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Novel Al-Cu-Mg-Ag Alloy for High Temperature Applications

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A novel age-hardenable Al–Cu–Mg–Ag alloy containing small additions of zirconium and scandium was developed for high temperature applications. Effect of heat treatment on microstructure and mechanical properties was studied at room temperature as well as at temperatures of 150 and 180°C. It was shown that the formation of nanoscale dispersoids of $Al_3(Sc,Zr)$ takes place under solution treatment. No primary AlCuSc particles were found. It was found that aging at 190°C for 5 hours provides highest hardening for this heat-resistant alloy. It was found that Ω – phase forming on the $\{111\}_{\alpha}$ planes is the dominant precipitation in the aluminum alloy. However, in the present alloy this phase is susceptible to coarsening at 200°C. The high strength was attributed to the high density of fine Ω precipitates. Stretching between quenching and aging leads to almost full disappearance of θ‘-phase precipitates.

Keywords: *age hardening; Al-Cu-Mg-Ag aluminum alloys; mechanical properties, microstructure.*

1. Introduction

In the past several decades, considerable commercial interest has been shown in the development of high strength aluminum alloys belonging to 2XXX series and having superior combination of mechanical properties at room and elevated temperatures. It makes it possible to consider them as a potential structural material for use in aircraft structures operating at high temperatures. There is two promising ways for increasing the service temperature of aluminum alloys; the first one is additional alloying by silver [1] and the second one is the alloying by zirconium and scandium [2].

It was shown [1,3-5] that silver additions (~0.5 wt.%) strongly enhances the age hardening of aluminum alloys belonging to Al–Cu–Mg system affecting the composition and crystallographic orientation of strengthening phases precipitated during artificial aging. It was found that highest positive effect of silver in high temperature strength and creep resistance takes place in alloys with Cu\Mg ratio of about 10 and copper content ranging from 5 to 6 wt.%. Under artificial aging, silver stimulates precipitations of a uniform dispersion of Ω-phase being a modification of the θ-phase (Al_2Cu) [3,5]. Due to the high dispersivity and enhanced thermal stability of the Ω-phase, the aluminum alloys belonging Al–Cu–Mg–Ag system exhibit increased strengthening and properties at temperatures up to 200°C [1,3,5].

The second approach to increase the service temperature of aluminum alloys is the additional alloying by Zr and/or Sc, which form nanoscale particles with a size ranging from 10 to 30 nm, these dispersoids are highly stable against the coalescence at elevated temperatures [5-9]. These particles have coherent or semi-coherent boundaries and act as an effective pinning agent hindering dynamic recovery [6] and dislocation glide [7-9]. Recently, the authors of [7,8] showed that the introduction of coherent Al_3Sc particles into an aluminum alloy makes it possible to increase its creep resistance. At the same time, it is known [9] that these particles suppress the development of recrystallization processes in the cold-worked aluminum alloy up to melting temperatures. Thus, we can expect that the development of an Al–Cu–Mg–Ag–Zr–Sc alloy gives a synergetic effect originated from superposition of $Al_3(Sc,Zr)$ and Ω-phase particles on its high temperature strength.

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The present study is dedicated to examine microstructure and mechanical properties of a Zr and Sc modified Al–Cu–Mg–Ag alloy. The effect of heat treatment conditions on microstructure and mechanical properties is considered to develop an optimal route providing the optimum combination of mechanical properties at ambient and elevated temperatures.

2. Materials and experimental procedures

Aluminum alloy with a chemical composition of Al–5.6%Cu–0.62%Mg–0.56%Ag –0.37%Mn–0.15%Sc–0.09%Zr (in wt %) denoted as Almagest2Sc, herein, was manufactured by direct chill casting. This alloy was homogenized at 520°C for 24 hours and slow cooled in a furnace. The ingots with dimensions of ∅ 40×120 mm^2 were forged with a forging ratio 4:1 into rods having a 17×17 mm^2 cross-section at a temperature of ~ 400°C. Next, the alloy was subjected to solution heat treatment at 520°C for 2 hour followed by water quenching. The following aging conditions were used:

- artificial aging with different dwelt times at temperatures of 185, 190, 200 and 250 °C (*i.e.* T6 temper);
- cold stretching to 1, 3, 5 and 7 % followed by artificial aging with different dwelt times at a temperature of 190°C (*i.e.* T8 temper).

The hardness measurements were carried out at room temperature by using Vickers microhardness tester with a load of 10 N. Tensile properties were determined in the longitudinal section of aged rods. Tensile specimens with a 15 mm gauge length and a 3×1.5 mm^2 cross-section were machined from the rods and tensioned at 20, 150 and 180°C. An Instron universal testing machine (Model 5882) equipped with a three-zone split furnace was used. Temperature accuracy was within ±3°C. Each specimen was held at a testing temperature for about 20 minutes in order to reach

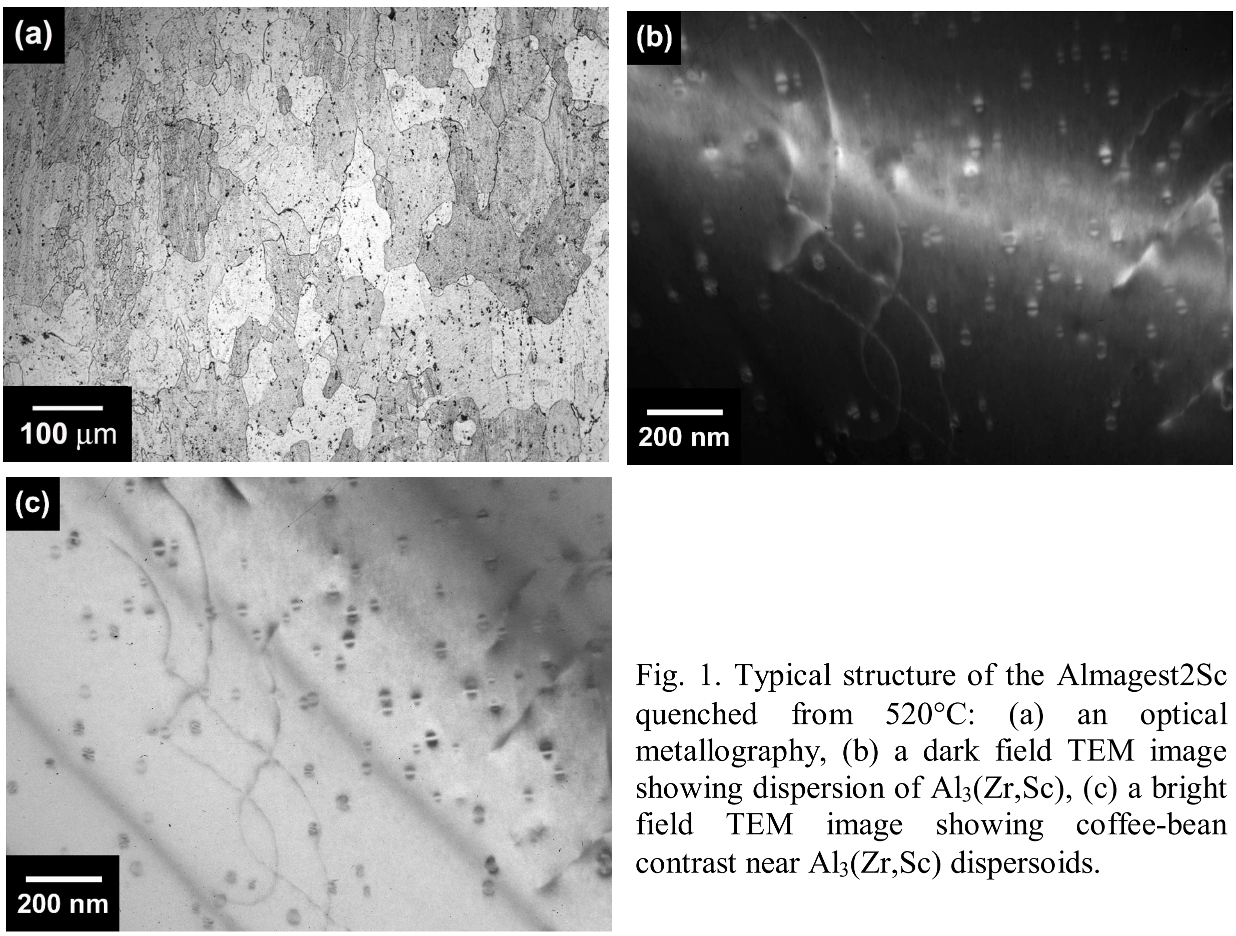

Fig. 1. Typical structure of the Almagest2Sc quenched from 520°C: (a) an optical metallography, (b) a dark field TEM image showing dispersion of $Al_3(Zr,Sc)$, (c) a bright field TEM image showing coffee-bean contrast near $Al_3(Zr,Sc)$ dispersoids.

a thermal equilibrium.

Specimens for metallographic examinations were etched using a standard Keller solution. Metallographic analysis was carried out using an Olympus GX70 optical microscope. For transmission electron microscopy (TEM) examinations, the samples were ground to about 0.1 mm. Discs with a 3 mm diameter were cut and electropolished to perforation with a Tenupol-5 twinjet polishing unit using a 25% nitric acid solution in methanol at –30°C and 15V. A Jeol JEM-2100 electron microscope with a double-tilt stage at an accelerating voltage of 200 kV was used.

3. Experimental results

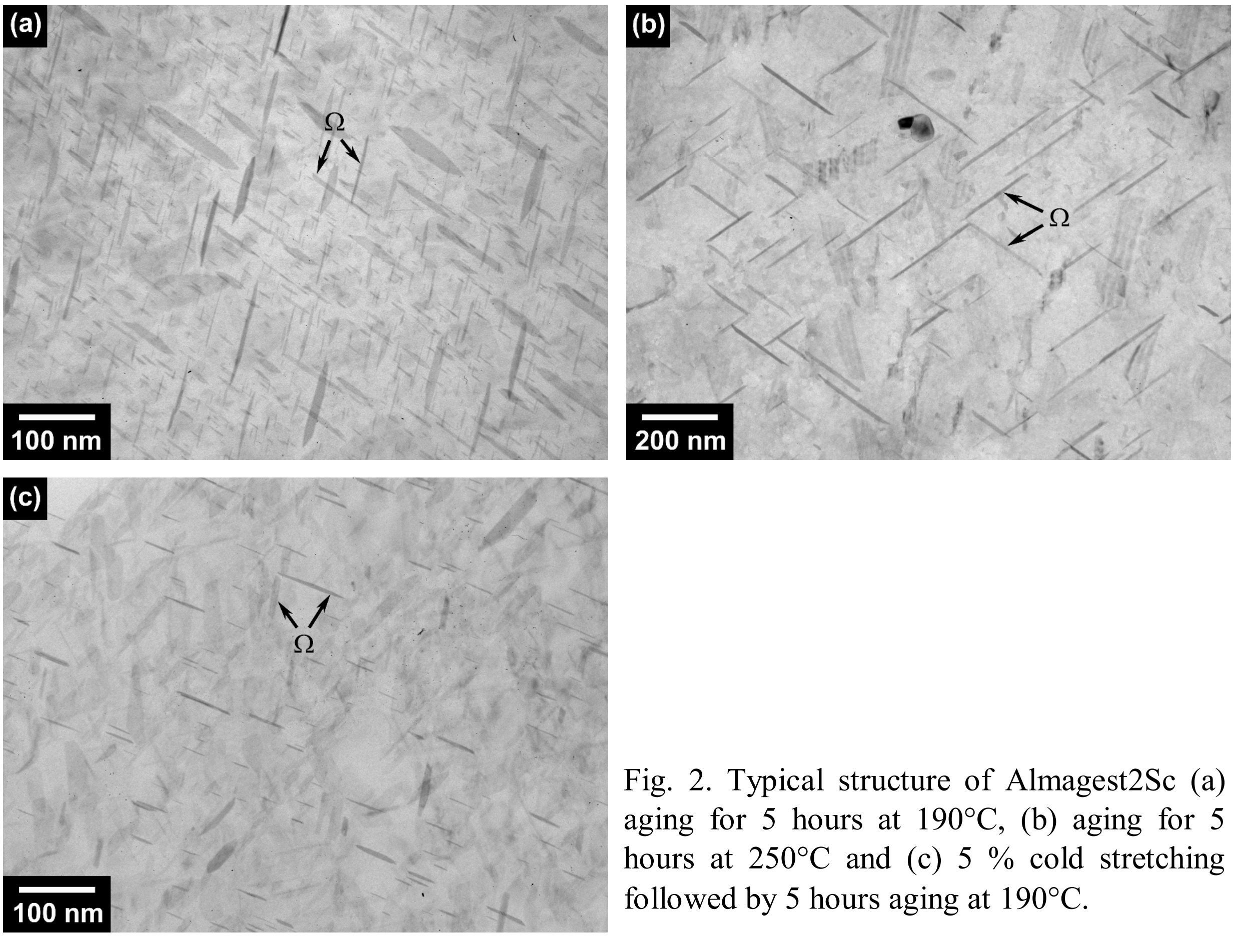

Fig. 2. Typical structure of Almagest2Sc (a) aging for 5 hours at 190°C, (b) aging for 5 hours at 250°C and (c) 5 % cold stretching followed by 5 hours aging at 190°C.

Typical microstructure of the Almagest2Sc in a quenched condition consists of coarse elongated grains with an average size of ~46 μm and ~24 μm in longitudinal and transverse direction, respectively (Fig. 1a). Careful structural characterization of the Almagest2Sc with a (110) dark field TEM image showed that there was a uniform distribution of $Al_3(Sc,Zr)$ dispersoids having an average size of ~20 nm (Fig. 1b). Examination of a bright field image showed that the most of these dispersoids exhibited coherent boundaries (Fig. 1c). The volume fraction of coherent $Al_3(Sc,Zr)$ dispersoids, distinguished by a specific coffee-bean contrast in aluminum matrix near the particles, was found to be of ~0.5%.

TEM images of the present alloys after T6 and T8 tempers are given in Fig. 2. The plate like and needle like second phase particles were identified as Ω – phase. It was found that Ω – phase appears on $\{111\}_\alpha$ planes; this phase is dominant. Meanwhile, a certain amount of θ'– phase locating on $\{001\}_\alpha$ planes and spherical $Al_3(Sc,Zr)$ particles randomly distributed within Al matrix were also observed after aging. It is apparent (Fig. 2) that precipitates of Ω – phase in the Almagest2Sc aged at

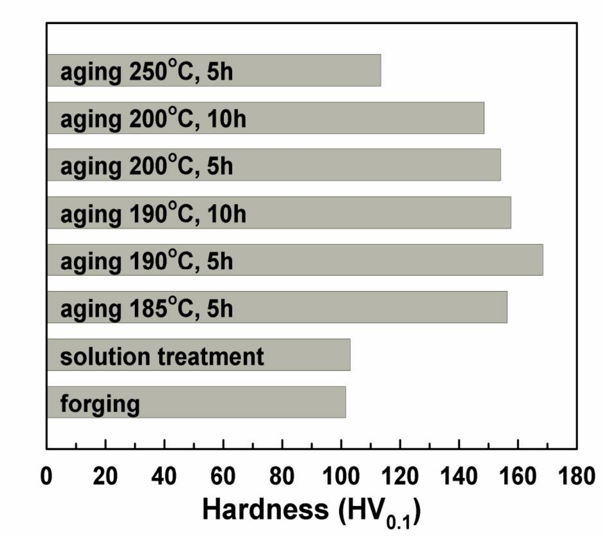

Fig. 3. Effect of heat treatment on Vickers hardness of present alloy.

190°C are finer and more uniform than those in the alloy aged at 250°C: their dimensions were of ~ 44.3 nm in diameter and ~1.6 nm in thickness, and of ~ 126 nm in diameter and 4 nm in thickness, respectively. These data are in contrast with well-known high dimension stability of Ω – phase at T≤200°C [3]. The densities of Ω – phase in the alloy aged at 190°C was higher than that in the alloy aged at 250°C. Cold stretching before aging results in more fine and uniform precipitation of Ω–phase in comparison with the alloy aged at 190°C. The diameter and thickness of Ω – phase in the stretched alloy were of ~33 nm and of ~1.6 nm, respectively. Notably the stretching leads to almost full disappearance of θ'– phase particles (Fig.2c).

The effect of heat treatment on Vickers microhardness of the Almagest2Sc is shown in Fig. 3. The hardness of the aged alloy is considerably higher than that of the alloy subjected to forging and solution heat treatment. Aging at 190°C for 5 hours provides a significant increase in hardness to ~170 HV. There is a gradual decrease in hardness of the alloy with following increase in aging time. The reduction in hardness with increasing the aging time and temperature results from decreasing density and increasing size of second phase particles.

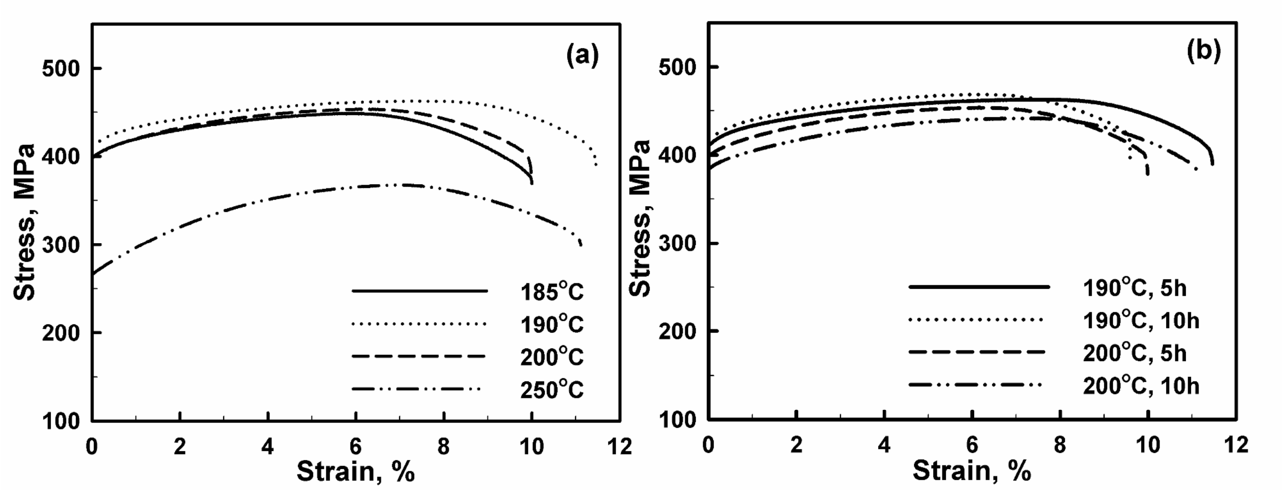

Fig. 4. Influence of aging temperature (a) and aging time (b) on strength of the Almagest2Sc.

The engineering stress–strain curves of the Almagest2Sc aged for 5 hours at various temperatures are shown in Fig. 4a. Yield stress increases with increasing the aging temperature from 185 to 190°C. Further temperature increase leads to a decrease in yield stress and ultimate strength. The alloy aged at 190°C for 5 hours demonstrates highest values of yield stress, $\sigma_{0.2}$, of ~410 MPa, ultimate tensile strength, σ_{UTS} of ~463 MPa and elongation to failure of ~11%. It is seen in Fig. 3 and Fig. 4a that the strength characteristics correlate with hardness of the alloy. Influence of aging time on room temperature strength was studied using specimens aged at 190 and 200°C. It is seen that strength and ductility of the Almagest2Sc aged at 190°C remain almost unchanged with increasing the aging time from 5 to 10 hours (Fig. 4b). While the decrease in duration of aging at 200°C leads to a decrease in

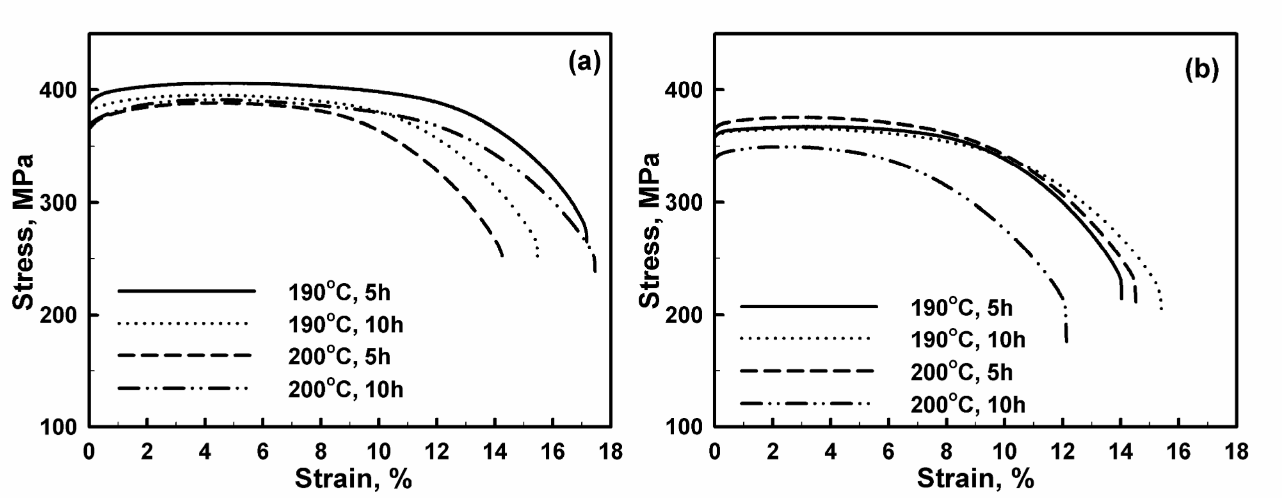

Fig. 5. Effect of testing temperature on tensile strength: (a) 150 °C and (b) 180 °C.

yield stress of the examined alloy. It is seen that the T6 temper at a temperature of ~190°C during 5 hours is an optimum hardening conditions for Almagest2Sc.

Influence of testing temperature on tensile strength of Almagest2Sc was studied on specimens tensioned at 150 and 180°C. The strength of the Almagest2Sc decreases with increasing the testing temperature as well as increasing the aging temperature (Fig. 5). The alloy aged at 190°C during 5 hours and tensioned at temperature of ~150°C demonstrate $\sigma_{0.2}$ of ~387 MPa and σ_{UTS} of ~ 406 MPa (Fig. 5a); these values slightly decrease with increasing temperature and period of aging. It is seen that the alloy aged at 190°C for 5 hours demonstrates highest strength due to increased fraction of dispersed strengthening phases. During testing at 180°C, the conditions of heat treatment have no effect on the strength and ductility except for aging at 200°C for 10 hours (Fig 5b) where noticeable decrease of strength was found. The decreased strength and ductility of the alloy aged at 200°C for 10 hours may be due to coarsening of strengthening particles.

It is known [9] that cold stretching after quenching may enhance the strength of Al–Cu–Mg–Ag alloys. In order to investigate the effect of stretching on tensile strength the specimens subjected to solution treatment followed by quenching were stretched with strain of ~1, 3, 5 and 7% prior 5 hours aging at 190°C (*i.e.* T8 temper). The data presented on Fig. 6 shows that the strength of the Almagest2Sc stretched to ~1 and 3% is similar to that obtained for the un-stretched and aged alloy; strength characteristics tend to increase with increasing strain of stretching from 5 to 7%. For example, the yield stress increases from 410 to 432 MPa then the cold stretching with strain of ~5 or ~7% was applied.

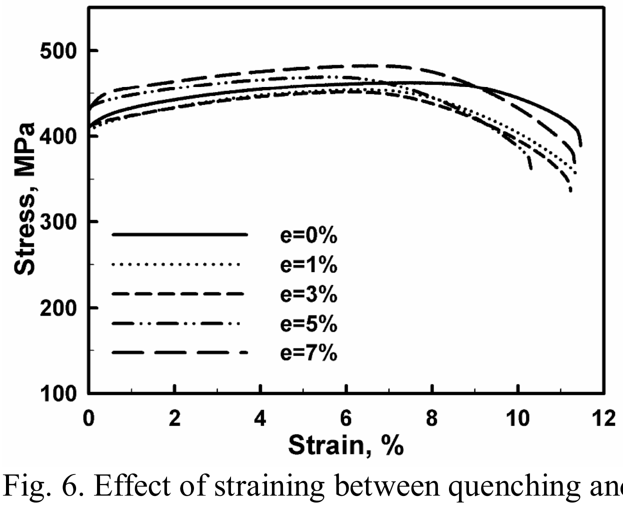

Fig. 6. Effect of straining between quenching and aging on the σ-ε curves.

4. Discussion

The Almagest2Sc alloy containing minor additions of zirconium and scandium was subjected to forging followed by age-hardening. It was found that this alloy is effectively strengthened by fine dispersion of Ω – phases which are uniformly distributed within matrix. Artificial aging at 190°C during 5 hours is an optimum hardening condition for the T6 temper. At ambient temperature, the alloy subjected to T6 temper at 190°C demonstrates yield stress of ~410 MPa, ultimate tensile strength of ~ 463 MPa and elongation to failure of ~11%. The highest yield stress of ~430 MPa, ultimate tensile strength of ~ 480 MPa and elongation of 11% were achieved in the alloy subjected to T8 temper at 190°C for 5 hours. The higher strength of the alloy after T8 temper is attributed to the higher density of fine Ω precipitates, which almost completely substituted the θ'– phase particles in addition to high dislocation density.

In several reports [1, 4] dedicated to mechanical properties of Al–Cu–Mg–Ag alloys the highest values of strength were obtained in alloys subjected to hot extrusion followed by artificial aging at similar conditions. The hot forging followed by artificial aging was used in present study. The present data showed that diameter and thickness of Ω – phases precipitated under aging at 190 °C during 5 hours was almost similar to that observed in Ref. [1, 10,11]. Therefore it is concluded that the moderate strength achieved in present experiment are attributed to hot forging instead of hot extrusion. It is known [12] that a strength increment in extruded bars is higher in comparison with forging at similar reductions. Thus it can be expected that the optimization of the parameters of the thermomechanical processing can provide enhanced strength of the Almagest2Sc.

5. Summary

Impact of heat treatment on tensile strength of Zr and Sc modified Al–Cu–Mg–Ag was studied. The alloy subjected to T6 temper at 190°C during 5 hours demonstrates optimum relation of hardness, strength and ductility. Yield stress of ~410 MPa, ultimate tensile strength of ~ 463 MPa and elongation to failure of ~11% were attained at room temperature. Increasing the testing temperature leads to a decrease in strength and ductility of the Almagest2Sc. In was shown that T8 temper including cold stretching with strains of ~ 5–7 % followed by aging at 190°C during 5 hours increase yield strength of examined alloy from 410 to 432 MPa.

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