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Influence of micro-alloying with silver on microstructure and mechanical properties of Al-Cu alloy

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ABSTRACT

The present study aims to investigate the microstructure and mechanical properties of Al-Cu-Zn-Fe-Ti-Mg alloy (≈ 2219 Al-alloy), micro-alloyed with silver (Ag in the range 0 − 0.1 wt%), under different thermo-mechanical process conditions. Investigation of the microstructure of cast alloys revealed the presence of intermetallic $CuAl_2$ and metastable Al-Cu-Fe-Zn-Si-Mn phases at the grain boundary regions. The as-cast dendritic structure was eliminated by heat treatment and subsequent rolling process resulting in improved mechanical properties. The strength and hardness increased with the increase in silver content up to 0.07 wt% in combination with reasonable ductility. Maximum strength for the alloy was achieved in the rolled and age hardened condition. Fractographic studies revealed brittle failure in as-cast alloys, whereas the heat treated alloys exhibited features typical of ductile failure.

1. Introduction

Aluminum alloys are used as structural materials for their high strength, light weight, reasonable ductility, and excellent formability [1,2]. These alloys are mainly classified into: (i) cast Al alloys which are solidified inside molds to obtain desired shape and size before use and (ii) wrought Al alloys which are cast into ingots and plastically deformed to obtain different sections like wires, rods, tubes, or sheets [3,4]. It is generally known that deformation processing of wrought alloys results in elimination of casting defects such as micro-porosities, dendritic structure, inter-dendritic segregation, presence of large second phase particles, etc. The deformation process also results in the refinement of grain size and reduction in the size of second phase particles present during the casting process leading to improved mechanical properties.

Among the aluminum alloys, wrought Al-Cu (2xxx), Al-Mg-Si (6xxx) and Al-Cu-Zn-Mg (7xxx) series alloys have been studied extensively due to their high specific strength [4]. These alloys, after plastic deformation, are subjected to heat treatments such as: (i) solid solution heat treatment where the solutes dissolve in the aluminum lattice resulting in strengthening and (ii) age hardening heat treatment of the solutionized alloy. The age hardening process is accompanied by uniform precipitation of fine intermetallic particles in the alloy matrix which acts as impediments for the movement of dislocations along the slip plane thereby improving the mechanical properties [5–7].

Sufficient information is available regarding the effect of mechanical properties of commercial wrought aluminum alloys produced by addition of one or more elements like Cu, Mg, Sn, Sc, Zn, Zr, Ti etc. [8–12] where the amount of alloying elements is generally greater than 1.0 wt%. The extent of strengthening these commercial alloys by various thermo-mechanical treatments has almost reached a saturation level. The recent research trend to obtain aluminum alloys with better combination of properties is by micro-alloying the existing commercial alloys i.e. by addition of trace amounts ($<$ 0.1 wt%) of elements like Sn, Cd, Sc, Ti, Ag, Zr, In, etc. Trace addition of these elements influences the microstructure and mechanical properties of the base alloy [13–16]. Addition of 0.05 wt% Ti has been found to increase the strength of Al-4.5Cu-0.3Mg alloy by around 10% [17]. Investigation reveals that even small variations in Sn (in the range 0–0.1 wt%) content results in major changes in microstructure and mechanical properties of 2219 alloy [16,18]. These studies reveal that the strength increases with increase in Sn content in the alloy up to 0.06 wt% and further addition of Sn reduces the strength.

Investigations have been carried out to study the effect of silver addition (0.3–0.5 wt%) on the mechanical properties, hot deformation characteristics and age hardening behavior of Al-Cu-Mg alloys [19–22]. Addition of 0.3 wt% Ag accelerates the precipitation hardening behavior resulting in an increase in the strength and hardness of Al-Cu-Mg (2519 Al) alloy [19]. Addition of 0.48 Ag reveals that the hot deformation microstructure is sensitive to strain rate and deformation temperature [20]. It also accelerates the precipitation kinetics with simultaneous increase in the peak hardness, yield strength and ultimate

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tensile strength of Al-Cu-Mg alloy [21]. The effect of ageing on the microstructure and mechanical properties of Al-Cu-Mg alloy containing 0.5 wt% Ag indicates that the peak hardness of the alloy is same for the T6 temper and T614 temper conditions [22].

Sufficient information is available regarding the precipitation sequence and its influence on the mechanical properties of Al-Cu-Mg alloys during the age hardening process [6–8,10,16,19,21]. The optimum mechanical properties which can be achieved by precipitation strengthening is influenced by: (i) nature of the precipitates, (ii) coherency between the precipitate and the matrix, (iii) size of the precipitates and (iv) inter-particle spacing between the precipitates in the matrix. The reaction sequence occurring in the supersaturated solid solution (SSS) Al-Cu-Mg alloy during age hardening initiates with the formation of GP-zones. GP zones contain clusters of monoatomic layer of Cu atom on the (001) planes of the Al lattice. Further age hardening results in formation of Ω phase by diffusion of Cu atoms into the matrix and formation of additional layers of GP-zones. The entire precipitate formation in the Al matrix occur by the following sequence:

$$\text{SSS} \rightarrow \text{GP-zone} \rightarrow \theta''\,\text{phase} \rightarrow \theta'\text{phase} \rightarrow \theta\text{phase}$$

The GP zone and θ″ phase are fully coherent with the matrix, whereas θ' phase is disc shaped and semi-coherent with the matrix. The final θ precipitate phase is almost spherical in shape and incoherent at the precipitate matrix interface regions. This precipitate exhibits a body centered tetragonal structure with a = b = 0.6066 nm, c = 0.4874 nm [16,23].

Precipitation sequence in Al-Cu-Mg alloys containing small amount of Ag (0.1 wt% ≤Ag ≤ 0.2 wt%) during age hardening was studied by researchers [23]. Studies revealed that the as-quenched ternary Al-1.7Cu-0.5Mg alloy was accompanied by the presence of high density of dislocation loops. It was observed that the first stage of hardening in this alloy was due to the formation of GPB zones from the solution of Cu-Mg co-clusters. Addition of 0.1 wt% Ag into this alloy revealed absence of dislocation loops indicating trapping of vacancies by silver atoms in the as-quenched condition. The early stage of age hardening in this tertiary alloy was accompanied by nucleation of Mg-Ag co-clusters, Mg-Cu co-clusters and Mg clusters in the matrix [24]. The final hardening of Al-Cu-Mg-Ag alloy has been attributed to the presence of GPB zones, finely dispersed hexagonal X′ phase, and S phase formed from the GPB zones [24]. Also the tertiary Al-Cu-Mg-(Ag) alloys with high Cu:Mg ratio and very low Mg content lie in the α + θ region of the ternary phase diagram [25].

Sufficient literature is available regarding the microstructure of Al-Cu alloys in the wrought condition. However, few reports are available regarding the microstructure of these alloys in the as-cast condition and modification of the microstructure by subsequent plastic deformation. Addition of silver in very small amount can have profound influence on the microstructure and strength of Al-Cu alloys. The available literature regarding the mechanical properties of Al-Cu-Mg-Ag alloys revealed that the silver content in the investigated alloys are 0.3 wt% or more [19,21]. From the few reports available, it is not obvious whether better mechanical properties for Al-Cu alloys can be achieved with silver content less than 0.1 wt%. Among the Al-Cu alloys, 2219 Al alloy exhibits high fracture toughness, good weldability and are less resistant to stress corrosion cracking in addition to the fact that the strength and ductility can be tailored by heat treatment [4]. The present work is therefore, aimed at investigating the influence of micro-alloying with silver (0 < Ag < 0.1 wt%) on the microstructure, and mechanical properties of Al-6.4Cu-0.01Mg alloy (~ 2219 Al). The microstructure and mechanical properties of the alloys in the as-cast, rolled and different heat treatment conditions are studied and a comparison of the properties under various processing conditions is made with respect to the various amount of silver in the alloy.

Fig. 1. Photograph of the alloys after sand casting.

2. Experimental procedures

Al-Cu-Zn-Fe-Ti-Mg alloy (≈ 2219 Al-alloy) and 2219 Al-alloys containing varying amounts of silver (0 < Ag < 0.1 wt%) was prepared by casting technique. Cylindrical rods and rectangular slabs of the alloys were obtained by casting in sand molds and metallic molds, respectively. The starting materials used were commercially pure AA1100 (99.6% pure) Al alloy ingot, electrical grade copper (99% pure) rods and high purity silver (99.96% pure). Initially Al-42 wt% Cu and Al-6 wt% Ag master alloys were prepared independently. Known quantities of the Al-Cu master alloy along with AA1100 ingots were then melted in a melting furnace. As the melt temperature reached 700 °C, Al-Ag master alloy was added to adjust the composition of silver in the melt and stirred well to attain a homogenous melt composition. The melt was then degassed with degasser tablets to remove any dissolved gases. The molten metal was finally poured into the mold to obtain 20 mm diameter × 200 mm high cylindrical rods for the preparation of tensile samples (Fig. 1). For the rolling purpose the molten metal was poured into flat 300 mm × 100 mm × 10 mm sized metallic molds and solidified.

Four different alloy melts of Al-Cu-Zn-Fe-Ti-Mg alloy (≈ 2219 Al-alloy) with 0, 0.03, 0.07 and 0.1 wt% of Ag additions were processed for the present investigation. These alloys are designated as Alloy-A, Alloy-B, Alloy-C and Alloy-D, respectively. The chemical composition of the alloys was determined by atomic absorption spectrophotometer (AAS) Make: Varian, Model: AA240. The results of the chemical composition analysis of all alloys are shown in Table 1. Cylindrical dumbells shaped tensile samples were machined from the cast rods. The flat samples were machined to 300 mm × 30 mm × 10 mm sized bars for rolling. These were homogenized annealed at 510 °C in a resistance heated muffle furnace for 10 h and subsequently furnace cooled. The annealed bars were then preheated to 230 °C followed by soaking at this temperature for 1 h and then subsequently warm rolled to obtain 4 mm thick bars. The final thickness was obtained in 6 passes. After each pass, the sample was soaked in the furnace for 1 h to ensure uniform temperature during the rolling operation. The rolled samples were then solution heat treated at 525 °C for 10 h (hence forth referred to as solutionized) and subsequently water quenched. Flat tensile specimens

Table 1
Chemical composition (wt%) of alloys.

Alloy Designation	Cu	Fe	Zn	Mg	Ti	Mn	Ag	Al
Alloy-A	6.85	0.60	0.68	0.01	0.06	0.20	0	Bal.
Alloy-B	6.78	0.62	0.76	0.01	0.08	0.19	0.03	Bal.
Alloy-C	6.37	0.57	0.66	0.01	0.06	0.18	0.07	Bal.
Alloy-D	6.84	0.61	0.73	0.01	0.02	0.18	0.1	Bal.