Effect of Precipitation Hardening Temperatures and Times on Microstructure, Hardness and Tensile Properties of Cast Aluminium Alloy A319

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Abstract – **In the present work, the effect of T6 precipitation hardening on microstructure, hardness and ultimate tensile strength of 5 wt%Si-3.5 wt%Cu-Al (A319) alloy was studied. As-cast A319 samples were solution treated at 503°C for 2-24 hours followed by aging at 150, 170, 200, 230°C for 1-48 hours. Microstructures were studied by OM and SEM-EDS. The phases present were determined by XRD. In the as-cast condition, the microstructure consists of a primary dendritic α-Al, acicular-plate or globular forms of Si eutectic and intermetallic phases comprising globular Al_2Cu and plate-like Al_5FeSi in the interdendritic regions. The microstructures after solution treatment and aging are similar to that of the as-cast condition, except that some spheroidisation of the eutectic Si has occurred. After solution treatment at 503°C for 8 hours plus aging at 170°C for 1, 6, 12, 24, 36 and 48 hours, the area fractions were decreased to about 11.25 %, 10.35 %, 9.70 %, 9.50 %, 9.90 % and 9.85 %, respectively. The precipitation hardening treatment increased the macro-hardness, micro-hardness, ultimate tensile strength and 0.2 %proof stress compared to the as-cast condition. Peak hardness and maximum levels of tensile strength were obtained after solution treatment at 503°C for 8 hours plus aging at 170°C for 24 hours. At lower aging temperatures or shorter times, the hardness and tensile strength were decreased due to incomplete precipitation. However, at higher aging temperature or longer time, the hardness and tensile strength were decreased most probably due to precipitate coarsening and associated loss in coherency effects.**

Keywords – Cast aluminium alloy A319, Solution treatment, Aging, Microstructure, Hardness

1. INTRODUCTION

For non-electrical applications, most aluminium is used in the form of alloys. These have much greater strength than pure aluminum yet retain the advantages of light weight, good conductivity and corrosion resistance [1]. Aluminium alloy castings find wide application in the automobile and aerospace industries. Improvement the structure and mechanical properties of these alloys include liquid metal treatments for grain refinement or for modification of the eutectic structure and subsequent heat treatment processes [2-3]. A319 aluminium-5 wt%Si-3 wt%Cu grade alloy is commonly used for automotive parts such as cylinder heads, internal combustion engine crankcases, typewriter frames, piano plates, etc. due to its excellent castability, corrosion resistance and particularly high strength-to-weight ratio in the heat-treated condition [4-5]. A319 alloy is a hypoeutectic Al-Si alloy with two main solidification stages: the formation of primary aluminium rich (Al) dendrites followed by Al-Si eutectic. However, the presence of additional alloying elements such as Cu and Mg, as well as of impurities such as Fe, Mn, Ni and Zn leads to a more complex solidification sequence and giving rise to other intermetallic eutectic phases such as Al_2Cu, Mg_2Si, $Al_8Mg_3FeSi_6$, $Al_{15}(Mn,Fe)_3Si_2$ and Al_5FeSi plates in addition to Al and Si [3,6-7]. Strengthening of this alloy by heat treatment depends on the size, type and volume fraction of particles that precipitate from supersaturated solid solution during suitable aging treatments. Research has continued to determine if additional alloying or other additions and variations to T5, T6 and T7 age hardening treatments can be used to further improve the mechanical properties [3, 8-10]. T6 treatment is the most popular heat treatment process since it normally yields optimum best tensile strength and hardness. In the previous research studies solution treatment and aging processes were performed at 495°C for 8 hours [11-13] and 200°C for 4 hours [11], 500°C for 4 hours and 160°C for 17 hours [14], 503°C for 8 hours and 195°C for 6 hours [15], 503°C for 24 hours and 175°C for 10 hours [16], 545°C for 8 hours and 200°C for 6 hours [17], respectively. Sepehrband [15] and Mahmudi [16] reported the maximum hardness levels. However, most research has studied only one temperature or one time for T6 age hardening heat treatment.

The aim of the present work, therefore, was studied the effect of T6 age hardening treatment on the hardness and tensile properties of an Al - 4.93 wt%Si - 3.47 wt%Cu alloy in relation to microstructure. The temperatures and times during solution treatment and aging were varied in the range of 503°C for 2-24 hours and 150-230°C for 1-48 hours. These temperatures and times were expected to give under aged, peak aged and over aged conditions. Quantitative examination of the eutectic structure was also studied in this work.

2. EXPERIMENTAL PROCEDURES

2.1 Materials preparation and heat treatments

An experimental alloy was prepared from commercial A319 alloy foundry ingot by melting a 30 kg charge in a graphite clay crucible in an electric furnace at a temperature of 800°C. At this temperature, the melt was degassed with high purity argon, and then the melt was poured at 730°C into a metal mould to produce tensile test bars according to the JIS standard as shown in Figure 1. The chemical composition of the alloy is given in Table 1. The T6 age hardening treatment consisted of solution treatment followed by quenching plus subsequent aging and quenching. In this work solution treatment was done at 503°C for 2, 4, 8, 12 and 24 hours followed by quenching into hot water at 80°C. The shortest solution time that gave maximum hardness was selected for the aging studies. Artificial aging was performed at 150, 170, 200 and 230°C for 1-48 hours followed by quenching into hot water at 80°C. The T6 age hardening treatment process is represented by Figure 1, where view (a) is a simple schematic view of treatment of an Al-4 %Cu alloy and view (b) is the treatment schedule of the present work

2.2 Characterization

Specimens for examination by optical microscopy (OM), scanning electron microscopy (SEM) and XRD were cut from the position that is shown in Figure 1 and then ground on silicon carbide papers to 1000 grit, and then progressively polished with 1 and 0.3 μm Al_2O_3. The etchant used for OM and SEM samples was 5 ml of HF in 100 ml in distilled water. The samples for XRD were not etched. The microstructures were studied using a LEO 1455LV scanning electron microscope equipped with energy dispersive X-ray spectroscopy (EDS) and the phases present determined by X-ray diffraction (XRD).

Table 1 Chemical composition (wt%) of the experimental cast A319 alloy

Si	Fe	Cu	Mn	Mg	Ni	Zn	Sn	Ti	Al
4.93	0.29	3.47	0.04	0.19	0.01	0.06	0.01	0.01	Bal.

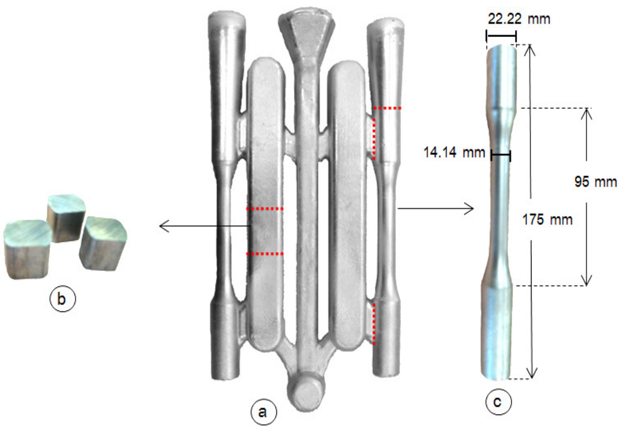
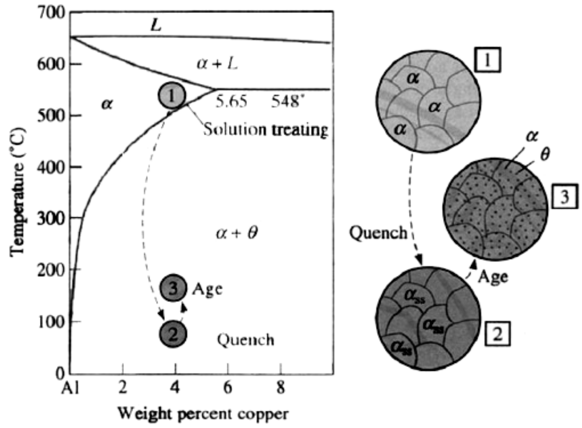
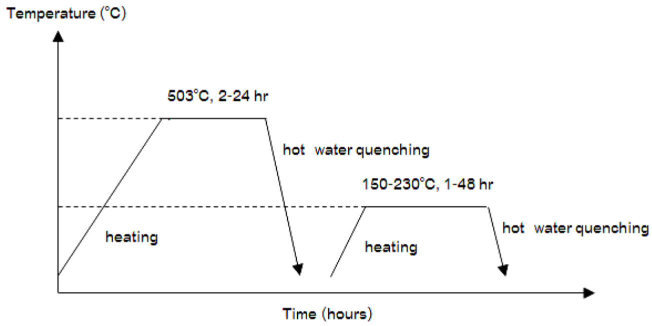


Figure 1 (a) The tensile test bars according to the JIS standard (b) specimens for microstructural study and hardness test (c) tensile test specimen.



(a)



(b)

Figure 2 (a) Precipitation hardening method and (b) T6 aged hardening treatment process in this experiment.

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2.3 Macro-hardness and Micro-hardness Measurements

Macro-hardness testing was performed on un-etched specimens with a Rockwell hardness tester using the B scale (HR_B) with steel ball, 100 kgf load and 15 seconds indenting time. Micro-hardness testing within the dendritic region was performed on etched specimens with a Vickers hardness tester ($HV_{0.05}$) with a diamond indenter, 50 kgf load and 15 seconds indenting time. The mean values are based on ten different areas on each specimen.

2.4 Tensile Test

Ultimate tensile strength and 0.2%proof stress were determined on tensile test bars of 14 mm in diameter and 95 mm in length using a Shimadzu Autograph, model AG-25TB. Tensile tests were performed on treatments showing the maximum hardness after solution treatment plus aging. Five samples were tested for each condition to obtain the mean values of ultimate tensile strength and 0.2%proof stress.

3. RESULTS AND DISCUSSION

3.1 Microstructural Investigation

Figure 3 shows the X-ray diffraction pattern in the as-cast condition, after solution treatment 503°C for 8 hours and after solution treatment at 503°C for 8 hours plus aging at 170°C for 6 hours. XRD result revealed that the phases present were Al, Si, Al_2Cu and Al_5FeSi.

Figure 4 shows the microstructures of the as-cast condition and after T6 heat treatment. In the as-cast condition the microstructure consists of a primary dendritic α-Al and interdendritic eutectic structure containing acicular-plate or globular forms of eutectic and intermetallic phases comprising globular and flake morphology. Microstructures after solution treatment and solution treatment plus aging, are similar to that of the as-cast condition, except that some spheroidisation of the eutectic has occurred.

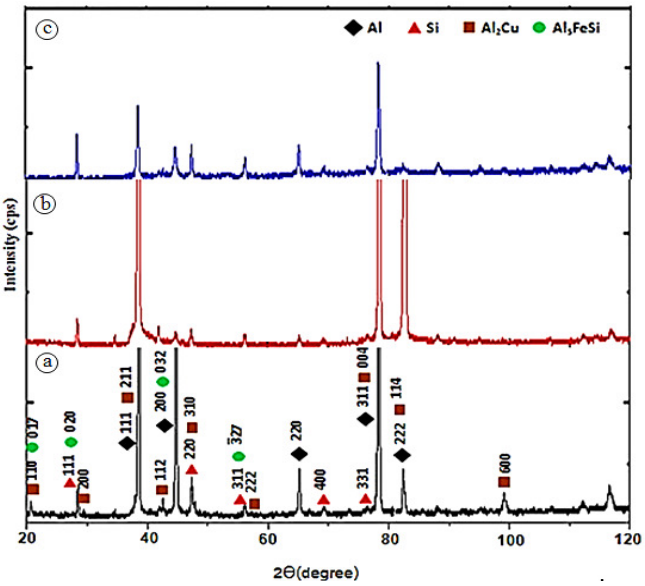

Figure 3 X-ray diffraction pattern of (a) as-cast condition (b) after solution treated at 503°C for 8 hours and (c) after solution treatment at 503°C for 8 hours plus aging at 170°C for 6 hours.

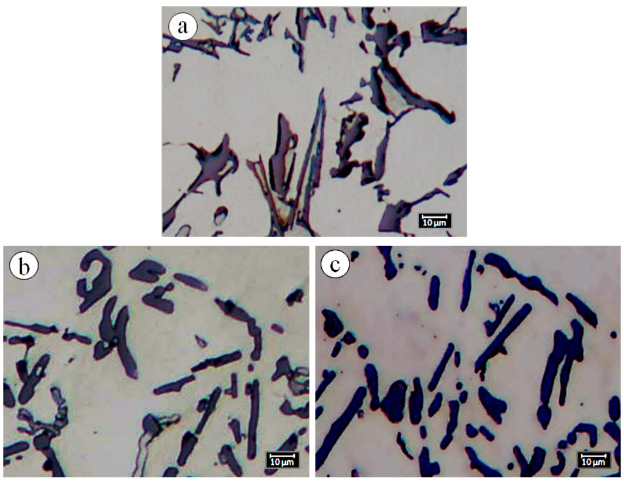

Figure 4 Optical micrographs show the microstructure of (a) as-cast condition (b) after solution treated at 503°C for 8 hours (c) after solution treated at 503°C for 8 hours plus aging at 170°C for 12 hours.

Figure 5 compares the area fraction of eutectic phases in the as-cast condition, after solution treatment, and after solution treatment plus aging was found that in the as-cast and solution treated at 503°C for 2, 4, 8, 12, 24 hours were 17.25 %, 12.75 %, 11.50 %, 11.70 %, 10.75 % and 11.05 %, respectively. After solution treated at 503°C for 8 hours plus aging at 170°C for 1, 6, 12, 24, 36 and 48 hours, the area fractions were decreased to about 11.25 %, 10.35 %, 9.70 %, 9.50 %, 9.90 % and 9.85 %, respectively. These results confirmed that dissolution of some intermetallic phases into the dendritic matrix occurred during solution treatment. At longer time, the area fraction of eutectic phases slightly decreased.

SEM-EDS analysis (in Figure 6) and the previous work [18-21] has revealed that the phases present in A319 alloy are α-Al-rich phase containing Cu, eutectic Si-rich phase containing Al, and intermetallics comprising globular Al_2Cu and a flake shape Al_5FeSi.

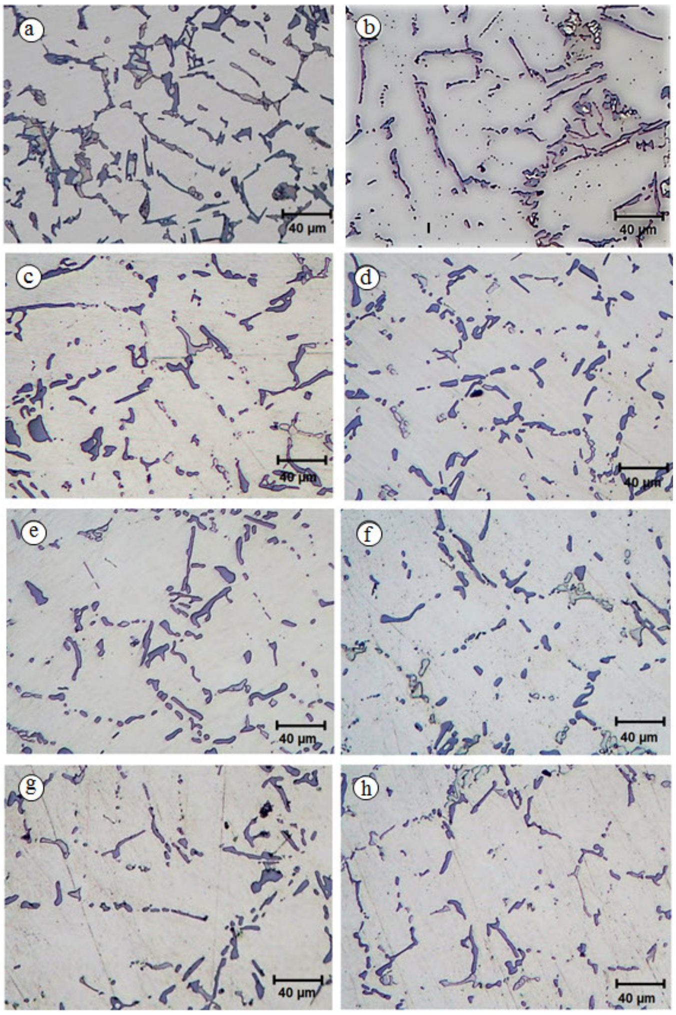

Figure 5 Optical micrographs compare the magnitude of eutectic structure of (a) as-cast condition (b) solution treated at 503°C for 8 hours (c-h) solution treated at 503°C for 8 hours plus aging at 170°C for 1 hour, 6 hours, 12 hours, 24 hours,36 hours, 48 hours, respectively.

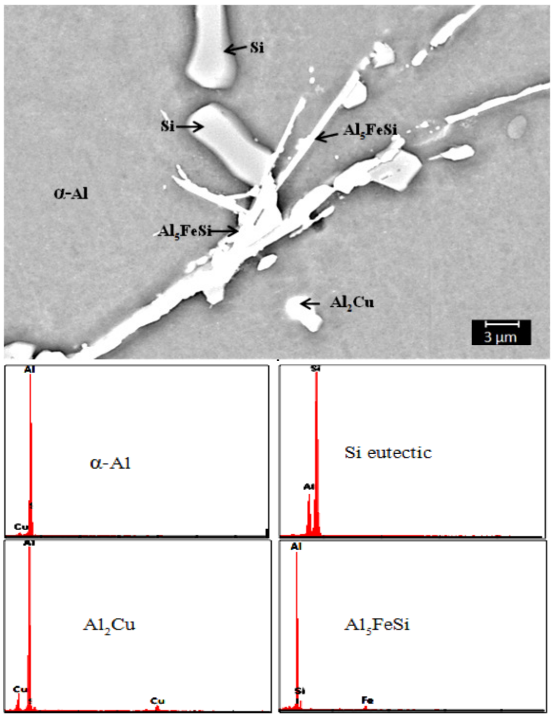

Figure 6 Backscattered electron image (BEI) shows the phases present and EDS spectrums after solution treated at 503°C for 8 hours plus aging at 170°C for 12 hours.

3.2 Macro-hardness and Micro-hardness within the dendritic region

Macro-hardness and micro-hardness levels were increased from 29 HR_B and 73 $HV_{0.05}$ in the as-cast condition up to peak hardness about 60 HR_B and 113 $HV_{0.05}$ after solution treated at 503°C for 8 hours (Figure 7). At shorter time, the macro-hardness and micro-hardness were decreased most probably due to incomplete solution of intermetallic phases. At longer time, the macro-hardness slightly decreased and tended to remain constant, as did the micro-hardness, as complete solution of soluble intermetallic phases and near homogeneity of the matrix was achieved, the corresponding microstructures are shown in Figure 5.

Figure 8 show the macro-hardness (Figure 8(a)) and micro-hardness (Figure 8(b)) results after solution treatment at 503°C for 8 hours, and solution treatment at 503°C for 8 hours plus aging at 150-230°C for 1-48 hours. It was found that the peak macro-hardness was increased up to 72 HR_B, 75 HR_B, 71 HR_B and 67 HR_B after solution treatment plus aging at 150°C for 36 hours, at 170°C for 24 hours, at 200°C for 12 hours and at 230°C for 3 hours, respectively. For the peak micro-hardness was increased up to 125 $HV_{0.05}$, 140 $HV_{0.05}$, 120 $HV_{0.05}$ and 119 $HV_{0.05}$ after solution treatment plus aging at 150°C for 36 hours, at 170°C for 24 hours, at 200°C for 12 hours and at 230°C for 3 hours, respectively. The maximum hardness was obtained after solution treatment at 503°C for 8 hours plus aging at 170°C for 24 hours, higher than quoted by Sepehrband [15] and Mahmudi [9]. At higher aging temperature the peak macro-hardness and micro-hardness were achieved after a shorter aging time, as also found by Mahmudi [9].

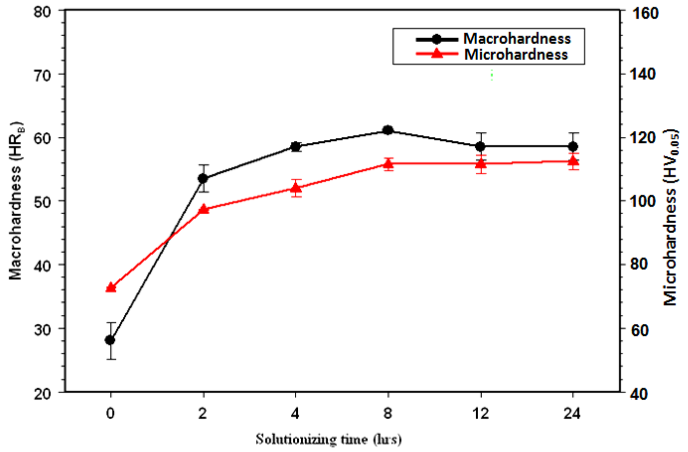

Figure 7 Effect of solution treatment on macro-hardness and micro-hardness within the dendritic region after solution treated at 503°C for different times.

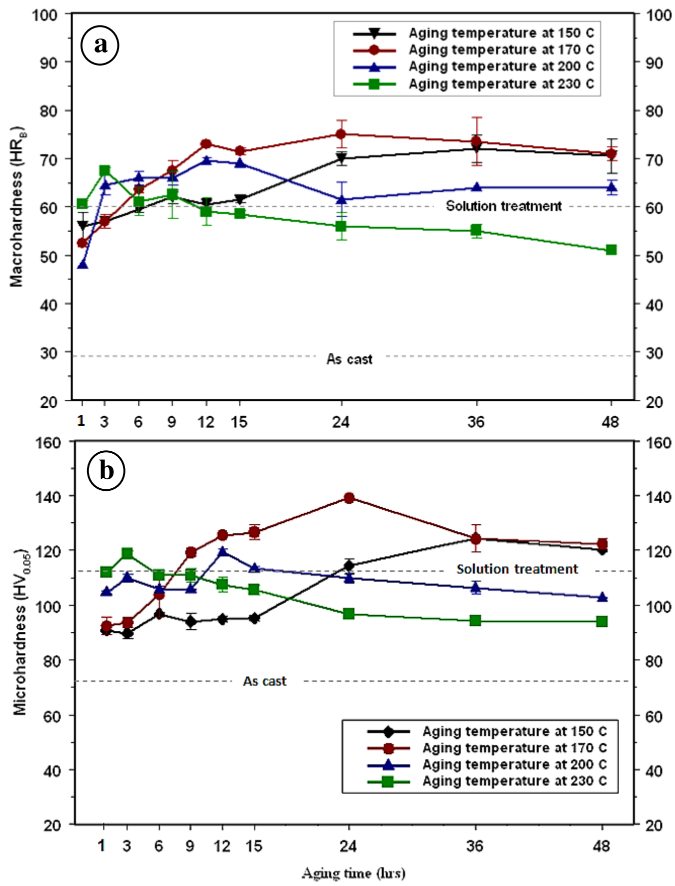

Figure 8 Effect of aging on (a) macro-hardness and (b) micro-hardness in the as-cast condition, after solution treatment at 503°C for 8 hours, and after solution treatment at 503°C for 8 hours plus aging at different temperatures and times.

3.3 Tensile Properties

Figure 9 shows the effect of T6 heat treatment on the tensile properties in the as-cast condition and heat treated conditions. Solution treatment and aging increased the ultimate tensile strength and 0.2%proof stress compared to that of the as-cast condition. The maximum ultimate tensile strength and 0.2%proof stress were increased from 227 MPa and 170 MPa, respectively in the as-cast condition up to 400 MPa and 389 MPa, respectively after solution treatment at 503°C for 8 hours plus aging at 170°C for 24 hours. These results corresponded with the trend in hardness levels. At shorter times, the hardness, 0.2%proof stress and ultimate tensile strength decreased due to incomplete precipitation. At longer times, the hardness, 0.2%proof stress and ultimate tensile strength were also reduced, most probably due to precipitate coarsening by Oswald ripening, which led to loss in coherency effects resulting in smaller strain fields in the matrix around each precipitate [3,20,22]. The fracture behaviour of this alloy is controlled by the brittle fracture of intermetallic Al_2Cu and Al_5FeSi phases and Si eutectic [23]. After solution treatment and after solution treatment plus aging the ultimate tensile strength and 0.2%proof stress were therefore also improved due to a lower area fraction of intermetallic Al_2Cu and Al_5FeSi phases.

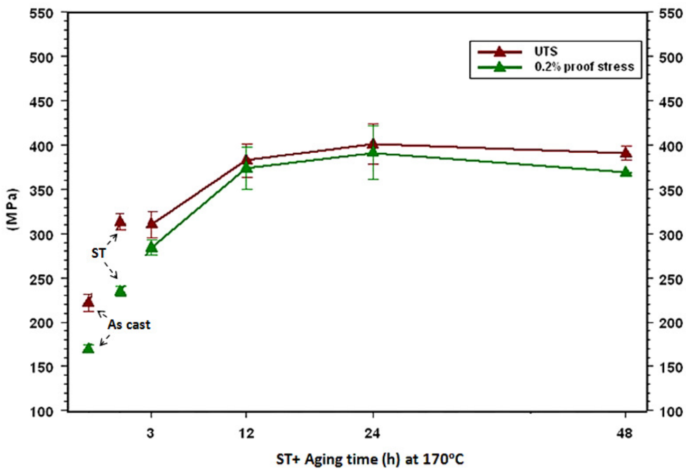

Figure 9 Effect of solution treatment (ST) at 503°C for 8 hours and aging at 170°C for different times on ultimate tensile strength and 0.2%proof stress.

4. Conclusion

The effects of solution treatment and aging temperatures and times on microstructure, hardness and ultimate tensile strength properties of cast aluminium alloy A319 were studied. In the as-cast condition, the microstructure consisted of primary α-Al dendrites with interdendritic eutectic constituents of Al_2Cu, Al_5FeSi and Si. After T6 treatment, some spheroidisation of the eutectic Si and some intermetallics occurred. The area fractions were decreased to about 11.25 %, 10.35 %, 9.70 %, 9.50 %, 9.90 % and 9.85 % after solution treatment at 503°C for 8 hours plus aging at 170°C for 1, 6, 12, 24, 36 and 48 hours, respectively. T6 treatment increased the hardness, 0.2%proof stress and ultimate tensile strength. Peak hardness, maximum tensile strength and 0.2%proof stress were obtained after solution treatment at 503°C for 8 hours plus aging at 170°C for 24 hours. At higher aging temperature the peak macro-hardness and micro-hardness were achieved after a shorter aging time. At shorter aging time, the hardness and tensile strength were lower due to incomplete precipitation. However, at longer time, the hardness and ultimate tensile strength were decreased from the optimum, which was most probably due to the precipitate coarsening and loss in coherency effects resulting in smaller strain fields in the matrix around each precipitate. Since the precipitated particles are smaller than 100 nm the characterization work is continuing using high resolution TEM.

5. Ackowledgment

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