on the scale will move as the handle is lowered. Wait for the needle on the scale to stop moving and stabilize. The length increment displayed on the tensile testing machine is recorded as if the testing machine were broken [17] [21].

2.7 Vickers Hardness Test

Research aims to determine the difference in each specialty's mechanical properties and determine which alloy has the best mechanical properties. The process is as follows: First, by preparing the specimen that has been ground and polished to maximize the results, prepare the tool with a diamond pyramid editor with a 136-degree subdued. Place the specimen on the anvil, making sure it is at the ideator's point, and apply a weight of 50kgf and the range specified in the test. Press the "start" button for 10-20 seconds, and the ideator will turn the specimen, and the diagonal screw of the drill will turn the outlier liens.[18]. Once the data is obtained from the roughness value of the product (HV), you can find the HVN value by using the formula below [21].

3. Results And Discussion

In this research, three tests were carried out, namely, density testing, Vickers hardness testing, and tensile testing, to find out the physical and mechanical properties of aluminum alloy 1100, which has been mixed with Mg and Cu with heat treatment. Also, from the results of the tests, data on the distribution of density, Vickers hardness, and tensile strength of the alloy heat treated with aging time for 2 hours were obtained.

3.1 Density Test Results

This test aims to measure the difference in density or bulk density of each specimen. In addition, this test will analyze the impact of the addition on aluminum magnesium castings with a percentage of 1.5% and copper percentage variations of 3.9%, 4.1%, and 4.3%. Table 3.3 below shows the results of the aging heat treatment.

Table 2. Results of Density Test

Materials			Heat Treatment		Results test		
Mg	**Cu**	**Al-1100**	**Temperature (ºC)**	**Aging (Hours)**	**Weight (gr)**	**Volume (cm^3)**	**Density (gr/cm^3)**
1,5%	3,9%	94,6%	100	2	17,39	6	2,78
			200	2	15,72	5	3,338
			300	2	16,69	5	3,144
			400	2	16,68	10	1,739
	4,1%	98,4%	100	2	15,80	5	3,16
			200	2	15,84	4	3,98
			300	2	15,95	6	2,659
			400	2	18,68	9	2,076
	4,3%	94,2%	100	2	16,28	6	2,741
			200	2	16,96	4	4,24
			300	2	17,07	5	3,404
			400	2	17,19	9	1,91

DOI: https://doi.org/10.71225/jstn.v1i3.61

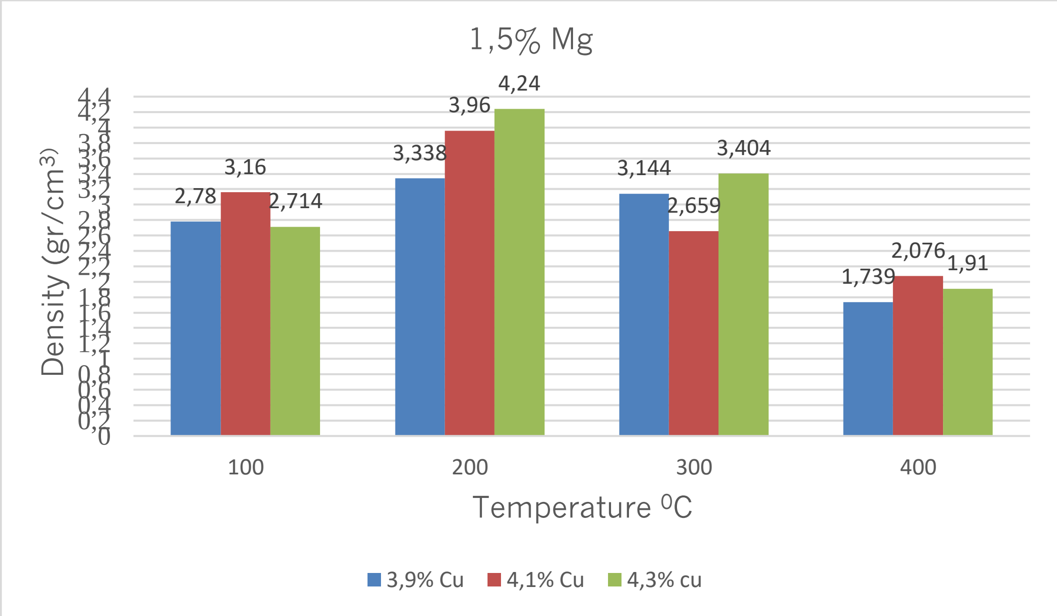

Figure 3. Diapghram of Density Test Results

The graph above shows the results of density testing on mixed specimens with a percentage of 1.5% magnesium (Mg) and 3.9%, 4.1%, and 4.3% copper (Cu) that have been heat treated with aging. The highest result in the density test is found in the percentage of magnesium 1.5% and copper 4.3% at a temperature of 200^0C, namely 4.24 gr / cm3, and the lowest value obtained in the rate of magnesium (Mg) 1.5% and copper (Cu) 3.9% at a temperature of 400^0C, namely 1.739 gr / cm^3.

In the results of the mixture of 1100 aluminum, magnesium (Mg), and copper (Cu) specimens that have been heating treated by aging, the highest value is obtained at a temperature of 200^0C, which is 4.24 gr/cm3 in a mixture of 1.5% magnesium and 4.3% copper. The highest result without heat treatment is 1.74 gr/cm^3. It can be concluded that the density of pure 1100 aluminum with a mixture of magnesium and copper in heat treatment and not in heat treatment is increasing density because pure 1100 aluminum has a lower density than aluminum alloys without heat treatment and aluminum alloys that have undergone heat treatment. According to the journal [19]. At a temperature of 200^0C, the density of a substance can increase. This happens because the molecules of a substance move more slowly and close together, thus increasing the average density of each other. Compared to specimens without heat treatment [22] [23].

3.2 Tensile Strength Test Results

This examination aims to determine the tensile strength and strain of the sample. In this study, the specimens used contained 1.5% magnesium, 3.9%, 4.1%, and 4.3% copper, respectively. They were given an aging heat treatment for two hours.

DOI: https://doi.org/10.71225/jstn.v1i3.61

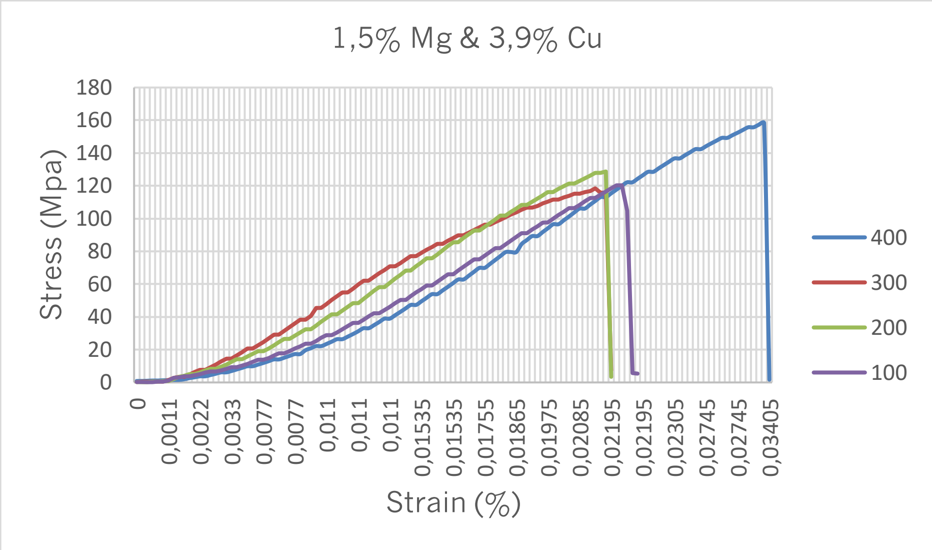

Figure 4. Stress-Strain of 3.9% Cu alloy

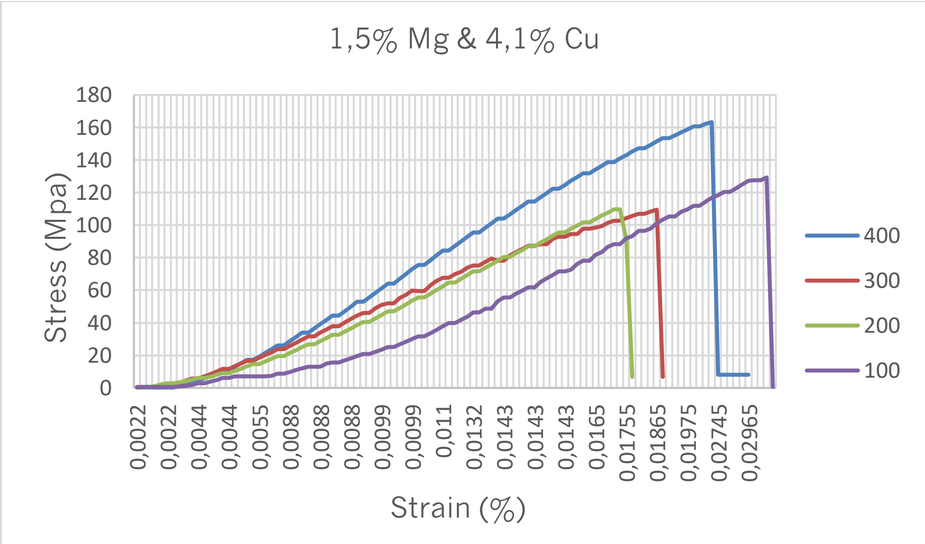

Figure 5. Stress-Strain of 3.9% Cu alloy

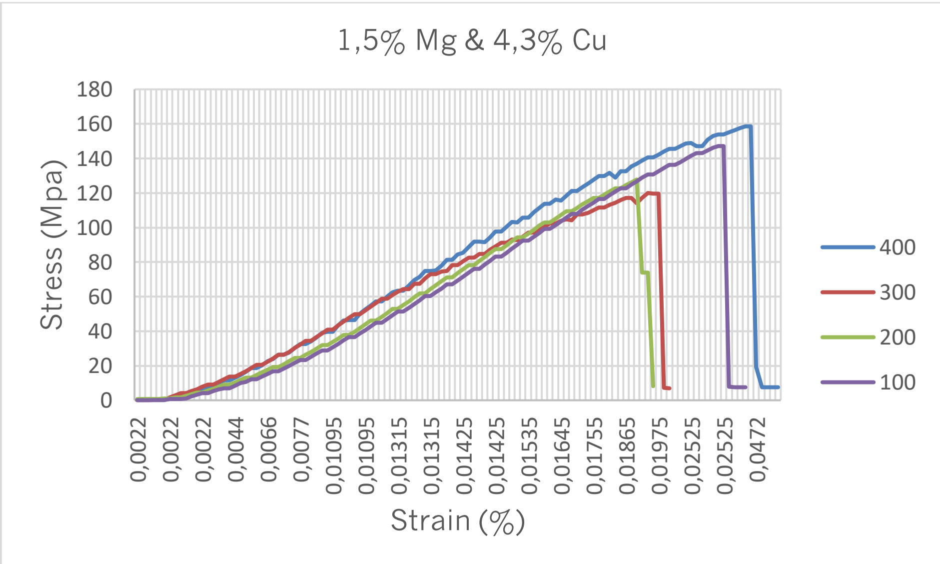

Figure 6. Stress-Strain of 3.9% Cu alloy

DOI: https://doi.org/10.71225/jstn.v1i3.61

The graph above shows that the comparison of the three variations of copper (Cu) mixture has some differences. The first difference is seen between the mixture of 3.9% Cu and 4.3% Cu, which has a difference that is not too high but has a longer strain on the mix of 4.3% Cu at a temperature of 400^0C. The stress in the 4,3% Cu mixture can increase due to the addition of copper (Cu), which has undergone aging heat treatment for 2 hours, so a significant increase in stress and strain is obtained.

The next difference is in the mixture of 4.1% Cu at a temperature of 400^0C, which has a quite high maximum tensile strength. It is almost double the tensile strength of the mix of 3.9% Cu and 4.1% Cu, with a stress strength value of 163.2698 Mpa. However, the 4.3% Cu mixture at a temperature of 400^0C has a pretty low strain compared to other mixed specimens, which only has a value of 0.02745%. The stress in the 4.1% Cu mixture specimen with a temperature of 400^0C can reach its highest target due to the more excellent mixture in the composition of magnesium and copper.

Specimens at a mixture of 4.1% Cu with a temperature of 400^0C have a tensile strength that is relatively high compared to other specimens due to the addition of copper and temperature. It can be interpreted that copper and heat treatment are still among the strongest compositions. This material has an excellent strength-to-weight ratio, making it outstanding in various applications. In addition, it is resistant to high heat and has high chemical or corrosion resistance, mainly when used with proper aging heat treatment. Its excellent flexibility also makes it suitable for a wide variety of uses.

From all specimens that have been tensile tested, it can be concluded that adding copper and heat treatment will be able to make the material more elastic and increase the length of the strain. If you add the composition of magnesium and copper with heat treatment, the material will touch the maximum value in tension. So, in this case, if an aluminum material is needed with maximum results in stress and strain, it must be able to get the suitable composition between magnesium and copper given heat treatment, which will create a material with maximum strength but still light and flexible.

Table 3. Elongation Test Result

Magnesium (Mg)	**Copper (Cu)**	**Aluminium 1100**	**Temperature ^{0}C**	**Aging (Hours)**	**Elongation (%)**
1,5%	3,9%	94,6%	400^0C	2 Hours	0,03405
			300^0C	2 Hours	0,02305
			200^0C	2 Hours	0,03845
			100^0C	2 Hours	0,02965
	4,1%	94,4%	400^0C	2 Hours	0,02745
			300^0C	2 Hours	0,02635
			200^0C	2 Hours	0,02415
			100^0C	2 Hours	0,03185
	4,3%	94,2%	400^0C	2 Hours	0,0472
			300^0C	2 Hours	0,03185
			200^0C	2 Hours	0,0406
			100^0C	2 Hours	0,0274

DOI: https://doi.org/10.71225/jstn.v1i3.61

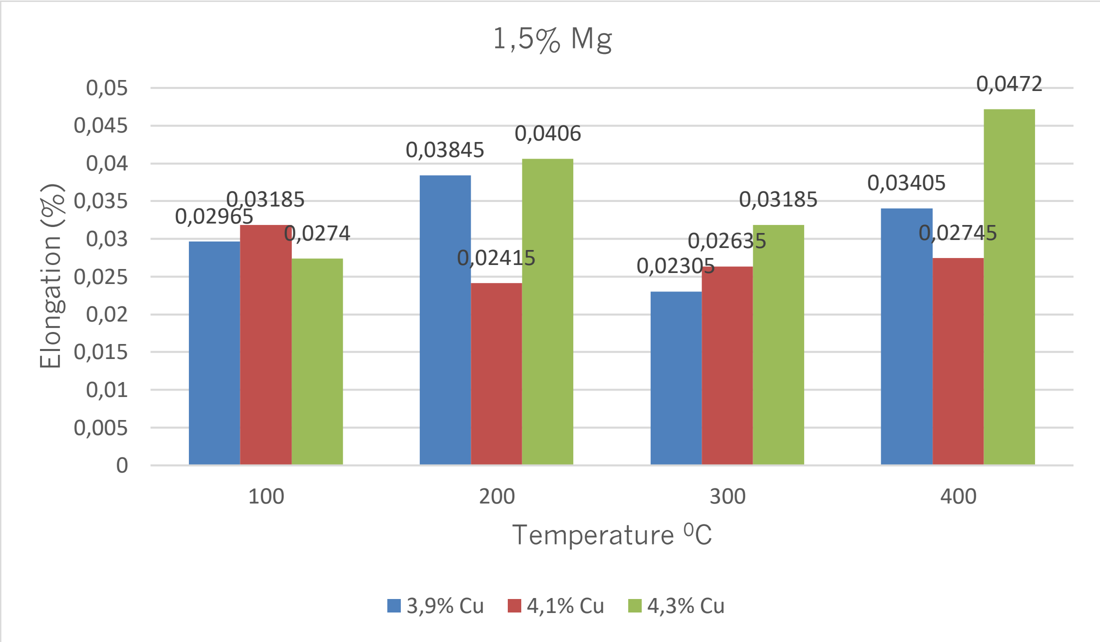

Figure 7. Elongation Test Result

From the comparison of the strain values obtained, it is different from the tensile stress results. If the stress value is obtained, the maximum strength is obtained in the 4.1% Cu mixture specimen, but this maximum strain value is actually in the 4.3% Cu mixture specimen. The strain value in the 4.3% Cu mixture specimen with a temperature of 400^0C has a maximum value of 0.0472%. The high strain value in the 4.3% Cu mixture specimen is obtained due to the addition of copper (Cu), which proves that this copper (Cu) mixture has elastic and robust properties. The highest maximum stress value in the 4.1% Cu mixture specimen could not support the strain value.

Table 3. Modulus Elasticity Test Result

Magnesium (Mg)	Copper (Cu)	Aluminium 1100	Temperature ^{0}C	Aging (Hours)	Modulus Elasticity (Mpa)
			400^0C	2 Hours	4647,491
	3,9%	94,6%	300^0C	2 Hours	4583,232
			200^0C	2 Hours	3348,208
			100^0C	2 Hours	4057,667
			400^0C	2 Hours	5947,898
1,5%	4,1%	94,4%	300^0C	2 Hours	4156,611
			200^0C	2 Hours	4543,066
			100^0C	2 Hours	4059,769
			400^0C	2 Hours	3360,008
	4,3%	94,2%	300^0C	2 Hours	3758,169
			200^0C	2 Hours	3147,319
			100^0C	2 Hours	5371,011

DOI: https://doi.org/10.71225/jstn.v1i3.61

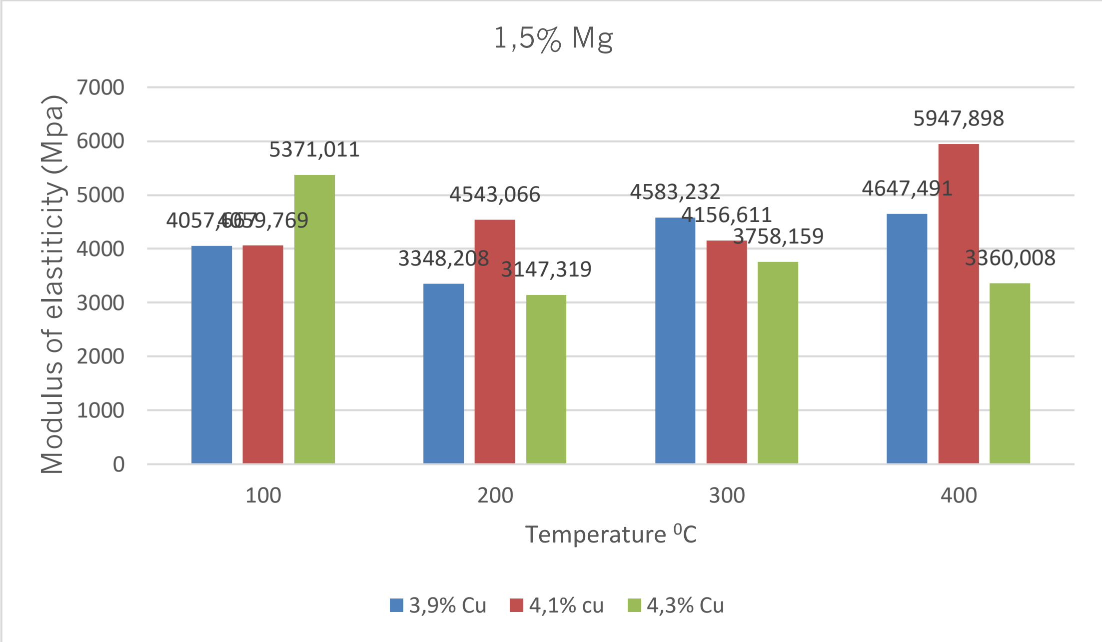

Figure 8. Modulus Elasticity Test Result

A considerable difference is obtained from calculating the elastic modulus of each copper mixture variation and heat treatment temperature variation. In the 3.9% Cu mixture specimen at a temperature of 200⁰C, the minimum value is 3348.208 Mpa, the 4.1% Cu mixture specimen at a temperature of 100⁰C gets a minimum value of 4059.769 Mpa, and the 4.3% Cu mixture specimen at a temperature of 200⁰C gets a minimum value of 3147.319 Mpa. These results show that the specimen with the smallest value is included in the elastic material. So, the 4.3% Cu mixture specimen with a temperature of 200⁰C is the most elastic variation compared to other variations, and the 4.1% Cu specimen with a temperature of 100⁰C is the most plastic variation compared to different variations. It can be concluded that adding magnesium, copper, and heat treatment temperature variations to the aluminum material makes it more elastic.

3.3 Vickers Strength Test Results

This test aims to measure the mechanical properties of hardness on specimens of the specified shape and size by current standards. In this test, specimens are made by melting 1100 aluminum with a mixture of magnesium and nickel and through heat treatment. This test uses specimens containing 1.5% magnesium and nickel variations of 3.9%, 4.1%, and 4.3%. The hardness test results can be seen in Figure 9. It is known that specimens with a percentage of 1.5% Mg and 3.9% Cu, 4.1% Cu, and 4.3% Cu with heat treatment aging for 2 hours have increased hardness values with the best percentage in the alloy, namely 4.3% Cu. With the addition of the percentage of Cu at each temperature from 400⁰C to 100⁰C, the hardness value of the material decreases. The highest hardness value is located in the specimen with a percentage of 4.3% Cu with a temperature of 400⁰C with a hardness value of 83.9 HVN, while the lowest hardness value is in the specimen with a rate of 3.9% Cu with a temperature of 100⁰C with a hardness value of 64.5 HVN.

The highest hardness value not in heat treatment is located at a percentage of 4.3% Cu, which has a hardness value of 83.3 HVN. And for the hardness value of pure 1100 aluminum of 39.79 HVN. As a comparison in this study. Because 1100 aluminum has a very low hardness level, it must be mixed

DOI: https://doi.org/10.71225/jstn.v1i3.61

with alloys and given heat treatment. The hardness value of this specimen increases due to the increase in the percentage of copper (Cu) and heat treatment, so the increase in the percentage of copper (Cu) will make the specimen harder and get a high value because the nature of Copper (Cu) is to increase the hardness of the material. According to the [20]With the higher temperature during the heat treatment process, the conditions at a temperature of 400^{0}C are optimal and good because they increase the hardness of the alloy, which is more stable in the material, therefore getting the highest and best results in the test, and what happens at a temperature of 100^{0}C the mechanical alloy properties have not yet reached optimal conditions so that the Vickers alloy hardness has not reached its peak so that it gets the lowest results in the test.

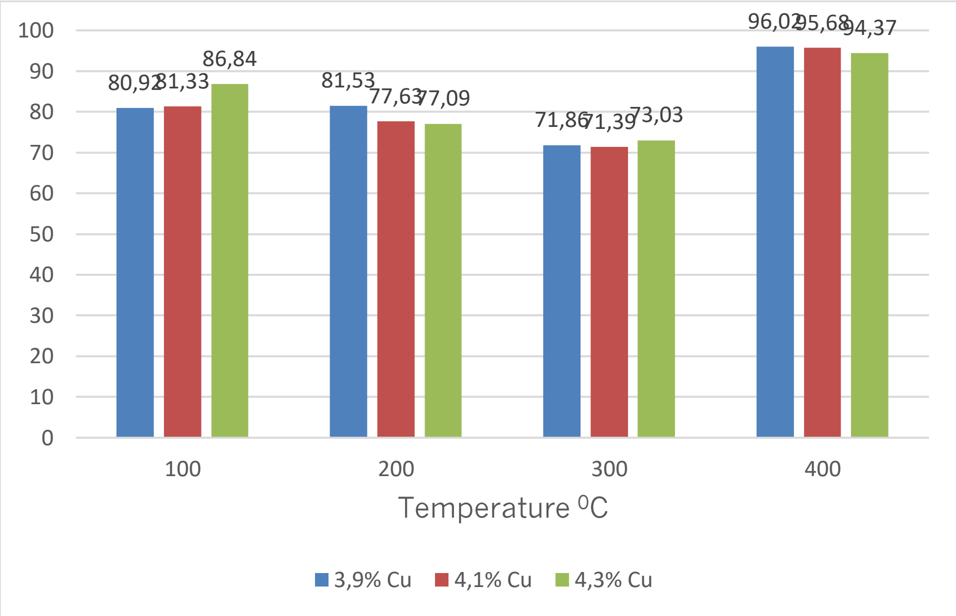

Figure 9. Vickers Hardness Test Results

4. Conclusion

In the research carried out, we can draw several conclusions as follows:

The heat treatment process on aluminum alloys that are increasing in profitability can significantly influence the density of aluminum alloys compared to pure aluminum and aluminum alloys alone, in general. This is because the heat treatment process can change the microstructure and phase distribution of the alloy, which in turn can increase the density of the alloy. However, this increase in density may not be very significant, depending on the heat treatment parameters used, and the highest result in the density test is the mixture of 4.3% Cu at 200ºC of 4.24 gr/cm^3. The heat treatment process on aluminum alloys is increasing in results that can improve the hardness of aluminum alloys compared to pure aluminum and aluminum alloys alone. This is because, in some cases, the heat treatment process on aluminum alloys can produce a denser and more homogeneous crystal structure, which in turn can increase the strength and hardness of the alloy. Therefore, the highest result obtained in the hardness test is in the mixture of 4.3% Cu at a temperature of 400ºC of 83.9 HV. Increased heat-treated aluminum alloys can have higher tensile strength than pure aluminum or aluminum alloys not subjected to heat treatment. This is due to the changes in microstructure and phase distribution that occur in the material after heat treatment. Heat processes such as heating, rapid cooling, or applying specific temperatures

DOI: https://doi.org/10.71225/jstn.v1i3.61

can optimize aluminum alloys' mechanical and strength properties, thereby increasing their tensile strength. Because, in general, heat treatment aims to increase the strength, toughness, and stability dimensions of aluminum alloy materials. Therefore, the highest result obtained in the tensile strength test is in the mixture of 3.9% Cu at a temperature of 400ºC of 96.02 Mpa.

Acknowledgments

We are also very grateful to Mr Bambang Junipitoyo from Politeknik Penerbangan Surabaya, for his guidance and support during the research process. In addition, we are also grateful for the support and encouragement provided by the Head of the Aircraft Engineering Study Programme, Mr. Nyaris Pambudiyatno. Their collaborative efforts and unwavering commitment have successfully completed the research on the ‘Effect of Adding Percentage 1.5% Mg to Al-Cu Alloy by Heat Treatment on Density Test, Vickers Hardness, and Tensile Strength. This research would not have been possible without their expertise and contributions. Lastly, we appreciate the support of our respective institutions, which provided the necessary resources and a conducive environment for this research.

References

[1] J. Lu, G. Wei, Y. Yu, C. Guo, and L. Jiang, “Aluminum alloy AA2024 anodized from the mixed acid system with enhanced mechanical properties,” *Surfaces and Interfaces*, vol. 13, no. January, pp. 46–50, 2018, doi: 10.1016/j.surfin.2018.08.003.

[2] A. Wisnujati, H. Wijayanto, and A. M. Widodo, *Proceedings of the First Mandalika International Multi-Conference on Science and Engineering 2022, MIMSE 2022 (Mechanical and Electrical)*, vol. 2. Atlantis Press International BV, 2023. doi: 10.2991/978-94-6463-078-7.

[3] H. Wang *et al.*, “Effect of Mg content on microstructure and properties of Zn-Al-Cu Alloy,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 675, no. 1, 2021, doi: 10.1088/1755-1315/675/1/012059.

[4] P. Li *et al.*, “Effect of post-weld heat treatment on the inhomogeneity of mechanical properties and corrosion behavior of rotary friction welded 2024 aluminum alloy joint,” *J. Manuf. Process.*, vol. 75, no. January 2022, pp. 1012–1022, 2022, doi: 10.1016/j.jmapro.2022.01.059.

[5] D. Brough and H. Jouhara, “The aluminium industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery,” *Int. J. Thermofluids*, vol. 1–2, 2020, doi: 10.1016/j.ijft.2019.100007.

[6] R. Wang, Q. Zhu, Y. Zuo, L. Cheng, and J. Wang, “The control of as-cast structure of 2024 aluminum alloy with intensive melt shearing and its effect on microstructure and mechanical properties after T4 treatment,” *J. Mater. Res. Technol.*, vol. 24, pp. 3179–3193, 2023, doi: 10.1016/j.jmrt.2023.03.225.

[7] Z. Sun, Y. Ma, S. Ma, H. Xiong, and B. Chen, “Mechanical properties and corrosion resistance enhancement of 2024 aluminum alloy for drill pipe after heat treatment and Sr modification,” *Mater. Today Commun.*, vol. 36, no. 938, p. 106805, 2023, doi: 10.1016/j.mtcomm.2023.106805.

[8] W. A. Wirawan *et al.*, “Investigation of mechanical and physical properties of continue drive welding on aluminium alloy (AA6061),” *AIP Conf. Proc.*, vol. 2592, no. November 2022, 2023, doi: 10.1063/5.0114916.

[9] W. Zhu, Y. Deng, and X. Guo, “Influence of adjusting the anodizing and aging sequences on the

DOI: https://doi.org/10.71225/jstn.v1i3.61

microstructure, fatigue property and corrosion resistance of anodized AA6082 alloys," *Mater. Charact.*, vol. 189, no. April, p. 111941, 2022, doi: 10.1016/j.matchar.2022.111941.

[10] X. Li and X. Liu, "Influence of CeO2 Nanoparticles on Structure and Properties of Anodic Oxide Film on 2024 Aluminum Alloy," *Int. J. Electrochem. Sci.*, vol. 17, no. 5, p. 220521, 2022, doi: 10.20964/2022.05.07.

[11] S. Sarker, M. S. Haque, M. S. A. Alvy, and M. M. H. Abir, "The effects of solution heat treatment on the microstructure and hardness of an aluminum-4% copper alloy with added nickel and tin," *J. Alloy. Metall. Syst.*, vol. 4, no. August, p. 100042, 2023, doi: 10.1016/j.jalmes.2023.100042.

[12] T. SAVAŞKAN, Z. AZAKLI, and A. P. HEKÌMOĞLU, "Effect of heat treatment on mechanical and wear properties of Zn–40Al–2Cu–2Si alloy," *Trans. Nonferrous Met. Soc. China (English Ed.*, vol. 31, no. 9, pp. 2651–2663, 2021, doi: 10.1016/S1003-6326(21)65682-0.

[13] R. D. Fu, J. F. Zhang, Y. J. Li, J. Kang, H. J. Liu, and F. C. Zhang, "Effect of welding heat input and post-welding natural aging on hardness of stir zone for friction stir-welded 2024-T3 aluminum alloy thin-sheet," *Mater. Sci. Eng. A*, vol. 559, no. 2013, pp. 319–324, 2013, doi: 10.1016/j.msea.2012.08.105.

[14] A. You, M. Be, and I. In, "The Effect of Heating Surface Treatment by Oxy-Acetylene," vol. 030017, no. December 2019, 2023.

[15] L. Hemmouche, C. Fares, and M. A. Belouchrani, "Influence of heat treatments and anodization on fatigue life of 2017A alloy," *Eng. Fail. Anal.*, vol. 35, pp. 554–561, 2013, doi: 10.1016/j.engfailanal.2013.05.003.

[16] S. Manojkumar, M. Kumar, M. Ananth, G. Mageshwaran, and P. Hariprakash, "The Effect of Mg and Mn Addition on Hardness, Tensile and Wear Properties of LM6 Aluminum Alloy," *Springer Proc. Mater.*, vol. 5, no. February 2021, pp. 599–606, 2021, doi: 10.1007/978-981-15-8319-3_59.

[17] A. Djili, B. Bezzazi, N. Zioui, and M. Haboussi, "Effect of natural aging on the tensile properties and the toughness of friction stir welds of 2024-T3 aluminum alloy," *J. Adv. Join. Process.*, vol. 8, no. July 2023, p. 100153, 2023, doi: 10.1016/j.jajp.2023.100153.

[18] S. Sun, Y. Fang, L. Zhang, C. Li, and S. Hu, "Effects of aging treatment and peripheral coarse grain on the exfoliation corrosion behaviour of 2024 aluminium alloy using SR-CT," *J. Mater. Res. Technol.*, vol. 9, no. 3, pp. 3219–3229, 2020, doi: 10.1016/j.jmrt.2020.01.069.

[19] F. C. García Rueda, J. Torres González, and J. M. Hernández-López, "Differences between the untreated and treated diffusion zone in the Alclad 2024-T3 aluminum alloy and hard anodic films," *Surf. Coatings Technol.*, vol. 429, no. August 2021, 2022, doi: 10.1016/j.surfcoat.2021.127939.

[20] M. Azis, Akid Abdul and -, Pramuko IP, Ir, "Pengaruh Artificial Aging Variasi Holding Time 60 Menit, 90 Menit dan 120 Menit Terhadap Struktur Mikro dan Kekerasan Pada Aluminium Paduan (Al-Cu)," *Skripsi thesis*, 2020, [Online]. Available: http://eprints.ums.ac.id/79983/

[21] Aghastya, A., Wahjono, H. B., Wirawan, W. A., Atmaja, D. S., Rachman, N. F., & Adi, W. T. (2023, May). The effect of heating surface treatment by oxy-acetylene gas on the microstructure

DOI: https://doi.org/10.71225/jstn.v1i3.61

and hardness of the UIC R42 rail. In *AIP Conference Proceedings* (Vol. 2592, No. 1). AIP Publishing.

[22] Boedi, H., Wirawan, W. A., Rozaq, F., & Atmaja, D. S. (2020). The effect of quenching media on surface treatment process on the rel UIC R42 (Union internasionale des chemins de fer-42) endurance. *International Journal of Advanced Science and Technology*, *29*, 1329-1336.

[23] Wirawan, W. A., Wahjono, H. B., Rachman, F. R. N. F., & Rhamadhani, A. (2023, July). Macrostructural and mechanical properties of rails cladded by automatic flame treatment. In *AIP Conference Proceedings* (Vol. 2689, No. 1). AIP Publishing.

DOI: https://doi.org/10.71225/jstn.v1i3.61