Strengthening of 6063 aluminium alloy by strain ageing

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Abstract

In this study, the artificial ageing behaviour of 6063 Al-alloy is investigated. A certain part of the aluminium test pieces was solution heat treated (SHT) at 520 °C for 2 h, water quenched, then aged at 180 °C for 1, 3, 5, 7, 9 and 15 h and the other part was pre-strained for 2 % in tension shortly after the solution heat treatment (SHTP), then aged at 180 °C for 1, 3, 5, 7, 9, 15 h in a furnace. Tensile strength, flow stress at 3 %, microhardness and electrical conductivity measurements were employed to investigate the effect of artificial ageing on the mechanical properties of Al-alloy. The variations in ageing time have improved the mechanical properties of the 6063 Al-alloy, whereas the ductility has decreased. The experimental work has revealed that different ageing times at 180 °C play a very important role in the precipitation hardening process of the 6063 Al-alloy.

K e y w o r d s: Al-alloys, ageing, solution heat treatment (SHT)

1. Introduction

Aluminium does not have good casting or mechanical properties. These properties can be achieved by adding magnesium and silicon to aluminium. The addition of these alloying elements increases the aluminium response to heat treatment due to formation of Mg_2Si intermetallic compound, which improves the casting, corrosion resistance property as well as the strength of the alloy. This alloy is named as the 6063 aluminium alloy [1]. The precipitation hardenable aluminium alloy 6063 is widely used in the structural applications and it is subjected to a solution heat treatment, quenching, and an artificial ageing treatment in order to obtain the optimum combination of mechanical properties [2]. The understanding of precipitation mechanisms during artificial ageing is critical for achieving optimal properties.

The properties of various aluminium alloys can be altered by specific designated heat treatment. Some aluminium alloys can be solution treated to increase their strength and hardness. The heat treatment process can be classified into two processes, including solution heat treatment and artificial ageing. This consists of heating the alloy to a temperature between 460 and 530 °C at which all the alloying elements are in solution. By heating the solution heat-treated material to a temperature above room temperature and holding it there, the precipitation accelerates and the strength is further increased compared to natural ageing and accompanied by a clear drop in ductility. This is called "artificial ageing", "age hardening" or just "ageing" and is generally carried out at temperatures up to approximately 200 °C (for 6000 aluminium alloys generally between 160 and 200 °C) [3–7].

A search of the literature has identified that considerable work has been carried out on precipitation hardening of 6063 aluminium alloys. As relatively inconclusive work is available in the literature, work is needed to study the effect of pre-strain, ageing time and temperature of Al-Si-Mg alloys on mechanical properties. Therefore, this paper is conducted with the objective of investigating the effect of pre-strain, ageing time and temperature on the mechanical behaviour of the 6063 Al-alloys. The paper focused mainly on examining the changes in the tensile strength, hardness and electrical conductivity of 6063 aluminium alloys when heat-treated at 180 °C for different ageing times.

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2. Materials and experimental procedure

The as-received 6063 Al-alloy used in this study is a plate with a thickness of 10 mm. Its chemical composition in weight percentage is 0.441 Si, 0.502 Mg, 0.008 Mn, 0.005 Cu and balance Al. The standard tensile test pieces 5.7 mm in diameter with a gauge length of 31 mm were machined from the as-received blanks. In order to preserve the supersaturated solid solution at room temperature, the 6063 Al-alloy test pieces were soaked in a furnace for 2 h at 520 ± 2 ℃ followed by quenching in water at room temperature. This process is known as solution heat treatment. After solution heat treatment, all the 6063 Al-alloy test pieces were kept in a freezer. This is very important to avoid the natural ageing of the alloy at room temperature.

While a batch of the tensile test pieces was pre-strained for 2 % in tension shortly after the solution treatment, other batch was processed without pre-straining for the sake of comparison. The amount of pre-strain to which each specimen was subjected was measured by marking a gauge length of 31 mm on the specimen and straining until this gauge length had extended to 31.62 mm for 2 % pre-strain. After the process of solution heat treatment and pre-straining, the specimens were artificially age hardened at 180 ℃ for a period of 1, 3, 5, 7, 9 and 15 h in a furnace and subsequently cooled in air. Finally, they were tested in tension at room temperature using a Schimadzu tensile testing machine at a strain rate of $1.07 \times 10^{-3}\ s^{-1}$. Triplicate samples were employed per run in order to correct for minor differences in experimental conditions.

Microhardness and electrical conductivity measurements tests were also employed to investigate the mechanisms responsible for artificial ageing. The aged samples were ground with SiC paper and hardness measurements were carried out using a Micro Vickers Hardness (HMV) instrument with 500 g load and a dwell time of 15 s. Four hardness readings were performed per sample. SI 1287 Electrochemical Interface Test Unit measured the electrical conductivity of the samples to determine the clustering, precipitation and dissolution activities.

The fractured surfaces of aged test pieces were also analysed using scanning electron microscope (SEM). Representative fractography specimens were sectioned from fractured tensile samples and mounted for scanning electron microscopy (SEM) investigation.

3. Results and discussion

The solution heat treated (SHT) and solution heat treated & 2 % pre-strained (SHTP) test pieces were age hardened at 180 ℃ for 1, 3, 5, 7, 9 and 15 h to study the effect of heat treatment on the tensile strength, flow stress at 3 %, hardness, and electrical conductivity of 6063 Al-alloy. The results of the mechanical properties of aged 6063 Al-alloy are presented in Figs. 1–4.

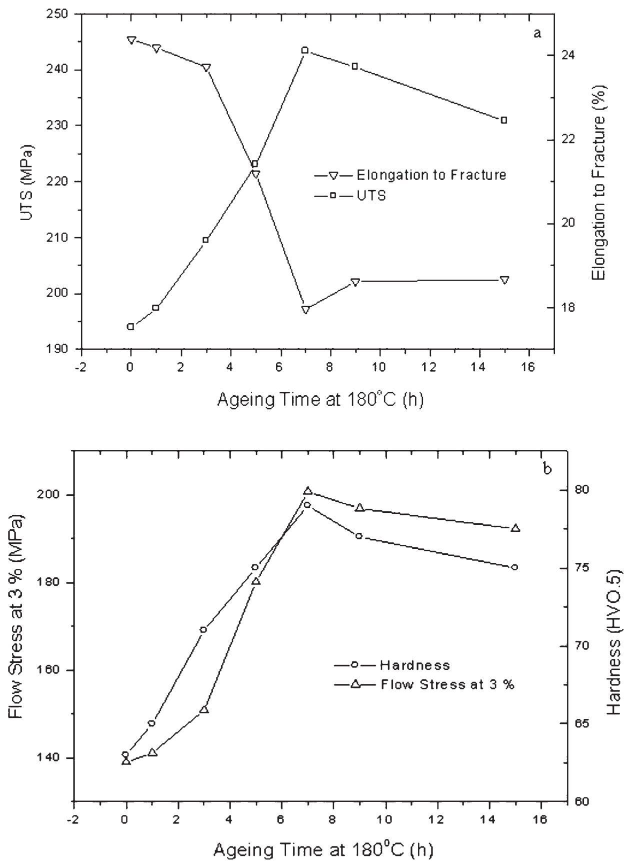
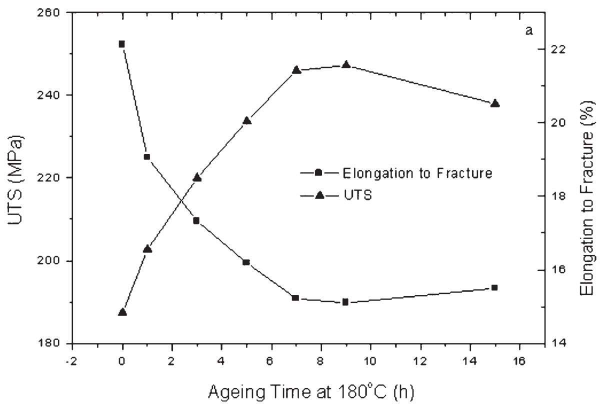


Fig. 1. The change in a) UTS and percentage elongation, b) flow stress and hardness of the solution heat-treated (SHT) test pieces aged at 180 ℃ for different times.

The variation in tensile strength and flow stress at 3 % when exposed to different intervals of time at 180 ℃ is shown in Figs. 1 and 2 for SHT and SHTP test pieces, respectively. It can be observed that as the ageing time increases for the ageing temperature of 180 ℃, a continuous increase in tensile strength and flow stress at 3 % is noticed. Maximum tensile strength and flow stress at 3 % are observed when the alloy is aged between 1 and 9 h at 180 ℃. Further increase in the ageing time of 15 h for 180 ℃ has reduced the tensile strength and flow stress at 3 % of the 6063 Al-alloy under conditions of SHT and SHTP. However, the percentage elongation in 6063 Al-alloy falls gradually with increase in time at 180 ℃. The aged specimens have shown the lowest ductility of 17.96 % for SHT and 15.1 % for SHTP test pieces when precipitation hardened at 180 ℃ for 7 or 9 h, respectively. Time and temperature play a very important role in age hardening of 6063 Al-alloy.

An increase in tensile strength and flow stress at



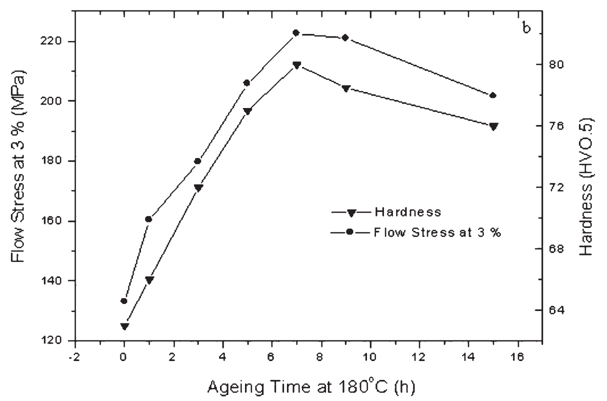


Fig. 2. The change in a) UTS and percentage elongation, b) flow stress and hardness of the solution heat-treated & 2 % pre-strained (SHTP) test pieces aged at 180 ℃ for different times.

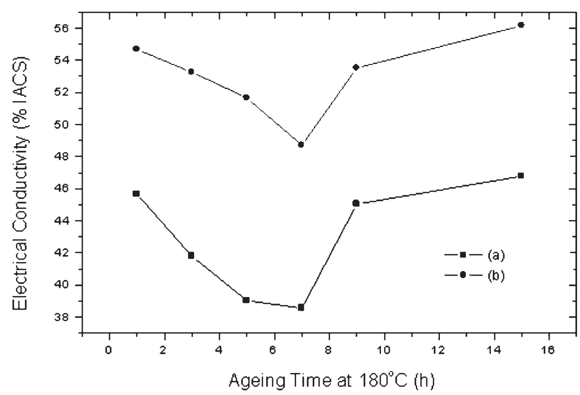


Fig. 3. The change in electrical conductivity of the a) solution heat-treated (SHT) and b) solution heat-treated & 2 % pre-strained (SHTP) test pieces.

3 % but a decrease in percentage elongation could be explained by diffusion-assisted mechanism, and also by hindrance of dislocation by impurity atoms, i.e. foreign particle of second phase, as the material after quenching from 520 ℃ (solution heat treatment) will have excessive vacancy concentration. Rafiq et al. [1] showed that as the ageing time and temperature increase, the density of GP zones will also increase. Hence, the degree of irregularity in the lattices will cause an increase in the mechanical properties of the Al-alloy.

The strengthening effect of 6063 Al-alloy could also be explained as a result of interference with the motion of dislocation due to the presence of foreign particle of any other phase. Further increase in the ageing time for 180 ℃ decreases the tensile strength, and flow stress at 3 % of the alloy. This could be due to coalescence of the precipitates leading not only a formation larger particles but also the distance between particles is higher and also due to annealing out of the defects.

The change in hardness for test pieces processed without and with pre-straining is illustrated in Figs. 1b and 2b as a function of ageing time. Each value here is the average of four measurements. An ageing time of 0 refers to processing without ageing. The hardness of the 6063 Al-alloy, immediately after solutionizing was as low as 63 HMV but a continuous and pronounced increase in hardness with the increase in ageing time for 180 ℃ is observed as seen in Figs. 1b and 2b. The alloy achieves its maximum hardness at 180 ℃ when aged for 7 or 9 h, thereafter, a decrease occurs as the time increased to 15 h. The reason for increase of the hardness values can be attributed to the solubility of magnesium silicide increasing markedly with solution treatment resulting in a higher amount of dissolved Mg_2Si in aluminium [2, 8, 9]. During quenching, this Mg-Si was retained in solution. Therefore, the Al phase would contain Mg-Si in a supersaturated solid solution at room temperature. During ageing, fine particles of Mg_2Si form and precipitate. Thus, the hardness of 6063 Al-alloy increases rapidly with artificial ageing time. Janeček et al. [10] also showed that natural ageing at room temperature after quenching of 6016 Al-alloy annealed at 500 or 550 ℃ for different times leads to gradual increase in hardness. This indicates that the annealing at higher temperature results in higher saturation of the aluminium solid solution with solute atoms of Mg and Si. The natural ageing of the sample treated at 550 ℃ obviously results in higher hardness.

Figure 3 where ageing time versus % IACS shows the electrical conductivity change for different ageing times at 180 ℃. IACS is an acronym for International Annealed Copper Standard or the material that was used to make traditional copper-wire. The conductivity of the annealed copper is 5.8108×10^7 S m^{-1} and copper is defined to be 100 % IACS at 20 ℃. All other conductivity values are related to this conductivity of annealed copper. From 1 to 7 h ageing time, there is a decrease in electrical conductivity in both SHT and SHTP test pieces. According to an investigation [11], Mg atoms in solid solution cause an average decrease in conductivity, while there is increase when the atoms

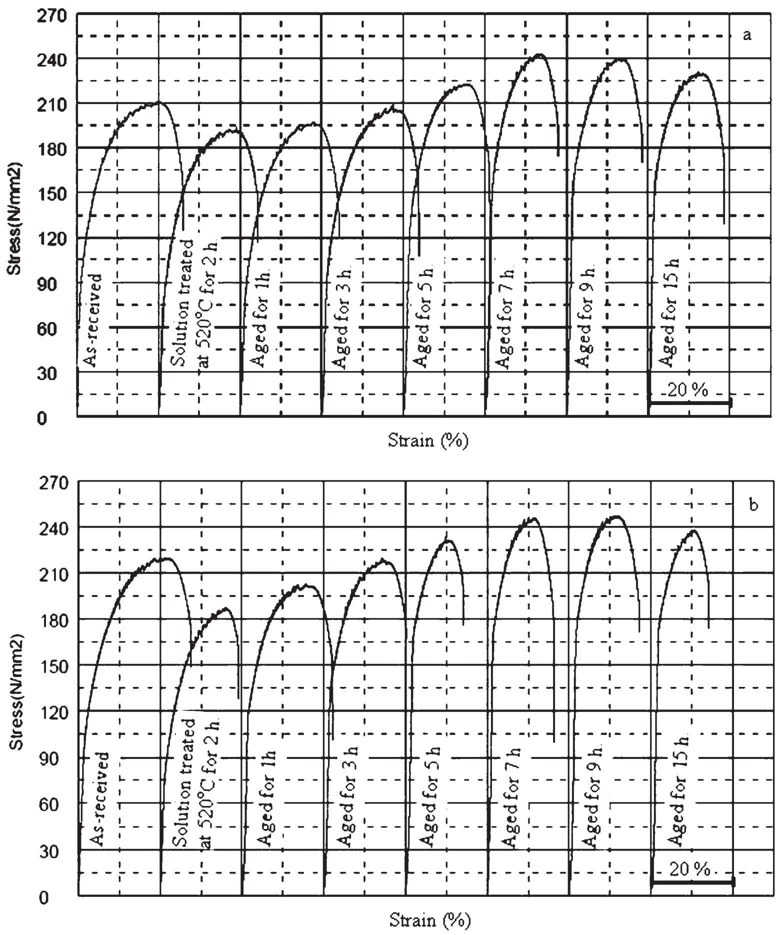


Fig. 4. Stress-strain curves with different ageing times for the a) solution heat-treated (SHT) and b) solution heat-treated & 2 % pre-strained (SHTP) test pieces.

are out of solid solution. The large increase in both SHT and SHTP test pieces for ageing times of 9 and 15 h indicates that a large amount of Mg atoms were precipitated out of solid solution since under such low temperature ageing for different times, the materials have not been recrystallized and there should be little change in conductivity if no Mg atoms are precipitated out.

Stulíková et al. [12] investigated the effect of composition on natural ageing of Al-Mg-Si alloys by the response of hardness HV 30 and electrical conductivity in five alloys (AA6xxx series) containing besides the main solutes Mg and Si also small additions of Cu and Cu with Sn. They showed that electrical conductivity decreases with time of natural ageing for all alloys studied. This behaviour was ascribed to a clustering of solutes (or GP zones) in the investigated specimens.

The results also indicated that electrical conductivity of the SHTP test pieces is higher than SHT test pieces (Fig. 3). This is consistent with the results obtained by Rossen et al. [13] who showed that the rate of change in conductivity with ageing time is higher in plastically deformed solution treated aluminium alloy compared to the undeformed alloy. This is due to the formation of larger size precipitates, which results in increase in conductivity.

Figures 4a and 4b show stress-strain diagrams for SHT and SHTP test pieces aged at 180 ℃ for different time intervals. It is seen that SHTP test pieces showed slightly higher strength properties than SHT test pieces for all ageing intervals. It was reported for aluminium alloys [14–16] that, intermediate plastic deformation increases ageing rate and improves strength reached by conventional ageing by providing homogeneously distributed nucleation sites for precipitation in the matrix. Cassada et al. [17, 18] demonstrated that increasing high levels of plastic deformation prior to artificial ageing for a near 2090 Al-alloy aged at 190 ℃ resulted in marked gains in yield strength for the under- and peak-aged conditions due to the enhanced volume fraction of fine matrix precipitates such as Al_2CuLi. Matrix precipitation of this more abundant and finer strengthening phase directly correlates to the increased strength of the material versus a non-stretched condition that exhibits only grain boundary precipitation [19]. Therefore, the higher strength of pre-strained and aged specimen (SHTP) can be attributed to the presence of

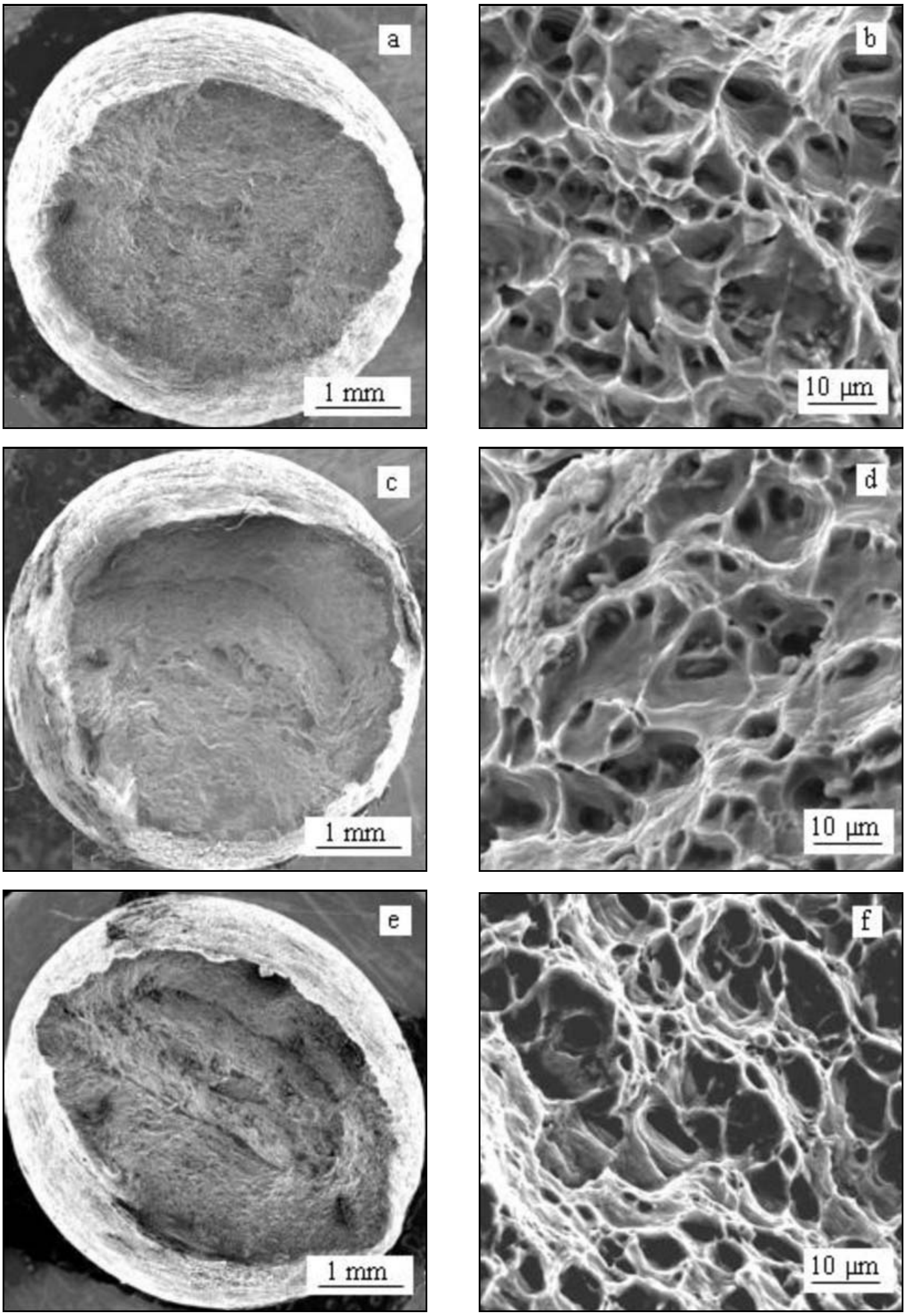


Fig. 5. Fracture surfaces of the solution heat-treated & 2 % pre-strained (SHTP) test pieces aged at 180 ℃ for 1 h (a, b), 7 h (c, d) and 15 h (e, f).

homogeneously distributed precipitates in the matrix.

Figure 5 shows tensile fracture surface of SHTP test pieces when aged at 180 ℃ for a period of 1, 7 and 15 h. As seen in Fig. 5, SHTP test pieces showed dimples and cleavage facets, indicating that the fracture is mixed type when the alloy was aged at 180 ℃ for a period of 7 h; this was manifest as low percentage elongation prior to fracture. The reduction in area also decreased at 180 ℃ for 7 h ageing time, which corresponds to embrittlement due to ageing result of the interaction between dislocation and precipitate particles. However, SHTP test pieces showed certain surface roughness typical of ductile fracture and microscopically a surface covered by dimples of several sizes was observed after ageing at 180 ℃ for a period of 15 h which lead to increase in percentage elongation due to coarsening of the precipitates on dislocations. This causes few obstacles to the movement of dislocations and hence the percentage elongation starts to increase.

4. Conclusions

In this work, the artificial ageing behaviour of solution heat treated (SHT) and solution heat treated & 2 % pre-strained (SHTP) 6063 Al-alloy was studied in artificially aged conditions. The conclusions derived from this study can be given as follows.

1. An increase in the tensile strength, flow stress at 3 % and hardness of SHT and SHTP Al-alloy with increase in ageing time for 180 ℃ can be explained by a diffusion assisted mechanism which causes an increase in the density of GP zones, distortion of lattice planes and hindering of dislocation movement by the impurity atoms. The strengthening effect can also be as a result of interference with the motion of dislocation, due to the formation of precipitates.

2. Further increase in ageing time decreases the tensile strength, flow stress at 3 % and hardness of the alloy. This could be due to coalescence of the precipitates leading not only a formation larger particles that are then fewer obstacles for the dislocation motion but also the distance between particles is higher and hence, the flow stress is lower.

3. SHTP test pieces showed slightly higher strength properties than SHT test pieces for all ageing intervals. This is due to pre-straining prior to artificial ageing which enhanced the competitive precipitation kinetics of the precipitate in the matrix. Matrix precipitation of this more abundant and finer strengthening phase directly correlates to the increased strength. Pre-straining may also lead to deformation hardening and thus gives a rather high strength.

4. There is a continuous decrease in electrical conductivity in both SHT and SHTP test pieces with increasing ageing time from 1 to 3, 5 or 7 h. As the ageing time increases for 180 ℃ ageing temperature, the density of GP zones will also increase. Hence, the degree of irregularity in the lattices will cause a decrease in electrical conductivity of the Al-alloy. Further increase in ageing time to 9 or 15 h caused an increase in electrical conductivity due to precipitation of larger size particles.

5. The rate of change in conductivity with ageing time is higher in pre-strained solution treated (SHTP) Al-alloy than undeformed solution treated (SHT) Al-alloy. This is due to formation of larger sizes precipitates, which results in increase of conductivity.

6. Fractographic analysis showed that SHT and SHTP Al-alloy underwent brittle and ductile fracture when aged at 180 ℃ for 7 h. In the case of increasing ageing time of 15 h for 180 ℃, fracture pattern changed from moderate ductile to ductile nature.

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