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Dominance of Natural Aging over Artificial Aging in Enhancing the Hardening Response of a Lean Al-4%Cu-0.8%Mg Alloy

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ABSTRACT

This paper analyses how addition and heat treatment during precipitation of Magnesium additions influence the microstructure and hardness of the Al-Cu alloys. Two different alloys, binary Al-4.1%Cu and ternary, Al-4%Cu-0.8%Mg were cast and hot- rolled (50% reduction). Solution heat treatment (SHT) of the samples at 520 ℃ was followed by artificial aging (T6) at 180 ℃ for 12 h or natural aging (T4) at room temperature. These findings demonstrate that a minor addition of 0.8 wt.% Mg significantly enhances precipitation strengthening through the formation of the S phase (Al_2CuMg). The microstructure and mechanical characteristics of the Al-Cu alloy are less affected by the solution holding time than by the solution temperature. Microstructural examination showed that the Mg addition facilitates the S-phase (Al_2CuMg) formation which is a harder phase than the binary θ-phase (Al_2Cu). It was verified by X-ray diffraction (XRD) that the ternary alloy contains the S-phase. The results reveal that the ternary Al-Cu-Mg alloy in the naturally aged state (T4) had a maximum hardness of 128 HV1, which was superior to that of the as-cast and the artificially aged state. Also, the finding explained the use of customized heat treatment parameters to enhance performance Al-4%Cu-0.8%Mg for lightweight engineering and structural applications.

1. INTRODUCTION

High-strength aluminum alloys of the Al-Cu-Mg series are widely used in the aerospace industry. Due to its exceptional formability, corrosion resistance, high specific strength, high elastic modulus, and low density, it is currently one of the most widely used lightweight structural materials [1, 2].

Traditional Al-Cu-Mg alloys are well known for their high mechanical strength, fatigue resistance, and excellent machinability. Furthermore, their low density and resistance to corrosion enable dependable performance under severe service conditions [3].

There has been some research on the thermal stability of Al-Cu alloys, particularly those with extremely thin structures [4, 5].

The intermetallic phase θ, which generally has the formula Al_2Cu, is in equilibrium with the aluminum-rich terminal solid solution in the binary aluminum-copper system. The addition of magnesium can result in the formation of further intermetallic compounds, including Al_2CuMg, Al_6CuMg_4, and AlCuMg [6].

The steps in the precipitation hardening process are as follows [7-9]:

$$\text{SSSS} \rightarrow \text{GPB zones} \rightarrow \text{S}'' \rightarrow \text{S}' \rightarrow \text{S } (Al_2CuMg)$$

where,

- SSSS: Supersaturated solid solution.
- GPB zones: Guinier-Preston-Bagaryatsky zones.

Scholars have examined the precipitation behavior of aluminum alloys in the Al-Cu-Mg series, as well as the deformation behavior and crystal structure of the Al_2Cu phase [10, 11]. Copper is the most crucial element in this alloy. This alloy is composed of 1.2%–1.8% magnesium, 3.8%–4.9% copper, and 90.7–94.7% aluminum [12, 13]. Heat treatment significantly influences the properties of aluminum alloys because different elements in aluminum dissolve at different temperatures [14-16]. Techniques for precipitation hardening and grain refinement significantly enhance the alloy strength [5]. A heat treatment [17] or a shot peening procedure [18] can achieve these enhancements. Heat treatment, which comprises heating, holding, and quenching alloys to increase mechanical qualities such as hardness, toughness, strength, and ductility, can be used to enhance the performance of AA2024 alloy [19-21]. Precipitation treatment (i) causes the intermetallic Al_2Cu phase to dissolve in a metal alloy; (ii) produces a supersaturated solid solution when quenched at room temperature; (iii) causes age hardening to produce saturated solid solution precipitates at room temperature, as in natural aging (T4), and at extremely high temperatures, as in artificial aging (T6) [13]. The present study aims to investigate the precise impact of magnesium addition on the precipitation hardening response of aluminum-copper systems, in contrast to earlier research that concentrated on commercial alloy 2024.

In particular, this study examines the hardness variations and microstructural evolution of a binary Al-4.1%Cu alloy and a ternary Al-4%Cu-0.8%Mg alloy under both as-cast and wrought circumstances, after which they undergo natural (T4) and artificial (T6) aging treatments.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1 Alloy preparation

Melting and casting were used to create the binary Al-Cu (Alloy A) and ternary Al-Cu-Mg (Alloy B) alloys. In an alumina crucible, high-purity aluminum (99.99%) was melted at 750 °C in an electric resistance furnace (Carbolite, Japan). The melt was supplemented with precise weights of magnesium and pure copper (99.95%). A stainless steel rod was used to stir the melt, 2% CaF2 flux was used to degas it, and the mixture was then poured into a steel mold (dimensions: 40 × 50 × 150 mm).

An optical emission spectrometer (ARL) was used to examine the chemical composition, as indicated in Table 1.

Table 1. The prepared alloys' chemical composition (wt%)

WT % Element	Cu	Mg	Fe	Si	Mn	Ti	Al
Alloy A	4.09	0.06	0.31	0.2	0.01	0.004	Balance
Alloy B	4.01	0.8	0.31	0.2	0.01	0.004	Balance

2.2 Thermomechanical processing

To ensure compositional consistency, the ingots were homogenized for 2 h at 480 °C. After that, the ingots were hot-rolled at 460 °C to a 50% thickness reduction of 2 mm in order to remove casting defects and enhance the microstructure.

2.3 Heat treatment

The samples were quenched in water and subjected to solution heat treatment (SHT) for 15 minutes at 520 °C. They were then subjected to two aging treatments:

T4 condition: kept for seven days at room temperature.

T6 condition: aged at 180 °C for 12 h.

2.4 Hardness and microstructural characterization

Alumina (Al_2O_3) suspension was used to polish the test samples after they had been wetted under silicon carbide (SiC) paper 220-1000. Keller reagent (1.5 mL HCl + 1 mL HF + 2.5 mL HNO_3 + 95 mL distilled water) was used to etch the microstructure. An optical microscope (MeF_2) was used to perform the optical microscopic analysis. According to ASTM E92, the Vickers hardness (HV1) was measured with a force of 1.0 kg and a dwell duration of 20 s.

3. RESULTS

The microstructural development and mechanical performance of the ternary Al-4%Cu-0.8%Mg alloy (designated Alloy B) and binary Al-4.1%Cu alloy (designated Alloy A) under various processing regimes are explained in the following sections.

3.1 Microstructural development and phase analysis

As-Cast and Homogenized Conditions: Figures 1 and 2 present optical micrographs of the as-cast materials that have a typical dendritic structure. In the binary Alloy A (Al-4.1%Cu), the microstructure is primary α-Al dendrite in the presence of a network of interdendritic eutectic θ (Al_2Cu) phase that is spread with grain boundaries. The use of 0.8%Mg in alloy alters the structure of solidification, which favors the development of ternary phases. There is a non-linear strengthening response as shown by a comparative analysis between the binary and ternary Al-4.1%Cu (Alloy A) and Al-4%Cu-0.8%Mg (Alloy B). In the homogenized state, 0.8% Mg is added and the hardness (45 HV1 to 55 HV1) then increases by a small percentage of 22, which can be credited to solid-solution strengthening. Under the peak-aged state, the equivalent magnesium is added, which provides 28 percent superiority to the binary counterpart (128 HV1 vs 100 HV1).

Effect of Mg addition: These results demonstrate that a comparably small addition of Mg (0.8) is an enhanced precipitation strengthening behavior, which alters the phase thermodynamics such that a larger fraction of the product is in the S-phase (Al_2CuMg). This observation has been in favor of the creation of lean-alloy compositions that not only maximize mechanical performance but also reduce alloying costs. The existence of the undissolved Al_2Cu phases implies that the homogenization parameters were insufficient to completely dissolve the non-equilibrium eutectic phases that were created during rapid cooling of the metal-mold cast.

Wrought Structure and Grain Refinement: The microstructure was significantly changed by a 50% thickness reduction at 460 °C through hot rolling. Mechanical deformation disturbed the dendritic network which was coarse as cast and re-allocated the intermetallic particles evenly around the matrix. This thermomechanical treatment presumably caused dynamic recovery, and in the process, this refined the grain size. The change in the coarse structure into a refined wrought structure is the main factor that leads to the increase in the baseline on the mechanical properties between the cast and the wrought specimens.

X-ray diffraction (XRD) Phase Identification: The phase constituents identified by XRD are consistent with the phase diagrams. In the as-cast spectrum, the peaks are sharp reflecting the presence of the (alpha)-Al matrix, and clear peaks are also observed and attributed to the equilibrium phases.

3.2 Phase transformation analysis

As-cast and homogenized: The optical micrographs of Figures 1 and 2 of the as-cast alloys reveal a typical dendritic microstructure.

The microstructure of the binary Alloy A (Al-4.1%Cu) consists of primary (α)-Al dendrites in an environment where there is a network of interdendritic eutectic phase.

Homogenization treatment was performed at 480–500 °C for 2 h to reduce micro-segregation. Nonetheless, even in Figures 3 and 4 the dissolution of the coarse intermetallic network was not obtained entirely. The fact that the un-dissolved Al_2Cu phases did not entirely disappear indicates the homogenization parameters were not enough to dissolve completely the non- equilibrium eutectic phases that had developed when the permanent mold casting was rapidly cooled.

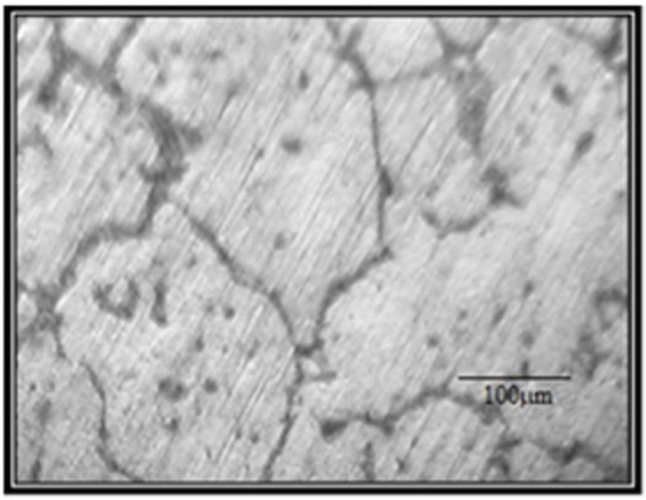

Figure 1. The microstructure of Alloy A_1 (Al-4.1%Cu) (as- cast + homogenized)

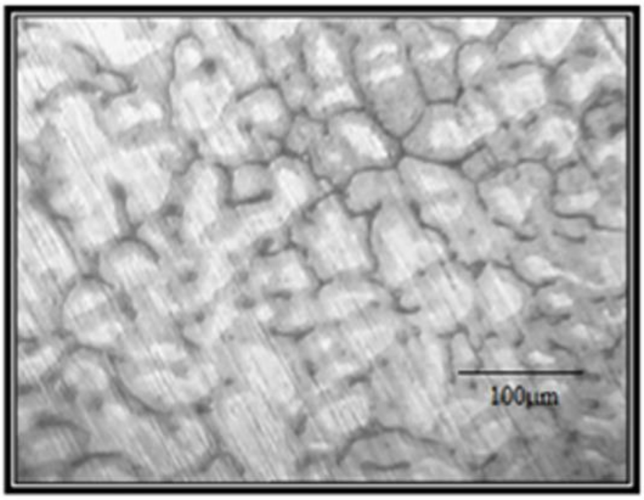

Figure 2. The microstructure of Alloy B_1 (Al-4%Cu-0.8%Mg) (as- cast + homogenized)

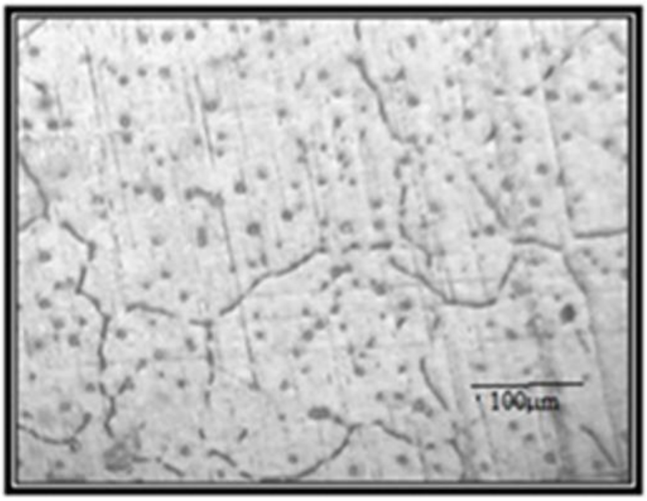

Figure 3. The microstructure of Alloy A_2 (Al-4.1%Cu) (as-cast + SHT + aging at 180 °C for 12 h)

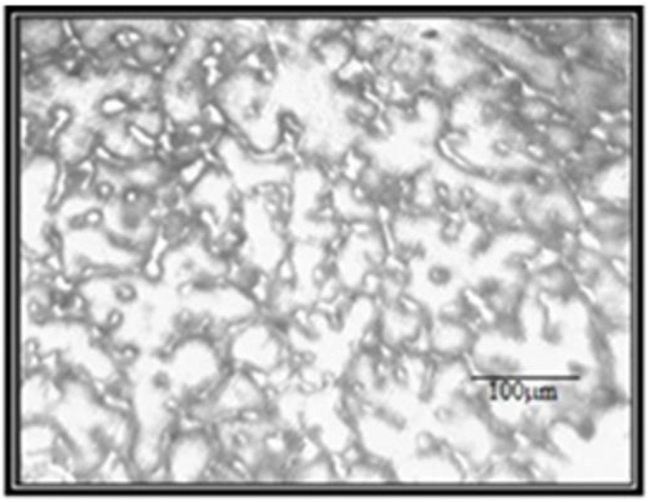

Figure 4. The microstructure of Alloy B_2 (Al-4%Cu-0.8%Mg) (as- cast + SHT + aging at 180 °C for 12 h)

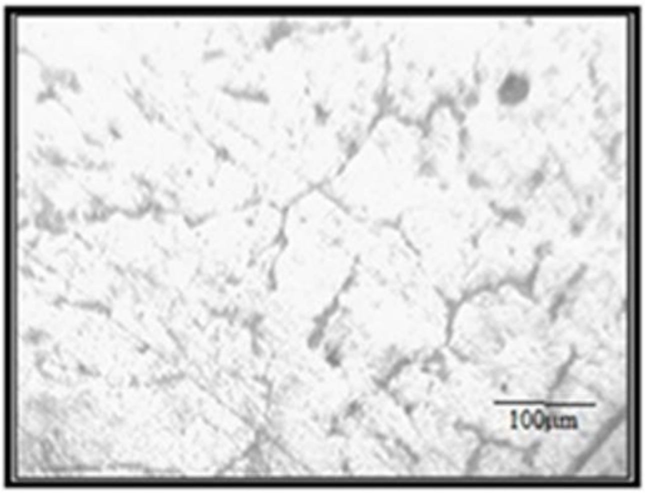

Figure 5. The microstructure of Alloy A_4 (Al-4.1%Cu) (as wrought + Solution heat treated + aging at 25 °C for 7 days)

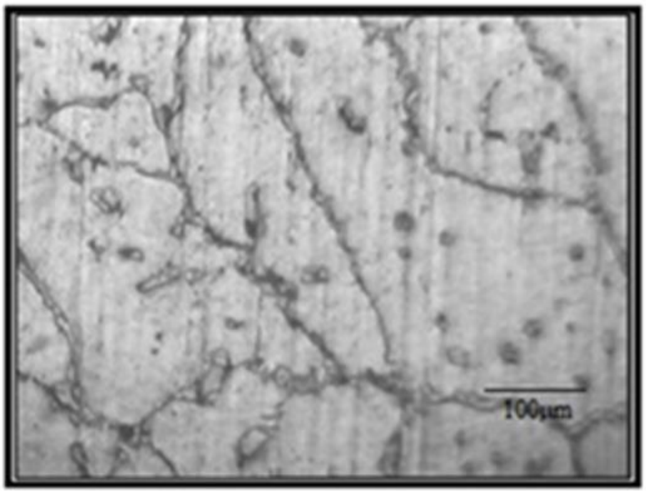

Figure 6. The microstructure of Alloy B_4 (Al-4%Cu-0.8%Mg) (as wrought + solution heat treated + aging at 25 °C for 7 days)

Hot rolling at 460 °C with a 50-percent reduction had significant changes on the microstructure as determined by Figures 5 and 6. Hot rolling disrupted the coarse dendritic cast structure and promoted a more homogeneous distribution of intermetallic particles, which caused the intermetallic particles to be more evenly spaced throughout the matrix. This thermomechanical processing probably aided dynamic recovery, which resulted in the refinement of the grains. The replacement of a coarse cast microstructure with a refined wrought microstructure is a major factor that is attributed to the difference in mechanical properties between the cast and the wrought specimens.

3.3 X-ray diffraction phase identification

The phase constituents as predicted by the equilibrium phase diagrams are supported by the X-ray diffraction (XRD) patterns (Figures 7 and 8). The as-cast (Figure 7) spectrum exhibits strong diffraction peaks that are associated with the α-Al matrix with clear peaks of the equilibrium Al_2Cu (θ) and S-phase (Al_2CuMg) phases. Another SHT followed by aging (Figure 8) demonstrates the continuation of these phases, hence proving that the aging process has effectively precipitated the S phase (Al_2CuMg). The S phase has been identified as is significant since it is the main strengthening stage in Al-Cu-Mg alloy and it provides better dislocation glide barriers than the θ phase present in the binary.

This finding is repeated after SHT and aging (Figure 8). The selective precipitation of the S phase (Al_2CuMg) is confirmed. The discovery of the S-phase residues is still of paramount significance since it gives Al-Cu-Mg systems superior mechanical strength due to the presence of strong barriers to dislocation movement, which is higher than that of the binary θ phase.

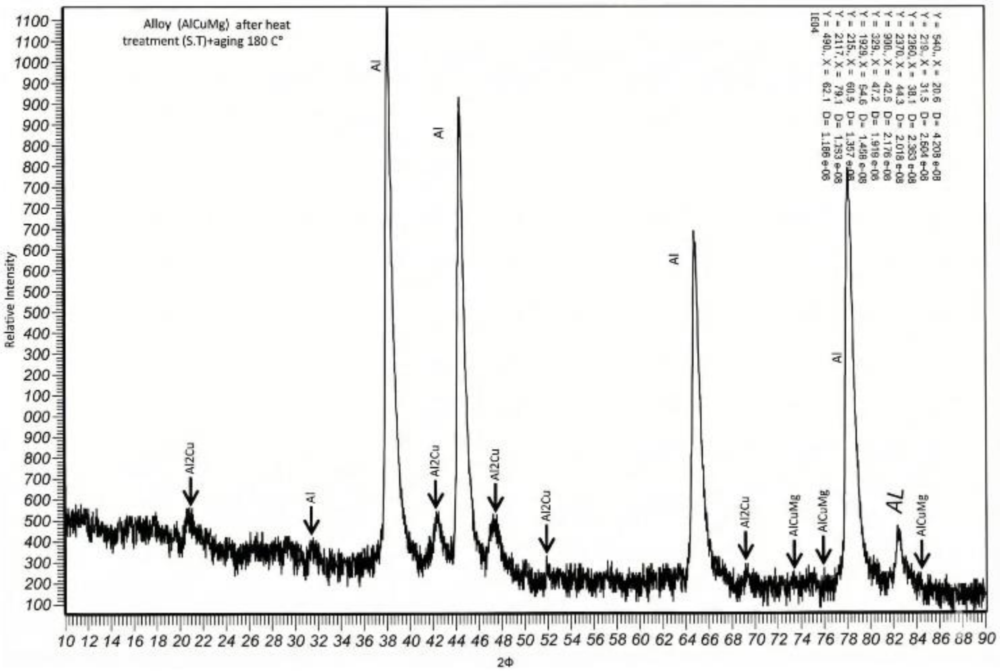

Figure 7. X-ray diffraction (XRD) chart for alloy (Al-Cu-Mg) as- cast homogenized

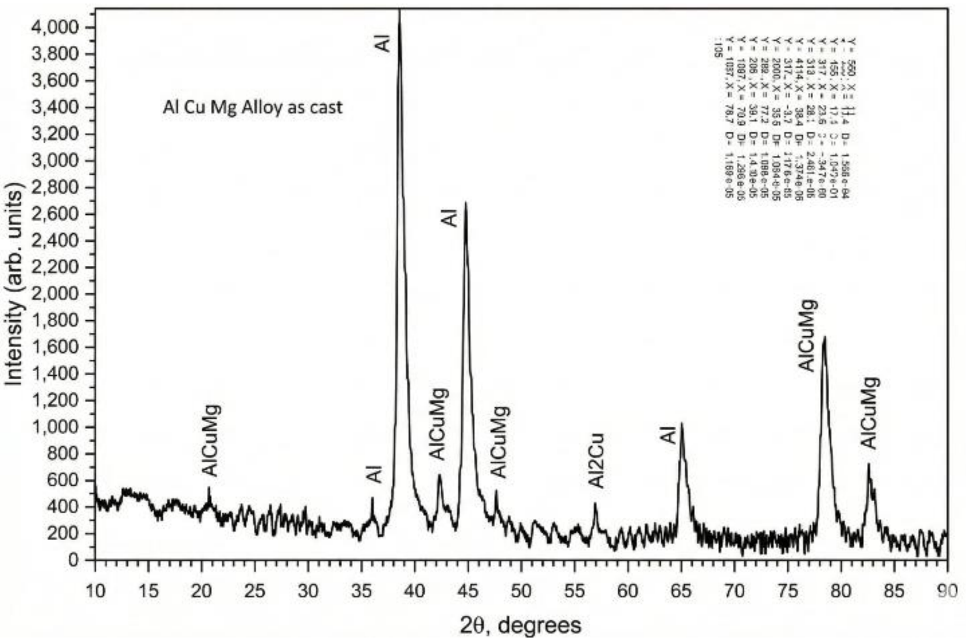

Figure 8. X-ray diffraction (XRD) chart for alloy (Al-Cu-Mg) after heat treatment

Table 2. The hardness values for two groups of Alloys (A and B) following precipitation heat treatments

Samples		Hardness kg/ mm^2	Samples		Hardness kg/ mm^2
Cast	A1	45	Cast	B1	55
	A2	89		B2	110
Wrought	A3	93	Wrought	B3	121
	A4	100		B4	128

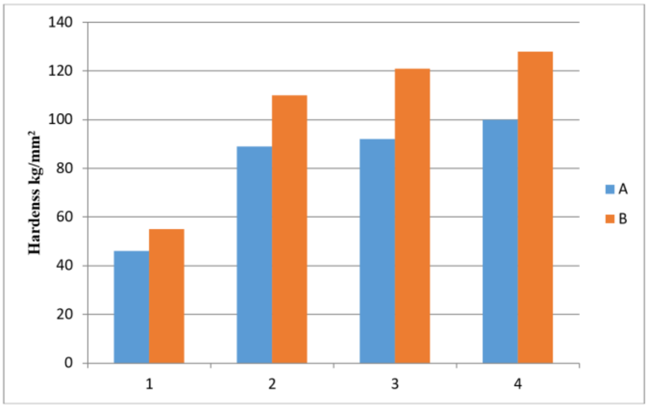

Figure 9. The hardness data from Table 2 for Alloys A and B

3.4 Hardness analysis and strengthening mechanisms

The combined effects of solid-solution strengthening, strain hardening, and precipitation hardening can be evidenced by the Vickers hardness measurements, which have been summarized in Table 2, as well as plotted in Figure 9.

1. Effect of Magnesium (Solid Solution Strengthening)

A comparative study of the two alloys in different conditions shows that the Al-4Cu-0.8Mg alloy (Alloy B) has always exhibited a high degree of hardness as compared to the binary Al-Cu alloy. As an example, the hardness of Alloy B in the as-cast state is 55 HV1, whereas Alloy A gives a value of 45 HV1. It is explained by solid solution strengthening, magnesium atoms (atomic radius 0.160 nm) impose a strain on the lattice of the aluminum matrix (atomic radius 0.143 nm), and prevent dislocation motion even before the aging process sets in.

2. Effect of Thermomechanical Processing (Cast vs. Wrought)

Greater hardening was found in the wrought specimens compared to the cast specimens. In the case of Alloy B, the hardness of the material increased to 121-128 HV1 (Wrought B3/B4) after the heat-treatment, as compared to 110 HV1 (Cast B2). This advancement is due to strain hardening and Hall-Petch effect. The rolling reduction of 50-percent makes the dislocation density high and the grain structure is refined; thus, increasing the grain-boundary area. The increased grain-boundary area is resistant to the dislocation glide, thus, increasing the material strength.

3. Effect of Precipitation Hardening (Aging Response)

SHT and aging gave the greatest hardness values.

- Alloy A (Al -Cu): Hardening is controlled by the order of the precipitation process (SSSS) → GP zones → θ” → θ’ → θ Sample A4 reached a hardness of 100 HV1, which means that coherent and semi-coherent precipitates were formed and slowed down the glide of dislocations via the Orowan mechanism.
- Alloy B (AlCuMg): Mg is added and the sequence of precipitation is altered to preclude the S-phase (Al$_2$CuMg). The highest hardness was 128 HV1 in sample B4. The pinning of dislocations is more effective by the S-phase precipitates as compared to the binary θ phases, hence the improved mechanical properties.

4. Comparison of Aging Regimes

Surprisingly, the samples that were subjected to natural aging (T4 condition, 7 days at room temperature) had slightly higher hardness than the samples subjected to artificial aging (180 °C for 12 h). In the case of Alloy B, natural aging (Sample B4) gave 128 HV1 and artificial aging (Sample B3) gave 121 HV1. This is an indication that the 180 °C for 12 h artificial aging state might have resulted in slight overaging or if the precipitate distribution was coarser as compared to the fine GPB zones and S/ clusters that naturally occur when alloys made of 2xxx series are allowed to age naturally.

4. CONCLUSION

The microstructural characteristics and hardness development of the Al-4.1%Cu and Al-4%Cu-0.8%Mg alloys under cast, wrought, and age-hardened processing conditions were examined in the current study.

The conclusions drawn are as follows:

1. X-ray diffraction (XRD) of the microstructure study confirms that the S-phase (Al$_2$CuMg) is established when magnesium is added to the Al-Cu alloy system.
2. The as-cast dendritic microstructure was effectively refined through hot rolling, which was carried out at a 50% strain of the microstructure. This resulted in a refined microstructure that exhibited improved mechanical properties.
3. Magnesium role: In terms of hardness, the ternary Al-Cu alloy consistently outperformed the binary Al-Cu alloy. Both the solid-solution hardness of magnesium atoms and the development of the potent S-phase (Al$_2$CuMg) during aging account for this high value.
4. Optimal Condition: The experiment showed that the best mechanical performance was obtained by solution heat treating wrought Al-4%Cu-0.8%Mg alloy (Alloy B) at 520 °C, followed by seven days of natural aging (T4). 128 HV is the optimal hardness. The condition offered a better balance of hardness than the conditions in casts or the particular artificial aging cycle (180 °C for 12 h) evaluated in this study.
5. Scientific contribution: When combined with natural aging (T4), thermo-mechanical processing (rolling) works particularly well in applications requiring the highest possible surface hardness in aluminum equivalents from the 2xxx family.

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NOMENCLATURE

GPB	Guinier-Preston-Bagaryatsky
XRD	X-ray diffraction
HV1	Vickers hardness for 1 kgf
SSSS	Supersaturated solid solution