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Contributed Paper

Effect of Hardness Test on Precipitation Hardening Aluminium Alloy 6061-T6

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Abstract

The paper presents an experimental study on precipitation of aluminium alloy 6061-T6 to determine the effect of artificial ageing on the hardness of aluminium alloy 6061-T6. The precipitation hardening is a thermal treatment, which consists of a heat treatment, quenching and artificial ageing process. The experimental study is focused on artificial ageing upon which the temperature is varying between 175°C to 420°C at different period of time. The Vickers hardness test is to evaluate the hardness of aluminium alloy 6061-T6 before and after ageing process. The optimum ageing time and temperature is determined at the end of this experiment to obtain reduction in energy and total cost. The study leads to the conclusion that the optimum aged was achieved between 175°C to 195°C with 2 to 6 hours of ageing time. The contribution of short time ageing is comparable to that of longer ageing time from previous studies.

Keywords: aluminium alloy 6061-T6, precipitation, hardness test, ageing.

1. Introduction

For over fifty years, aluminium ranks at second to iron and steel in the metal market. The demand of aluminium growths rapidly because it is attributed to a unique combination of properties which makes it become one of the most versatile of engineering and construction material. Aluminium is light in weight, the specific gravity of aluminium is 2.7; which is only 30% heavy of copper and one third of iron. Except for magnesium, it is lightest of all common metal. Some of its alloy even has greater strengths than structure steel. Besides, it has good electrical and thermal conductivities and high reflectivity to both heat and light. It is non-toxic and highly corrosion-resistant under any service conditions. Aluminium can be given a wide variety of surface finishes and it can be cast and produced into almost any form of product. It is not surprisingly that aluminium have became prime importance as engineering material with all these outstanding properties.

In this study, the hardness of aluminium alloy 6061-T6 was conducted by using precipitation hardening process. Precipitation hardening is a process that enhances the strength and hardness of metal alloys by the formation of extremely small uniformly dispersed particle of a second phase within the original phase matrix. In other way, the general requirement for precipitation strengthening of supersaturated solid solution involves the formation of finely dispersed [1]. The precipitate particle nucleates and grows; by the diffusion of solute atoms into it from the matrix phase. It is called precipitation because the small particles of the new phase are termed "precipitates" [2]. Artificial ageing will be accomplished not only below the equilibrium solvus temperature, but below a meta-stable miscibility gap called Guinier-Preston (GP) zone solvus line. The paper describes a case study of preceding hardness text experiment on aluminium alloy 6061-T6.

2. RESEARCH ON PRECIPITATION PROCESS ON ALUMINIUM

The basic requirement of a precipitation hardening alloy system is that the solid solubility limit should be decreased by decreasing the temperature. During the precipitation hardening, the aluminium alloy 6061-T6 was heated up at high temperature and subsequently cooled by quenching it into the water or some other cooling medium. The rapid cooling suppresses the separation of the θ-phase so that the alloy exists at the low temperature under unstable supersaturated state. If, however, after quenching, the alloy is allowed to 'age' for a sufficient of time, the second phase precipitates out [3].

Zhao et al. [4] performed the enhanced mechanical properties in ultrafine grained 7075 Al alloy. The highest strength for 7075 Al alloy was obtained by combining the equal-channel-angular pressing (ECAP) and natural ageing processes. The tensile yield strength and ultimate strength of the ECAP processed and naturally aged sample were 103% and 35% respectively, than those of the coarse-grained 7075 Al alloy counterpart. The enhanced strength was produced from high densities of Guinier-Preston (G-P) zones and dislocations. The study showed that severe plastic deformation has potential to enhance the mechanical properties of precipitate hardening 7000 series Al alloys significantly.

Kulkarni et al. [5] conducted the study on the effect of particle size distribution on strength of precipitation-hardened alloys. Ageing of precipitation hardened alloys results in particle coarsening, which in turn affects the strength. In this study, the effect of particle size distribution on the strength of precipitation-hardened alloys was considered, to better represent real alloys, the particle radii were distributed using Wangner and Lifshitz and Slyozov (WLS) particle size distribution theory.

Lumley et al. [6] proposed the control of secondary precipitation to improve the performance of aluminium alloy. Beneficial effects of under ageing in enhancing the creep resistance of certain aluminium alloys may be diminished or lost if the alloys are held at close to ambient temperatures prior to testing. This problem is associated with undesirable secondary precipitation during the dwell period and might be overcome by cooling the alloys slowly from the initial ageing temperature. A method for successfully exploiting secondary precipitation to improve the mechanical properties of aluminium alloys has been developed which involve interrupting artificial ageing with a low-temperature dwell period. Average increases in 0.2% proof stress of 10-15%, combined with improved fracture toughness, have been achieved in a wide range of alloys when compared with equivalent obtained by conventional T6 tempers. These effects arise because the interrupted ageing promotes nucleation of more finely dispersed precipitates in the final microstructures.

The study of Eskin [7] explained the hardening and precipitation in the Al-Cu-Mg-Si alloying system. The composition and hardening phase in Al-Cu-Mg-Si alloys containing 2.5%-4.5% Cu are considered with respect to the chemical composition of the supersaturated solid solution. For the first time, composition of the supersaturated solid solution was calculated using Thermocalc software as the equilibrium composition at a quenching temperature. The influence of precipitation on the work-hardening behavior of the Aluminium Alloys AA6111 and AA7030 were carried out by Cheng et al. [8]. Tensile tests were conducted on the aluminium alloy AA6111, after various artificial ageing treatments in order to examine the influence of precipitation state on yield stress and work-hardening behavior.

Schiffmann et al. [9] performed the evolution of precipitates during age-hardening of AW 6016 alloy. Specimens of a sheet of his commercial age-hardening aluminium alloy 6016 were treated with heat in order to produce different hardening stages. By neutron small angle scattering (SANS), the precipitation sequence and its development in the nanometer range can be monitored. A variation in the precipitation sequence is observed at different age-hardening temperatures.

Sauer et al. [10] analyzed the influence of precipitate free zones on the test direction dependence of high strength aluminium alloys mechanical properties. High strength Al-alloys exhibit soft zones along grain boundaries, resulting from precipitate free zones. The preferred microstructure for application of high strength Al-alloys is an unrecrystallized pancake shaped grain structure. This grain shape with soft zones along the grain boundaries causes anisotropy of mechanical properties. The work evaluates for two Al-alloys (7475,7075) tensile ductility, HCF strength, fracture toughness, the nucleation and propagation behavior of self-initiated microcracks, and the propagation behavior large fatigue cracks as a function of the inclined angle of the stress pancakes (0^o, 30^o, 45^o, 60^o, 90^o).

Qiang et al. [11] performed the influence of ageing conditions on the microstructure and tensile strength of aluminium alloy 6063. Materials in three pre-ageing conditions i.e. 288 hour natural ageing (ageing at room temperature (RT); 3 hours natural ageing; and 3 hours natural ageing plus 5 hours ageing at 80C^o, were subsequently aged at 165^{o}C, 185^{o}C and 205^{o}C from 0.25 to 64 hours. Tensile tests were performed after ageing. Microstructure study was performed using transmission electron microscopy (TEM) and atom probe field ion microscopy (APFIM). The results showed that for materials with the same pre-ageing condition, the higher subsequent ageing temperature, the lower the peak strength and the shorter time it takes to reach peak strength.

Kang et al. [12] performed the effect of applied pressure and heat treatment condition on microstructural characteristics and mechanical properties of the thixoforged 357 aluminum alloy. The characteristics of the microstructure and mechanical properties of thixoforged 357 Al parts with an arbitrary shape were studied for microstructure and mechanical property variations as a result of changes in the applied pressure (110, 140, and 170 MPa) and the solution heat treatment ageing time (4, 6, and 10 hours). Though the experiment of thixoforging with combination of T6 heat treatments, a sample part with good mechanical properties was obtained. For a six-hour heat treat ageing time, an ultimate tensile strength of 394 MPa was obtained. The percentage elongation for this sample was 10%.

Milan and Bowen [13] conducted the tensile and fracture toughness properties of SiCp reinforced aluminium alloys on the effects of particle size; particle volume fraction, and matrix strength. The goal of this work was to evaluate the effects of particle size, particle volume fraction, and matrix strength on the monotonic fracture properties of two different Al alloys, namely T1-A12124 and T1-A16061 where both alloys were reinforced with silicon carbide particles (SiCp).

3. METHODOLOGY

For the heat treatment, samples for hardness test were prepared. Aluminium alloy 6061-T6 is lathed to round shape at 12.7 mm nominal diameter and the gauge length for measurement of elongation is four times the nominal diameter i.e. 50.8 mm. The outside gauge length was approximately 200 mm. The samples were cut into approximately 20 mm and 10 mm for Vickers hardness test.

The aluminium alloy 6061-T6 specimens were treated to the specific parameters. Specimens were provided with a specific number, heat treatment temperature (about 500^{o}C to 550^{o}C), soaking temperature (500^{o}C but below solidus of 595^{o}C), quenching medium (water at room temperature), an aqueous solution of polyalkylene glycol and ageing time (175^{o}C to 420^{o}C from a few minutes to an hour). For austenitization process, the specimens were placed in the gas furnace. After that, the specimens were heated up to the required temperature and hold at the temperature for required time. For quenching process, the specimens were immersed deeply into the specified quenching medium for rapid cooling processes. For ageing process, the specimens were aged by artificial ageing temperature, 175^{o}C to 420^{o}C between a few minutes to a few hours.

The aluminium alloy 6061-T6 specimens were tested for hardness to distinguish between annealed, cold-worked, and heat treated grades. The purpose of the hardness test is to investigate the effect of variation precipitation heat treatment temperature and to obtain time of aluminium alloy 6061-T6's hardness.

4. HARDNESS TEST

Time and temperature were two variables in this study. The samples were age-hardened for 30 minutes until 10 hours at different temperature (175^{o}C, 185^{o}C, 195^{o}C, 220^{o}C, 350^{o}C and 420^{o}C). A total of ten readings were taken for every ageing time at the respective temperatures and average value was calculated. It is noted that the higher strengths were obtained at the lower temperature for longer times [14].

4.1 The Coefficient of the relationship between the hardness and the ultimate tensile strength

Table 1 shows the coefficient, hardness and ultimate tensile strength value for highest hardness and lowest hardness value at different ageing temperature. The highest and lowest hardness value in various temperatures was recorded to acquire the average range of coefficient, A. The result showed that the range of coefficient, A, is in between 2.54 to 2.83. It was showed that there is a correlation between the hardness and tensile strength.

Table 1. Hardness, ultimate tensile strength and coefficient, and value for highest hardness value and lowest hardness of various temperature.

Ageing Temperature (°C)	Highest Hardness Value of Various Temperature			Lowest Hardness Value of Various Temperature		
	Hardness, HV	Ultimate Tensile Strength, UTS (1×10^6 kPa)	Coefficient, A	Hardness, HV	Ultimate Tensile Strength, UTS (1×10^6 kPa)	Coefficient, A
0	95.4	331.44	2.82	95.4	331.44	2.82
175	106.28	387.24	2.69	71.76	201.96	3.48
185	121.60	432.84	2.76	78.14	304.57	2.51
195	117.06	342.28	3.35	81.35	285.02	2.80
220	117.16	336.03	3.42	73.87	315.81	2.29
350	48.88	208.94	2.29	25.74	131.79	1.92
420	41.46	165.17	2.46	33.98	149.52	2.23

4.2 The equation of the relationship between the hardness and the ultimate tensile strength

The graph of ultimate tensile strength (UTS) versus hardness at various temperatures (Figure 1) shows the relationship between hardness and the ultimate tensile strength. An equation of y can be use to predict the hardness and the tensile strength of aluminium alloy 6061-T6.

Equation from Figure 1 (a):

$$y = 2.647\ x + 68.369 \quad (1)$$

Equation from Figure 1 (b):

$$y = 2.9839\ x + 50.005 \quad (2)$$

From equation (i) and (ii),

$$y = 2.8515\ x + 59.187 \quad (3)$$

Where,

y = Ultimate Tensile Strength (MPa)

x = Hardness (HV)

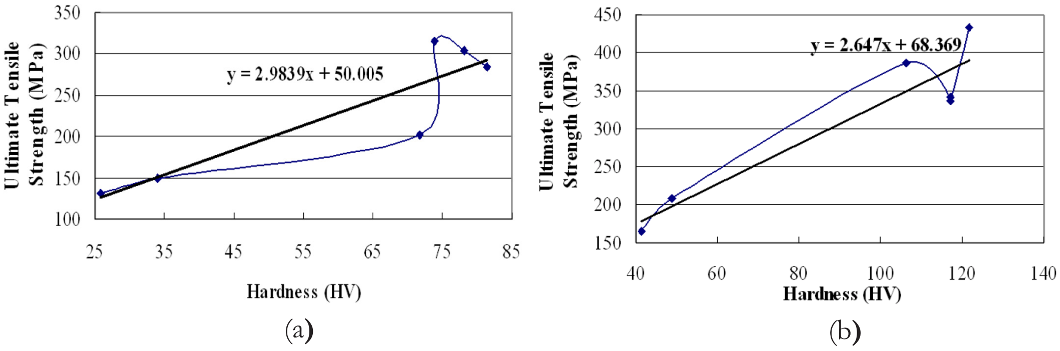

Figure 1. Graph of the ultimate tensile strength versus hardness value; (a) highest hardness value, (b) lowest hardness value.

4.3 Hardness test analysis for original sample

The theoretical hardness value for aluminium alloy 6061-T6 is 95 HV [15]. The hardness value of test specimen is 95.4 HV. This value is used to compare with the sample that has undergone age-hardening.

4.4 Hardness test analysis for samples ageing at 175°C

At ½ hour of ageing, the hardness of sample dropped until 71.8 HV. Extended ageing of artificial aged alloys at 175°C eventually led to the increment of hardness up to a peak value of 106.3 HV (Figure 2). It dropped to 100.9 HV at 10 hours of ageing. The hardness values showed that a linear increment from 0.5 hour of ageing to 4 hours of ageing where it began to decrease. It can be concluded that peak aged was achieved at 4 hours ageing at 175°C and the over aged region starting to form at longer ageing time after the 4 hours ageing time.

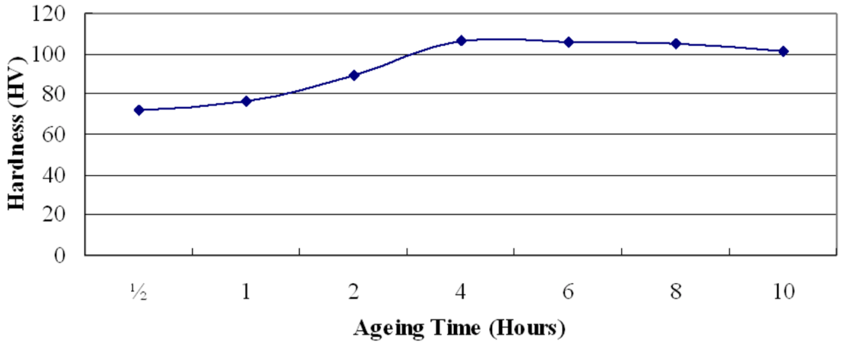

Figure 2. Graph of the hardness versus ageing time for ageing at 175°C.

4.5 Hardness Test Analysis for Samples Ageing at 185°C

Figure 3 shows that the hardness of the alloy increased gradually from under aged region to peak region. However, it decreased over aged region. It shows a small decrement of hardness from 80.7 HV at ½ an hour ageing to 78.1 HV at 1 hour ageing. In contrast, rapid hardening occurred in 2 hours ageing which was 112.7 HV. Extended ageing

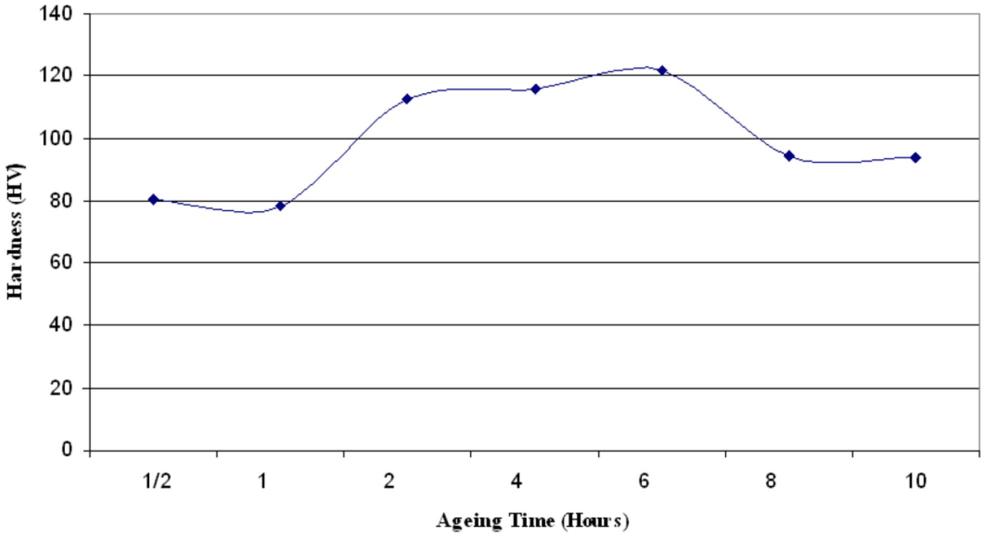

Figure 3. Graph of the hardness versus ageing time for ageing at 185°C.

time to 6 hours has brought aluminium alloy 6061-T6 to reach the optimum hardness, which was 121.6 HV. The highest strength was generally achieved when a large amount of closely spaced, small and round precipitates are coherently dispersed throughout an alloy [16]. The hardness of aluminium alloy 6061-T6 started to decrease to 94.4 HV at 8 hours ageing time. However, there was a small increment in hardness to 94.1 HV at 10 hours of ageing. Thus, if longer ageing time is given, the hardness might still be able to increase a little to reach its highest strength.

4.6 Hardness test analysis for samples ageing at 195°C

After the heat treatment, the hardness of aluminium alloy 60601-T6 was increased significantly after 1 hour ageing and increased further after 2 hours which reached the optimum hardness of 117.06 HV (Figure 4). Subsequently, the hardness of aluminium alloy 6061-T6 began to fall constantly from 106.37 HV of 4 hours ageing until 81.35 HV of 10 hours ageing time. It shows clearly that ageing of alloy which exceeded 2 hours would come to the over aged region. From both peak aged were compared i.e. occurred during 6 hours of ageing at 185°C and 2 hours of ageing at 195□C, it can be concluded that peak aged can be achieved at a shorter ageing time by using higher ageing temperature. On the other hand, previous research showed that the value of hardness can be reach until 134.3 HV at 40 hours aging time. Thus, there is a very high possibility that the maximum hardness can be obtained with further ageing time.

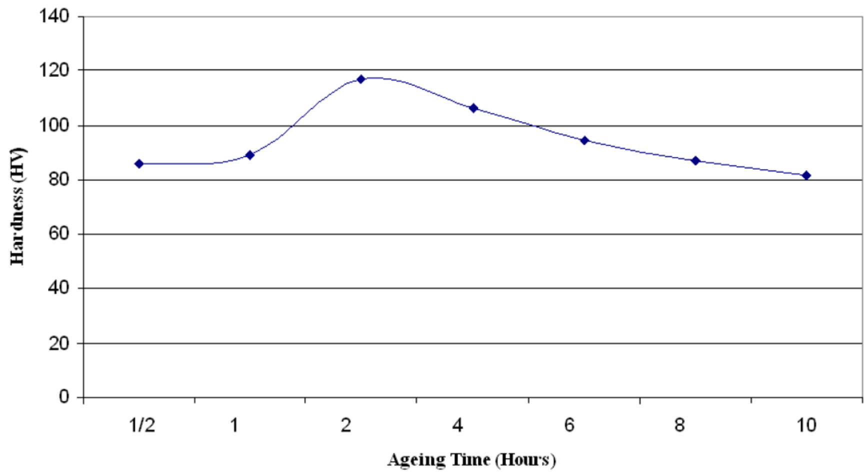

Figure 4. Graph of the hardness versus ageing time graph for ageing at 195°C.

4.7 Hardness test analysis for samples ageing at 220°C

Figure 5 shows that the maximum hardness of aluminium alloy 6061-T6 is 117.16 HV at 1 hour ageing. The hardness of aluminium alloy 6061-T6 increased from 106.97 HV ageing at □ an hour ageing to its maximum hardness of 117.16 HV at 1 hour ageing. Then it reduced to 102.14 HV for 2 hours ageing and 73.87 HV at 4 hours ageing. However, at 6 hours ageing, the hardness increased slightly to 83.92 HV which might be due to an error.

The peak aged which occurred at 2 hours ageing in previous ageing temperature of 195°C, the peak aged obtained at 220°C showed a shorter ageing time where its peak aged was achieved at 2 hours. It was again proved that peak aged can be achieved at a shorter ageing time by using higher ageing temperature.

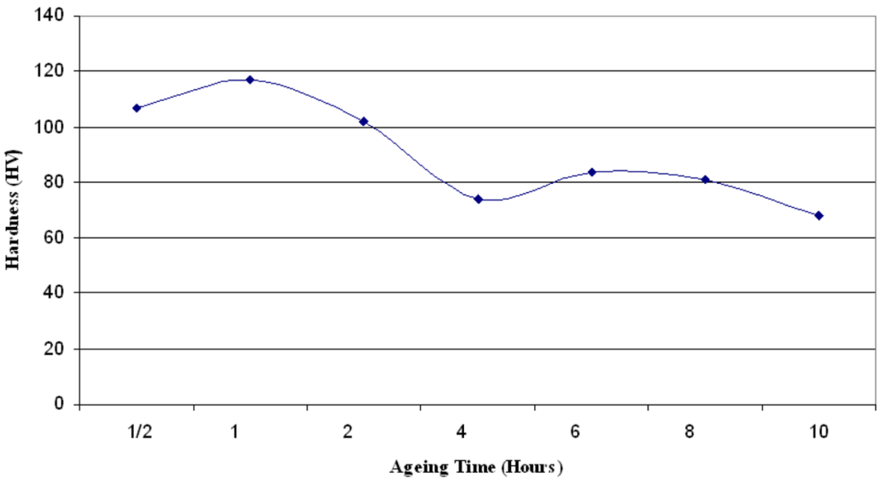

Figure 5. Graph of the hardness versus ageing time for ageing at 220^{o}C.

4.8 Hardness test analysis for samples ageing at 350^{o}C

In Figure 6, hardness of aluminium alloy 6061-T6 started to decline consistently from the maximum value of 48.88 HV to 47.34 HV at 1 hour ageing, and 25.74 HV at 10 hours ageing. It shows that the ageing process had reached the over aged region. The precipitate particles continued coalesce as ageing progress caused the particle size to increase and thus decreased the degree of complication for the dislocations to break the magnesium-silicon bonds when they pass through the precipitates. Thus, it was concluded that the higher the ageing temperature, the softer the sample became which then caused its loose of good mechanical properties such as hardness and tensile strength. Therefore, ageing at temperatures which are too high must be avoided at all cause.

At longer ageing time, there is a point where the strength and hardness began to fall rapidly. At this point, the thermal activation is such that tiny non-coherent particles of b' (Mg_2Si) begin to form in accordance with phase equilibrium as follows:

$$\beta' (Mg_2Si) \quad \beta (Mg_2Si)$$

By increasing the temperature, particle size is increase and the precipitation process continues to coalesce as ageing progresses [2].

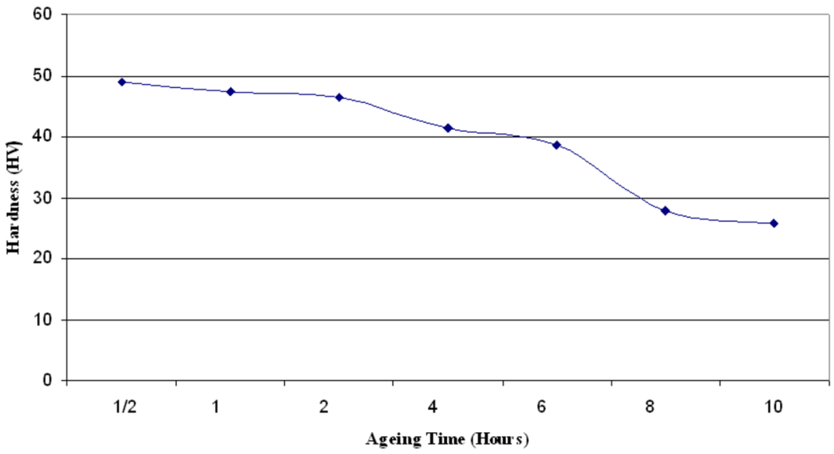

Figure 6. Graph of the hardness versus ageing time for ageing at 350^{o}C.

4.9 Hardness test analysis for samples ageing at 420°C

The hardening effect of aluminium alloy 6061-T6 was totally eliminated because of the ageing temperature was too high. For the samples which was aged at half an hour to 10 hours, the results showed that the hardness values were inconsistent (Figure 7). This inconsistency and the softening of the samples caused ageing at 420°C not suitable.

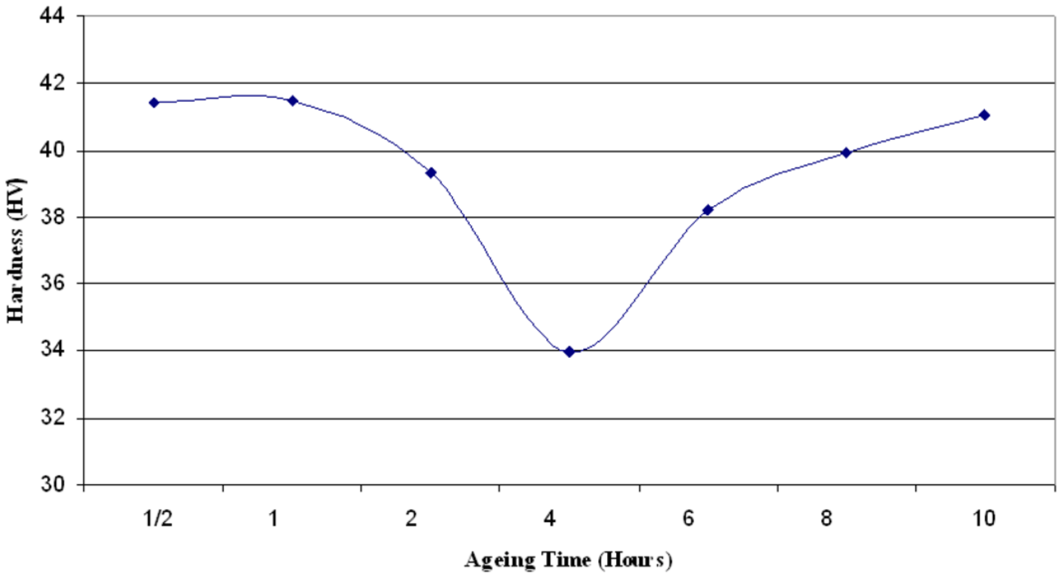

Figure 7. Graph of the hardness versus ageing time for ageing at 420°C.

5. Discussion

The effect of artificial ageing time at different temperature on the Vickers hardness of solid solution, peak aged and over aged specimen is shown is Figure 8. The Vickers hardness value of the specimen was 95.4 HV. The effect of ageing temperature and time varies with different artificial aged specimens. The highest hardness of aluminium alloy 6061-T6 was 121.6 HV at 185°C and 6 hours ageing time. The tensile strength was raised and it is proportional to the hardness. The peak aged point was determined when the hardness of the specimen started to drop gradually.

However, for the ageing temperature of 350°C and 420°C, the hardness of the aluminium alloy 6061-T6 decreased rapidly reaching the smallest value of hardness, which is 25.74 HV, at 10 hours ageing time. At the thermodynamic grounds, the raised of the temperature has caused the ageing rate to increase from the enhanced rate of diffusion of solid atom through the matrix. For an alloy composition, the mode of particles is widely space and less effective in inhibiting slip, and to the decrease in volume fraction of the precipitate resulting from the increase in solid solubility with increase in temperature. Furthermore, the amounts of the particles were found less compared to particles at peak aged which were numerous. Under this condition, the mechanical properties have fallen but it can be minimized by selecting alloys with low values of σ.

To get the appropriate mechanical properties of aluminium alloy 6061-T6 up to an ultimate strength of 432.84 MPa, longer ageing time (> 6 hours) can be used at an ageing temperature of 185°C. To obtain a better elongation rate for the aluminium alloy 6061-T6, the ageing temperature can be increased to 420°C in over-aged condition. With an ageing treatment at temperature of 420°C for 4 hours ageing, an optimum elongation until 28.75% was obtained. SEM results showed that the small, plate-shaped and dark precipitate particles being increase, the intermediate precipitate coalesces and coarsens the alloy overages and become weaker at 420°C. Among the various post-process heat treatments studied i.e. 2 hours ageing at 175°C, 4 hours ageing at 175°C and 6 hours ageing at 175°C, the best mechanical properties were obtained by ageing the specimen for 6 hours at 185°C.

Precipitation hardening increased the hardness further for about 11%, 27%, 23% and 22% at 175°C, 185°C, 195°C and 220°C ageing temperature respectively. However, it is not effective for the ageing temperature of 350°C and 420°C, in which the hardness of specimens after ageing was less than tested specimen due to over aged region.

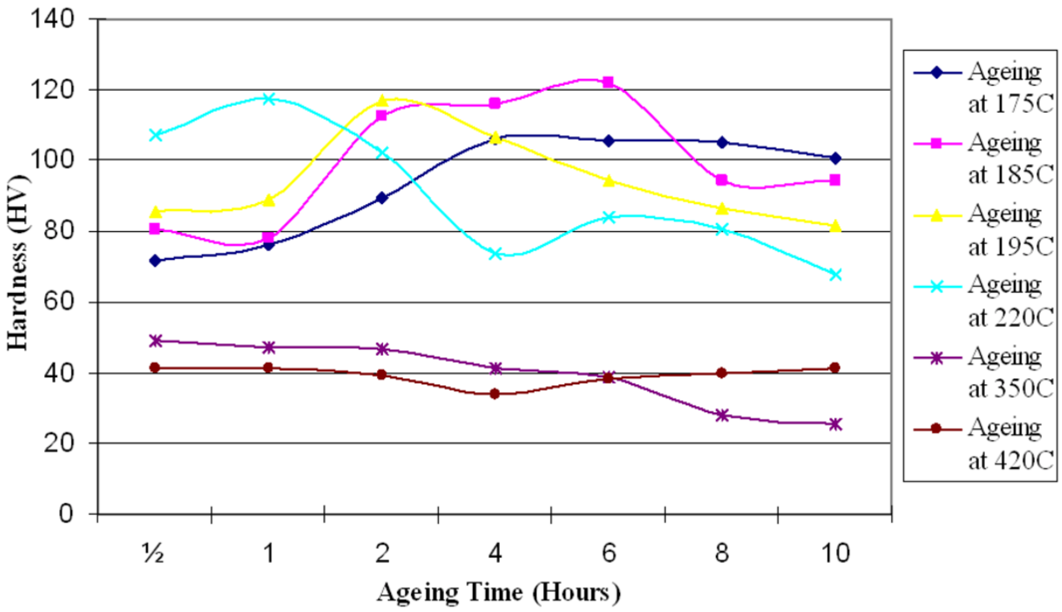

Figure 8. Graph of the hardness versus ageing time for ageing temperature at 175°C, 185°C, 195°C, 220°C, 350°C, and 420°C.

6. CONCLUSIONS

This study revealed that artificial ageing presented a positive effect on mechanical properties of the aluminium alloy 60601-T6. As a preliminary research programmed at evaluating the precipitation hardening on aluminium alloy 6061-T6s, this study identified its hardness behavior in different ageing temperature and time. This analysis led to conclusion that the optimum aged could be achieved from 175°C to 195°C between 2 to 6 hours of ageing time. It showed that 6 hours of ageing could exhibit a maximum strength of 432.84 MPa, at a temperature of 185°C. The highest strength could be achieve by placing a large amount of close space, small and round precipitates are coherently dispersed throughout the alloy. SEM results has provided an importance evidence of the relevance of artificial ageing on the formation of hardenable precipitates of the presence of small plate-shaped dard precipitate particles particle coarsen a little due started of the over aged region at ageing temperature 420°C. Based on the results, the inconsistency and the softening of the samples makes ageing at 420°C not suitable. Therefore, ageing at exteremely high temperatures must be avoided at all cause. The optimum aged can be produced by applying a longer ageing time at low temperature.

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