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The influence of artificial aging on tensile properties of Al 6061-T4

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Abstract

This paper presents an explanation related to experimental testing in the form of the tensile properties of Al 6061. Al 6061 was heat treated by the precipitation hardening method. The precipitation hardening consisted of T4 and T6 treatment. Al 6061 samples were heat-treated at a temperature of 430°C for 2 hours, then cooled slowly at room temperature. The T4 was conducted at a temperature of 530°C for 2 hours, followed by rapid cooling in a water medium and natural ageing at a temperature of 70°C for six days. Temperature T6 is the final process of applying precipitation hardening treatment to Al 6061. Temperature T6 is carried out at 530°C for 2 hours, then cooled rapidly in a water medium and continued with artificial ageing at 190°C with a variation of ageing time for 3 hours, 5 hours, and 7 hours. The effect of the applied treatment was observed to increase the maximum strength value of the tensile test of Al 6061.

Keywords: Al 6061, precipitation hardening, ultimate tensile strength

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1 Introduction

For over fifty years, aluminium (Al) alloy has ranked second after iron and steel, widely supplied in the metal market. The rapid growth in demand for Als is attributed to the attractive characteristics of these alloys [1]. Aluminium alloy has been used in aircraft construction since the 1930s. As the industrial sector with the most use of Al materials, the aerospace industry relies heavily on Al types 2024 and 7075. Considerations for using Al 6061 are based on the properties of the alloy, namely low weight, good strength, formability, weldability, and durability. High corrosion resistance and low cost [2]. Although generally more expensive than ferrous metal, the applicability of Al has increased in use and has become competitive with ferrous alloys [3, 4]. Various heat treatment studies on Al 6061 were selected to improve the properties of the alloy's mechanical structure. Heat treatment is a series of processes that involve heating and cooling metallic materials in their solid-state.

The applied heat treatment aims to cause desired changes in the mechanical structure and the properties of the metal parts. By applying heat treatment, metals can be made tougher, stronger, and more resistant to impact. Under the same conditions, heat treatment can also make metal materials softer and more elastic [5]. In particular, the effect of solution heat treatment and artificial ageing has been studied on the mechanical properties of Al 7030 and 7108. The obtained results were the relationship between the decrease in the peak strength value of the mechanical properties of Al 7030 and 7108 on the widening of the size distribution of the deposits. It is further explained that differences in the type, volume fraction, size and distribution of the deposited particles regulate the properties and changes that occur due to time and temperature, which is based on the initial state of the structure. The initial structure of a wrought material can vary depending on the structure of the material not undergoing crystallization to recrystallization so that these conditions, as well as the time and temperature of the precipitation heat treatment, affect the final structure and the resulting mechanical properties [6, 7, 8, 9]. The metastable precursor of the equilibrium phase 6061 is precipitated in a process involving one or more combinations of complex elements. Chemical content, heat treatment parameters, and casting conditions significantly affect the extrusion ability and determine the combined microstructure. These results show that the properties of some Al can be increased through a specific heat-treatment process. Heat treatment can be done either by heating the solution or artificial ageing. In the process of heating the solution, the alloy is heated to a temperature range of 400°C to 530°C and then rapidly cooled in an aqueous medium to room temperature. Especially for the Al 6xxx group, the artificial ageing treatment is carried out at a temperature of 200 °C, while the average ageing hardening temperature is usually 160°C to 200°C [9, 10].

Aluminium alloy subjected to a solution heating treatment is believed to have varying mechanical properties, affecting the machining capabilities to which the Al is applied. Some of the mechanical properties possessed by Al 6061 are associated with the type of treatment, such as solution treatment, ageing time, and temperature applied to the alloy [11]. Al 6061 has an intermetallic phase structure composed of Si and generally alloys composed of AlMgSi elements and related alloys. Maximum strength can be achieved by precipitation hardening, but the alloy's ductility is reduced. Conversely, the ductility can be increased by using an annealing process, but this process causes the strength of the alloy to decrease [12, 13] into the artificial ageing treatment for 98 hours at 175°C. Based on the results studied, the microstructural and mechanical properties of the specimens were not affected by the artificial ageing treatment applied as a result of the previous precipitation strengthening process [14, 15]. Based on the research literature that has been conducted [16, 17], the T6 tempering process in alloy 6061 involves the formation of very thin deposits. The precipitate formed represents β", which is oriented to the three sequences of deposits formed in the alloy's matrix. The size of the alloy matrix formed is on a nanometric scale and is coherent. From the considerations carried out, several studies provide further details showing the order in detail of the composition of the phases contained in the Al-Mg-Si alloy. The general compositions for deposits formed on Als are listed in Table 1.

The study presented includes experimental observations of tensile tests using a universal testing machine with 200 kN capacity and investigated Al 6061-T4 to characterize tensile test properties under T6 temper ageing conditions. From the observations made in the test, it is possible to determine the distribution of the tensile

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properties experienced by the alloy. The initial condition is shown as a thermal loading process, namely the application of annealing or normalizing treatments, temper T4, and temper T6. The thermal loading process applied to alloy 6061 is limited to the solid-state of the alloy. Therefore, the maximum temperature to be used is under the solidus temperature of 582°C. After the thermal loading process is applied, it is followed by observing the tensile test results through computerization. From the review of the cited literature, it was observed that there was no work on artificial ageing or the response to precipitation hardening of 6061 Als applying T4 and T6 temper heat treatment by varying the time of artificial ageing, as well as their effect on the tensile behaviour of 6061-T4 Als. Therefore, the study focused on the variation of the ageing time of temper T6 on the tensile strength behaviour of 6061-T4.

Table 1. Compositions of the precipitates contained in Al-Mg-Si alloys.

Phase	Composition
GP zone	Mg_1Si_1
β''	Mg_5Si_6
β'	Mg_9Si_5
β	Mg_2Si

2 Research Methodology

2.1 Specimen preparation

Cylindrical specimens with a length of 100 mm and a specimen diameter of 22 mm are supplied in the form of extruded rods which are then subjected to conventional machining processes to reduce the specimen diameter to 17 mm. In the following process, the specimen is formed by the standard dimensions specified in the form of ASTM E8 for tensile strength testing. After going through various heat treatments given to each specimen, the specimen is then reconstructed through conventional machining. For the tensile test, the specimens formed by conventional machining for each variation amount to two specimens with four variations, so the total number of specimens provided is eight. Several specimens of Al 6061-T4 prepared for tensile strength testing are shown in Figure 1 based on the ASTM E8 standard. Based on the time variations in the artificial ageing treatment of temper T6 applied to Al 6061-T4, the specimens are sequentially categorized into several groupings in Table 2.

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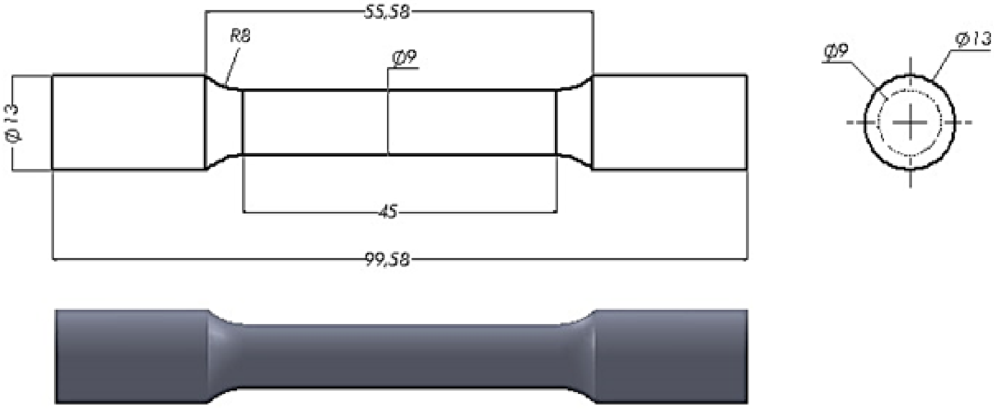

Figure 1. Tensile test specimen

Table 2. Categorization of specimens

Specimen category	Condition of specimen
a	Base metal without treatment
b	SHT 530°C for 2 h and AA 190°C for 3 h
c	SHT 530°C for 2 h and AA 190°C for 5 h
d	SHT 530°C for 2 h and AA 190°C for 7 h

2.2 Heat Treatment

In metallurgical components, several processes affect the hardening mechanism of the mechanical structure of a material. The processes applied to Al 6061 include the annealing or normalizing processes, temper T4, and temper T6. In the primary process, specimens were given normalizing heat treatment at a temperature of 430°C and held for 2 hours. Then, the specimens were cooled slowly at room temperature. Furthermore, the specimens were heated for 2 hours at 530°C to obtain a solid solution phase before being rapidly cooled in water media to room temperature. Then in the following process, the specimens are left at room temperature for six days or 144 hours. This process is a series of T4 tempering treatment processes. The heat treatment of solid solution T6 and selected artificial ageing for Al 6061 is the final process of hardening the alloy's structure. First, the alloy was heat-treated for 2 hours at a temperature of 530°C and then cooled in a water medium at room temperature before being heated again with a variation of 3, 5, and 7 hours at a temperature of 190°C.

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2.3 Tension Test

The tensile test is one of the most commonly used mechanical stress-strain tests. The tensile testing process begins with fixing the specimen on the holding grip, then continuously and simultaneously measuring the applied load occurs instantly. The output of the tensile strength test is recorded as the relationship of the load or force applied to the cross-sectional area of the specimen surface. The specimens, with and without additional heat treatment, were tested under uniaxial loads with high static and load loading rates. Tensile strength tests on specimens were determined using a universal testing machine with a capacity of 200 kN with a deformation rate of 0.01mm per second.

3 Results and Discussion

3.1. Tensile Test Data

Based on the tensile test result, the mechanical properties of the 6061-T4 Al specimen were obtained, shown in Table 3. Investigation of the effects of artificial ageing time variation applied to Al 6061-T4 is reported in this analysis. The behaviour of the tensile properties is analyzed in a tensile test cycle, the maximum tensile strength and the limit of tensile strength before the material fracture, elastic strength, plastic character, and the relationship to the stress-strain cycle. It is shown visually in Figure 2 that the maximum strength value of the highest tensile test on Al 6061-T4 is obtained at the ageing time condition of 3 hours, and then sequentially followed by the ageing time conditions of 5 and 7 hours and finally, normal conditions.

Tabel 3. Mechanical properties of the specimens aluminium alloy 6061-T4.

Specimen category	a	b	c	d
Ultimate tensile stress (MPa)	102.36	264.73	219.74	199.51
Fracture stress (MPa)	66.11	204.10	162.34	111.07
Yield stress (MPa)	48.164	217.19	177.67	175.31
Modulus elasticity (MPa)	2305.76	3086.40	2003.60	2712.85
Strain hardening exponent	0.19	0.031	0.088	0.048

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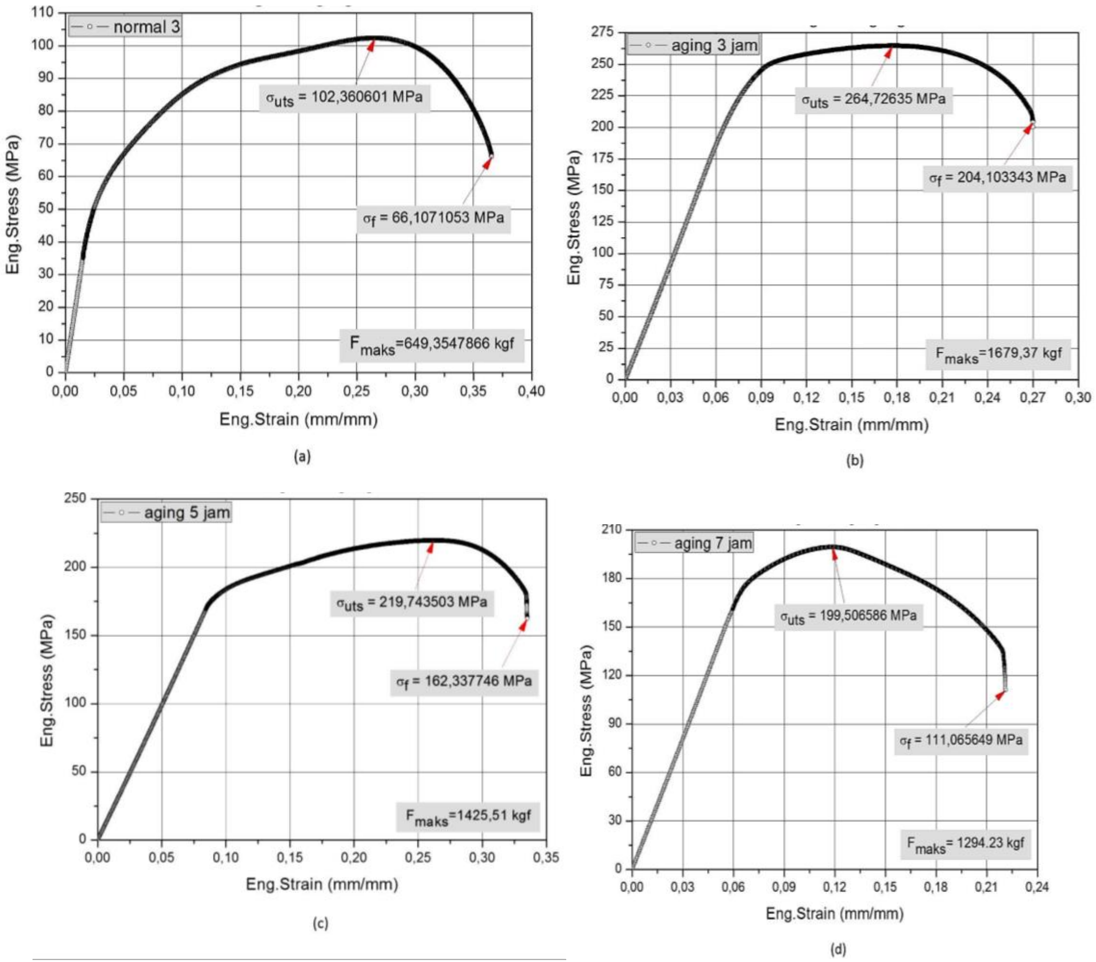

Figure 2. Tensile test result with various aging time

Inversely proportional to the maximum tensile strength, the highest durability in Al 6061-T4 starts under normal conditions and then continues with the ageing time conditions of 5, 3, and 7 hours. Durability, or can be referred to as the mechanical resistance of a material, is a condition in which the material can maintain the structure of the atomic particles in the material matrix in a non-loading state until it reaches a weakening state and finally experiences final failure. The increase in change in the shape of the material structure is represented by the increase in the data points shown in Figure 2. Figure 3 shows that the highest maximum tensile strength value starts from the condition 3 hours ageing time of 264,73 MPa. Then, the 5 hours ageing time condition

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is 219.74 MPa, followed by 7 hours ageing time of 199.51 MPa, and finally, the normal condition is 102.36 MPa.

In addition to the maximum tensile strength value, Figure 2 also shows the value of the endurance limit or mechanical resistance of Al 6061-T4, which is shown as the value of fracture stress. Based on the Figure, the value of each fracture stress is shown as follows, starting from the normal condition of 66.11 MPa with the resulting stretch range reaching ± 0.35 mm/mm, then the 5-hour ageing time condition is 162.34 MPa with The resulting stretch range is ± 0.30 mm/mm, then the 3 hours ageing condition is 204.10 MPa with a range of ± 0.27 mm/mm stretch, and finally the 7 hours ageing time condition is 111.07 MPa with the resulting stretch range of ± 0.21 mm/mm. The results obtained in the analysis of Figure 3 show that there are differences in data values between fracture stress and stretch range; the basis of the comparison between the two mechanical resistance parameters lies in the object seen from the behaviour of the 6061-T4 Al structure, namely the characteristics of ductile and brittle properties. Specifically, based on the theory, the characteristics of ductile and brittle materials can be determined by comparing the value of the maximum tensile strength to the yield stress. Furthermore, the comparison is limited by specific value criteria, which are factors of the ductility and brittle characteristics of the material. The resulting value of the comparison is also known as the stretch hardening ratio value. Based on the theory, it is explained that if the stretch hardening ratio value is > 1.4, the alloy material will experience cyclically softening. At the same time, for the stretch hardening ratio value > 1.2, the alloy material will experience cyclic hardening. Through Table 4, the highest comparative value for the stretch hardening ratio is obtained under normal conditions. In order, the value of the stretch hardening ratio obtained is as follows, namely, under normal conditions, the yield hardening ratio value is 2.13, the condition for 5 hours of ageing is 1.24, the condition for 3 hours the ageing time is 1.22, and the ageing time condition 7 hours of 1.14.

These results show that under normal conditions, the 6061-T4 experiences softening in a cycle, as evidenced by the stretch hardening ratio value more significant than the reference factor in theory, namely 1.4. This proves that the stretch hardening ratio value under normal conditions describes the tensile properties of Al 6061-T4, which is

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cyclically softened. Conversely, in the conditions of variation in artificial ageing, the structure of the Al 6061-T4 material undergoes cyclical hardening, which is evidenced by the hardening ratio obtained in the range of reference factors. Thus, the conditions for artificial ageing variations meet the established standards that the resulting value is between the range 1,2 to 1,4. Furthermore, the calculations showed that the highest value achieved in the stretch hardening ratio values is produced at the ageing time condition of 5 hours. Therefore, the ageing time condition is 3 hours, and the ageing time condition is 7 hours. From another point of view, it can also be seen that the stretch hardening exponential value is for the stretch hardening exponential value > 0.2. Therefore, the alloy material will harden cyclically. In contrast, in the condition of the stretch hardening exponential value > 0.1, the alloy material will experience softening on a cycle basis. For average conditions, the stretch hardening exponent's value is equal to 0.19372 > 0.1 so that the material is softened cyclically.

4 Conclusion

Al 6061 can experience an increase in strength by applying T4 and T6 temper treatment with ageing time variations of 3, 5, and 7 hours. A decrease follows an increase in the strength properties of the alloy in ductility. The highest strength value was achieved at 3 hours ageing time of 264.73 MPa with a reduction in ductility of 10% in terms of a decrease in the stretch value to normal conditions. From the results shown, it is also explained that each variation of ageing time that is applied successfully increases the strength of aluminum 6061-T4 alloy significantly while maintaining the ductility and elasticity of the alloy with a reduction in value that is not too far. Investigations on the stretch hardening ratio value and the stretch hardening exponent proved that the increase in strength of the Al 6061-T4 occurred due to the structure of the alloy matrix successfully hardening or strengthening with the formation of an intermetallic phase, namely Si in the alloy matrix structure.

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