International Journal of Mechatronics and Applied Mechanics
2025, Issue 21, Vol. 1

THE EFFECT OF SILVER ON THE OROWAN STRENGTHENING OF AL-MG-AG ALLOYS AFTER THERMO-MECHANICAL PROCESSING

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Abstract - Strengthening process of Al-Mg-Ag alloys after thermo-mechanical processing is important for enhancing the mechanical properties of alloys that used in automotive and aerospace and applications. Understanding how silver affect mechanism of strengthening allows for the development of stronger and lighter materials, enhancing the durability and performance in demanding environments. This study investigates the influence of silver content (0.75%, 1%, and 1.5%) and thermo-mechanical processing parameters on the mechanical properties and fracture behavior of Al-Mg-Ag alloys. Through systematic experimentation, the effects of cold rolling and aging treatments at various temperatures (150°C, 180°C, and 210°C) and durations (6h, 12h, and 24h), were examined. The results demonstrated that the optimal mechanical properties were achieved with 1.5% Ag content aged at 150°C for 24 hours, yielding an ultimate tensile strength of approximately 310 MPa while maintaining reasonable ductility. The fractographic analysis showed different failure mechanisms across different processing conditions: the rolled specimens showed characteristics of the predominantly brittle fracture, while aged specimens and solution-treated showed the main features of the ductile. The advancement in mechanical properties is attributed to the effective Orowan strengthening through the finely dispersed precipitates formation, whose morphology and distribution are significantly affected by both processing parameters and silver content. These results provided valuable insights into the optimization methodologies of Al-Mg-Ag alloys for structural applications that require high strength-to-weight ratios.

Keywords: Al alloys, Thermo-mechanical processing, Design of experiment (DOE), Mechanical behavior, Fracture morphology, Hardness test.

1. Introduction

A The development of high-strength Al alloys is still in demand for aerospace and automotive industries where the priority is to reduce the weight of the parts as well as enhance their mechanical properties [1], [2]. Al, which is a good conductor, lightweight and similar in terms of properties to copper, possesses diverse properties, such as corrosion resistance and being easily cast, and is suitable for the production of products for consumers [3], [4], [5]. Further, Al is an eco-friendly choice, as due to its high recyclability and energy-demanding production technique [6]. Nevertheless, the softness and inferior strength of pure Al restrict its explicitness as of other metals [7]. On the other hand, Al is difficult to weld, especially with resistance welding, because of its very high thermal conductivity and the oxide layer [8]. Al alloys can be significantly modified regarding their mechanical properties by other element addition through alloying and formation of some structures during solidification, heat treatment, and cold working [9], [10].

While Al-Mg alloys have remained the subject of extensive investigation, the role of silver as a microaddition in enhancing their mechanical

dx.doi.org/10.17683/ijomam/issue21.23

properties by mechanisms of Orowan strengthening is worth investigating in detail [11]. By addition of silver (Ag) and rolling operations, significant enhancement can be achieved in properties of Al-magnesium (Al-Mg) alloys [12], [13]. Ag addition fosters the formation of ultrafine dispersed rod-shaped and granulate-form phases in the matrix during aging [14]. Concurrently, rolling grain refines, resulting in elevated strength, improved ductility, and grain orientation effect [15], [16]. Combined application of silver and controlled rolling offers an efficient means of developing Al-Mg alloys and acquiring advanced properties.

In binary alloys, Al-Mg alloys have attracted both scientific interest and industrial use. The alloys are characterized by their excellent formability, corrosion resistance, surface properties, and weldability and machinability [9]. Their efficacy as strengtheners is, however, constrained because of their interaction with averaged precipitates [20]. Previous studies have extensively explored age-hardening in Al-Mg alloys, with a focus on examining the phase diagram [18], [21], [22], [23]. The findings reveal that alloys containing 7% to 10% magnesium exhibit relatively low age-hardening compared to precipitation hardening alloys like Al-Cu [23]. Conversely, alloys with less than 5% magnesium show minimal age-hardening effects [22]. It is important to note that the addition of magnesium as an alloying element leads to a softening effect, which becomes more pronounced as the level of stress decreases [17]. While magnesium has little impact on the open circuit potential of Al in solid solution, it plays a crucial role in enhancing corrosion resistance by slowing down the rate of the cathodic reaction [24]. As the magnesium content in Al-Mg alloys increases, the mechanical properties show progressive improvement [25]. However, in industrial wrought alloys, the magnesium content is typically limited to 5 wt.% due to stability concerns, especially at elevated temperatures. It is recommended to restrict the magnesium content to a maximum of 5 wt.% in wrought alloys to prevent sensitization to intergranular corrosion and stress corrosion cracking, which can be caused by the precipitation of the β-phase $Al3Mg2$ at grain boundaries [26]. Alloys with higher magnesium contents are more susceptible to intergranular corrosion and stress corrosion, leading industrial alloys to strictly adhere to the 5 wt.% limit to mitigate these concerns [27].

The substructure of Al-Mg alloys is similar to that of Al, but with a smaller subgrain size, approximately one-fifth of Al, due to increased stress levels. Under stress, Al-magnesium alloys exhibit complex substructures influenced by alloying elements and stress conditions, resulting in dislocation arrangements and subgrain formation [28]. It is worth noting that pre-existing dislocations can serve as preferred nucleation sites for precipitates, and plastic deformation can be used to control the distribution of dislocations and precipitates. Therefore, it is crucial to characterize the microstructures of as-quenched alloys, particularly in terms of pre-existing defects or defect clusters and their distribution [29]. At high temperatures, true stress-strain curves of Al-Mg alloys display decreasing stress levels, increased ductility, and dependence on strain rate [30]. However, it is important to be cautious with sensitized Al-Mg alloys, especially those with higher magnesium content, as they are prone to stress corrosion cracking [31]. Additionally, hot cracking is a common welding defect in Al alloys with wide solidification ranges, although mitigating measures can be implemented through modifications to the alloy composition [32].

Orowan strengthening in Al-Mg alloys arises from the uniform dispersion of dimensionally stable hard particles, like precipitates or nanoparticles, within the metal matrix [33]. These hard particles act as obstacles, hindering the motion of dislocations during deformation and impeding plastic flow. As a result, the presence of these reinforcing particles significantly enhances the strength and hardness of the Al-Mg alloy, thereby improving its mechanical properties [34]. Addition of Ag in Al-Mg alloys precipitates the Ag2Al phase, which is accountable for alloy strengthening through Orowan strengthening and solid solution strengthening mechanisms [33]. Silver atoms incorporated into the Al matrix occupy lattice sites, preventing the movement of dislocations and causing increased alloy strength. Furthermore, Ag enables the formation of elliptical-shaped Guinier-Preston (GP) zones during the early-aged stage, which transform into a metastable MgAg phase [35]. The effectiveness of Orowan strengthening relies on several parameters, including the volume fraction of solute, solute distribution within the grain, and the coarse grain size. Among these, the most significant influence on Orowan strengthening is the volume fraction of solute, followed by solute distribution, and then coarse grain size [36]. These variables need to be carefully controlled in order to maximize the strengthening effect and achieve a good balance between strength and ductility. One of the unique advantages of Orowan strengthening is that it can be combined with low-temperature surface hardening. This synergy allows one to achieve a simultaneous realization of both surface and bulk property development of the alloy in a single processing step [33]. By carefully optimizing alloy composition and processing conditions, manufacturers can achieve an optimum balance between strength, ductility, and surface hardness.

Though Orowan strengthening is the cause of enhancement of mechanical properties of Al alloys, its effect may vary for the specific alloy and microstructural characteristics. For example, in some composites, the Orowan strengthening may be negligible due to coarser reinforcing particles as well as wide particle spacing [37]. However, the presence of microscopic insoluble particle dispersions can still improve creep resistance and mechanical properties in certain cases [38].

The addition of silver (Ag) to Al-magnesium (Al-Mg) alloys has significant effects, demonstrating high solid solubility in Al, reaching up to 55% [14]. While using binary Al-silver alloys is limited due to cost considerations, incorporating small amounts of silver proves effective in enhancing the strength and stress-corrosion resistance of Al-magnesium alloys [39]. Moreover, Ag's large atomic number difference from Al makes it particularly useful for studying the fundamental processes of decomposition in supersaturated alloys [40]. Despite this potential, Al-Ag alloys with very low Ag concentrations have received limited attention, and the mechanism of formation and migration of Ag clusters in these alloys remains unclear.

One of the notable contributions of Ag to Al-Mg alloys lies in its positive impact on hardening effects. Ag induces new precipitation or stimulates existing precipitates, resulting in increased strength and hardness [41]. Moreover, Ag may enhance ductility, reduce the width of precipitate-free zones, and inhibit solute atom migration to grain boundaries during the aging process [42]. In Al-Mg-Ag alloys, the addition of Ag promotes the formation of elliptical-shaped Guinier-Preston (GP) zones at the early-aged stage, which later transform into the metastable MgAg phase and T phase. Upon addition of Ag to Al-Mg base alloys, there are finer precipitates formed in the matrix, and the strength is appreciably enhanced [39]. Besides, Ag atoms have strong affinity for vacancies and therefore Ag–V complexes are formed, enabling the formation of GP zones [43]. Fracture toughness of Al-Mg-Zn alloys is affected by the addition of Ag.

While 0.2 wt% Ag improves the fracture toughness, higher Ag content weakens the alloy's fracture resistance due to the presence of coarse particles acting as potential sources of cracks or microvoids [44]. The addition of Ag also influences the interaction between metal particles (MPts) and dislocations in Al-Mg-Zn alloys. Ag alters the strength effect of dislocation movement through MPts without changing the type of MPts present [44].

The initial experiments exploring the microalloying of Ag in Al-5% Mg alloys demonstrated a limited or negligible age-hardening response [45]. However, recent studies have shown that the addition of Ag can effectively induce age-hardening in the binary alloy. Similarly, in alloys with higher magnesium content, such as 10% Mg, microalloying with Ag significantly improves the modest age-hardening response observed in the binary alloy [46], [47].

The influence of cold working on the aging behavior of Al-Mg alloys has also been investigated. While a 5% strain did not notably enhance the age-hardening response in an Al-10% Mg alloy, cold work had the opposite effect on an Al-8% Mg alloy, indicating an increase in hardness with increasing cold reduction [48]. However, there is a lack of experimental research on the impact of cold work on the precipitation hardening response in Al-Mg-Ag alloys.

In terms of corrosion resistance, the addition of Ag inhibits the formation of the β phase (Al3Mg2) along the grain boundary and raises the corrosion potential of Al-Mg alloys, thereby improving their intergranular corrosion resistance [49]. Ag addition also leads to the formation of various precipitates, including granulate-shaped, rod-like, and disk-like phases. These precipitates contribute to improved mechanical properties, such as ultimate tensile strength (UTS) and yield strength (YS), during aging [14]. At the peak-aged stages, Ag-bearing alloys exhibit higher intergranular corrosion resistance compared to Ag-free alloys [50].

Previous research has primarily focused on conventional precipitation hardening in Al-Mg systems, leaving a significant knowledge gap regarding silver's influence on dispersoid formation and distribution during thermomechanical processing. The unique interaction between silver atoms and magnesium clusters during deformation and subsequent heat treatment could potentially offer new pathways for microstructural control. This study investigates how varying silver concentrations affect the formation, size distribution, and spatial arrangement of strengthening particles in Al-Mg-Ag alloys subjected to specific thermomechanical processing routes. Understanding these mechanisms is essential for designing next-generation Al alloys with optimized strength-to-weight ratios. Our research combines advanced characterization techniques with systematic processing parameter variation to elucidate the fundamental relationships between silver content, processing conditions, and resultant mechanical properties.

2. Materials and Methods

A 20 mm diameter rod shape Al alloy was used in this research study. The chemical composition of the used Al alloy is listed in Table 1. Firstly, the rod samples were cut in sheets using wire cut electric discharge machining (EDM) method then the sheets were ground and polished to remove the scratches and residual stresses on the surfaces of the sheets. Afterward, the sheets annealed at the temperature of 400°C in order to homogenize the microstructure of the material. Furthermore, cold rolling and aging processes were conducted to observe the effect of thermo-mechanical processing on the mechanical behavior of the samples with different percentage of Ag. Rolling was applied at the room temperature with the thickness reduction rate of 0.05 mm/pass. 50% thickness reduction conducted for all the samples and the thickness of the sheets reduced from 4 mm to 2 mm after rolling process.

Table 1. Chemical compositions of different Al alloys utilized in the research study.

Alloy	**Chemical Composition (wt. %)**		
	Al	Mg	Ag
Type 1	Bal.	3	0.5
Type 2	Bal.	3	1
Type 3	Bal.	3	1.5

The aging process were conducted using electric resistance furnace at different temperatures of 150°C, 180°C, and 210°C. Also, durations of the aging were selected as 6h, 12h, and 24h for all the samples with different Ag percentage. The samples were cut using EDM from the rolled and heat-treated samples and subsequently ground and polished to remove the residual stresses before tensile testing. Hydraulic mechanical testing frame was utilized to test the tensile behavior of the samples at room temperature. 10^{-3} s^{-1} strain rate was employed to investigate the tensile properties of all the conditions under the quasi-static loading condition. Scanning electron microscopy (SEM) was employed to study the fracture morphology and fracture mechanism of the specimens with different conditions.

2.1 Hardness Test

Hardness testing of samples of aluminum magnesium silver alloys was conducted by Vickers hardness test method with the assistance of ARS9000 fully automatic micro hardness test system (Future Teach, FM-300e, Kanagawa, Japan) with a load of 1000 g for 5 seconds. Three observations on each of the samples were done and the average is provided.

3. Results and Discussion

3.1 Hardness Measurements

Figure 1 illustrates the values of hardness for the various percentages of silver (Ag) addition, demonstrating a considerable trend for mechanical enhancement. Silver addition to aluminum-magnesium alloys greatly changes their mechanical behavior, primarily through age-hardening-based mechanisms. The precipitation of silver-containing phases plays an important role in this enhancement. The formation of specific microstructures, such as MgAg and T-Mg32(Ag,Al) [49], is accountable for the overall alloy performance. These precipitates not only refine the microstructure but also enable a more uniform distribution of stress in the matrix, leading to the hardness improvement for all the tested silver contents. In addition, the observed improvement in the hardness values, as evident from the figure, suggests that the optimal content of silver can result in significant mechanical advantages. Statistical error bars in the graph reveal the existence of variability in the hardness values, possibly due to processing conditions and homogeneity of the alloy. Nevertheless, the overall trend depicts a linear correlation between silver content and hardness, revealing the efficacy of silver as a strengthening agent.

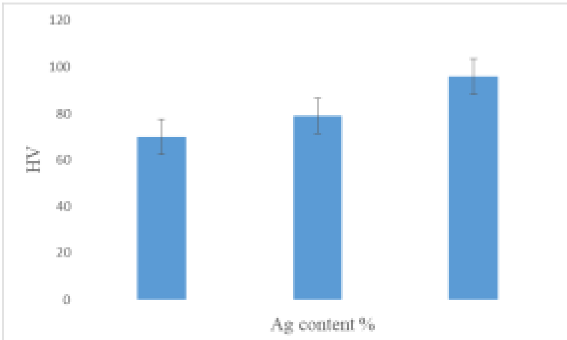

Figure 1: the relation between hardness values and Ag content

3.2 Mechanical Behavior

Mechanical properties of Al-Mg-Ag alloys with different percentages of Ag were examined using Vickers hardness testing and tensile testing. It was shown that the introduction of a small percentage of the Ag element played an important role in increasing tensile strength. This is due to the introduction of precipitates in the system with the addition of the Ag particles, which act as very good barriers for dislocation motion, leading to improved strength. The tensile strength and hardness increased with higher Ag content, which proved enhanced Orowan strengthening of the alloys. This result is in agreement with previous studies that observed positive improvement in mechanical properties due to additions of Ag in Al-Mg alloys [41-51].

Fig. 2 shows the stress-strain curves of Al-Mg-Ag alloys of various Ag percentages at as-received and O conditions. The findings show great disparities in mechanical properties between As-Received and O-Condition samples of Al-Mg alloys of different silver content. In the As-Received condition, the alloys demonstrate superior mechanical properties, with the 0.75% Ag composition achieving the highest ultimate tensile strength of approximately 210 MPa. This strength advantage in the As-Received condition suggests an optimized microstructure resulting from the initial processing conditions. When examining the effect of silver content, an interesting trend emerges. In the O-Condition samples, increasing the silver content to 1% leads to improved strength compared to the 0.75% composition. However, further increasing the silver content to 1.5% shows no additional benefits, indicating a possible saturation effect in the strengthening mechanism. Conversely, in the As-Received condition, the highest strength is achieved with 0.75% silver content, and increasing silver concentration actually results in a decrease in overall strength.

The ductility characteristics also show marked differences between the two conditions. The As-Received samples exhibit superior elongation to failure, reaching strains of approximately 0.15-0.16. In contrast, the O-Condition samples show reduced ductility, with failure occurring at strains between 0.06-0.08. All samples demonstrate typical work hardening behavior, though this effect is more pronounced in the As-Received condition.

The consistency in the initial slope of all curves indicates that the elastic modulus remains relatively unchanged across different compositions and conditions. This observation suggests that the primary differences in mechanical properties arise from variations in the plastic deformation behavior. Overall, the results indicate that the processing history (As-Received versus O-Condition) has a more substantial impact on the mechanical properties than variations in silver content.

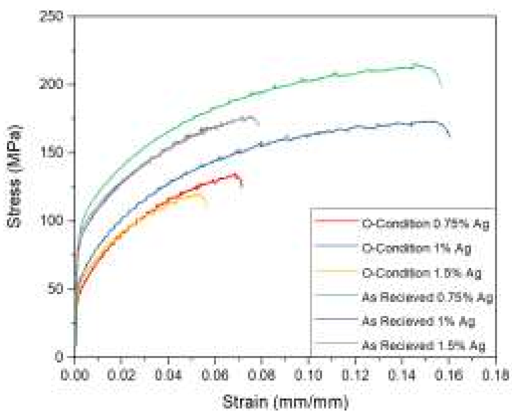

Figure 2: Stress-strain curves of Al-Mg-Ag alloys with different Ag percentages at as-received and O conditions

The stress-strain curves reveal distinct mechanical behaviors between rolled and O-condition Al-Mg-Ag alloys across different silver concentrations, which can be explained through fundamental deformation mechanisms and microstructural characteristics as shown in Fig. 3. In the rolled condition, all compositions exhibit significantly higher yield and ultimate tensile strengths (reaching ~270-280 MPa) compared to their O-condition counterparts. This enhancement can be attributed to several strengthening mechanisms: (1) strain hardening from the rolling process, which introduces a high density of dislocations, (2) grain refinement through dynamic recrystallization during rolling, and (3) potential formation of deformation-induced precipitates that act as obstacles to dislocation motion. The 1.5% Ag composition shows marginally higher strength, suggesting effective solid solution strengthening and possibly enhanced precipitation during deformation.

However, the rolled samples demonstrate limited ductility (strain ~0.02-0.04), characteristic of heavily cold-worked materials. This behavior results from the reduced dislocation mobility due to the high dislocation density and strong dislocation-precipitate interactions. The rapid work hardening observed in the plastic region indicates strong dislocation-dislocation interactions and limited recovery processes.

In contrast, the O-condition samples exhibit substantially lower strength (130-170 MPa) but significantly improved ductility (strain ~0.14-0.16). This trade-off reflects the annealed microstructure with: (1) lower dislocation density, (2) larger grain size, and (3) dissolution or coarsening of strengthening precipitates. The 1% Ag composition in O-condition shows slightly superior strength-ductility combination, suggesting an optimal concentration for balanced precipitation strengthening without excessive solute clustering that might embrittle the matrix. The distinct elastic-plastic transition between the two conditions also indicates fundamental differences in the initial microstructural state and subsequent deformation mechanisms. The rolled samples show a sharp yield point, suggesting strong pinning of existing dislocations, while the O-condition samples exhibit more gradual yielding, consistent with homogeneous dislocation nucleation and motion in an annealed matrix.

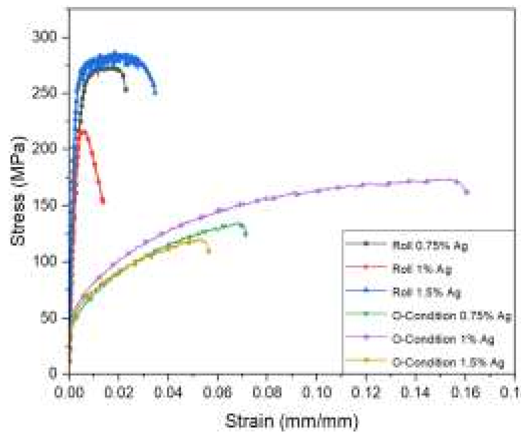

Figure 3: Stress-strain curves of Al-Mg-Ag alloys with different Ag percentages at O-condition and after rolling.

The stress-strain curves demonstrate the complex interplay between silver content, aging temperature, and aging duration in rolled Al-Mg-Ag alloys (Fig. 4).

The mechanical properties show distinct variations across different processing conditions, with the 1.5% Ag composition aged at 150°C for 24 hours exhibiting the highest ultimate tensile strength of approximately 310 MPa. This superior strength performance suggests an optimal combination of silver content and aging parameters that promotes effective precipitation strengthening.

When analyzing the aging temperature effects, samples aged at lower temperatures (150°C) generally show higher strength levels compared to those aged at higher temperatures (210°C) for the same silver content. This behavior indicates that lower aging temperatures likely promote the formation of finer, more densely distributed precipitates that contribute more effectively to strengthening. The aging duration also plays a crucial role, with longer aging times (24 hours) typically resulting in better strength properties at lower temperatures, while shorter aging times (6 hours) appear more effective at higher temperatures.

The ductility characteristics vary significantly across the different processing conditions. Most samples show relatively limited elongation, with strain at failure ranging between 0.04-0.10. Notably, the 1.5% Ag sample aged at 150°C for 24 hours not only achieves the highest strength but also maintains reasonable ductility with strain extending to about 0.10. This suggests a well-balanced microstructure that effectively combines strength and ductility. All compositions display similar elastic behavior, as evidenced by the comparable initial slopes of the stress-strain curves. However, the work hardening behavior varies considerably depending on the processing conditions, with some samples showing more pronounced strain hardening than others. This variation in work hardening rates indicates different dislocation-precipitate interaction mechanisms influenced by the aging parameters and silver content.

The stress-strain curves for the Al-Mg alloy with 1.5% Ag content demonstrate clear variations in mechanical behavior across different aging temperatures and durations (Fig. 5). The sample aged at 150°C for 24 hours exhibits the highest ultimate tensile strength, reaching approximately 310 MPa, while maintaining good ductility with strain extending to about 0.10. This condition appears to represent the optimal aging parameters for maximizing strength in this alloy composition.

A systematic trend emerges when comparing aging temperatures. Samples aged at lower temperatures (150°C) consistently show superior strength compared to those aged at higher temperatures (180°C and 210°C). This suggests that lower aging temperatures promote more favorable precipitation characteristics, likely resulting in finer and more uniformly distributed strengthening precipitates. The aging duration also plays a crucial role, with longer aging times (24 hours) at lower temperatures producing better strength properties than shorter durations.

Interestingly, at higher aging temperatures (210°C), increasing the aging time from 6 to 12 hours results in slightly lower strength values, indicating possible precipitate coarsening or overaging effects. The sample aged at 180°C for 24 hours shows relatively poor ductility, failing at a strain of approximately 0.04, suggesting that this combination of temperature and time may lead to unfavorable microstructural features.

All samples display similar elastic behavior, as evidenced by the comparable initial slopes of their stress-strain curves. However, the work hardening rates vary significantly among different aging conditions, particularly in the plastic deformation region. The optimal combination of strength and ductility achieved at 150°C/24 hours suggests that these conditions provide the best balance of precipitation strengthening while maintaining adequate matrix ductility.

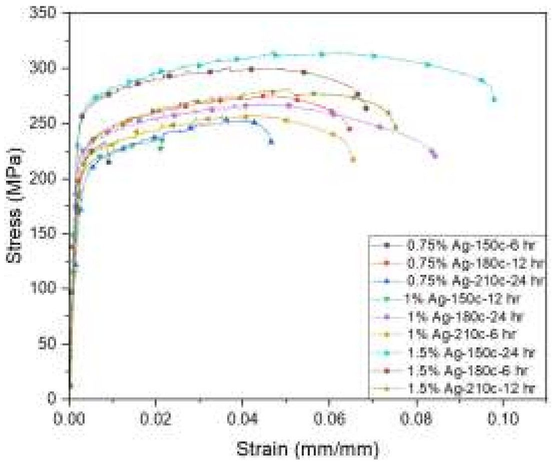

Figure 4. Stress-strain curves of Al-Mg-Ag alloys with different Ag percentages after various thermo-mechanical processing at different conditions.

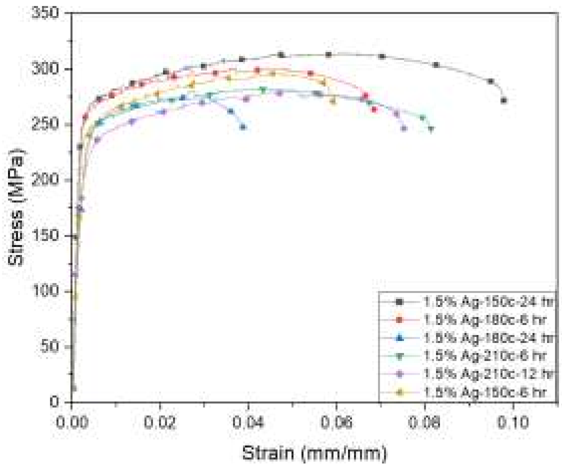

Figure 5. Stress-strain curves of Al-Mg-Ag alloys with 1.5% Ag after various thermo-mechanical processing at different conditions.

3.2 Fracture Morphology

The fracture morphology of the tested samples provided insights into the fracture mechanisms under different conditions. For the rolled samples, a typical brittle fracture surface represented by facets was observed as shown in Fig. 6. The presence of Ag particles, along with the deformation introduced by rolling, promoted the initiation and propagation of cracks, resulting in the brittle fracture behavior. However, for the solution-treated samples and aged samples with high aging durations, the fracture mechanism was dominated by ductile fracture. Intergranular fracture surfaces and dimples were observed, which indicated more ductile behavior in these conditions. The Ag particle-dislocation interaction and microstructural development during aging caused the improvement in ductility and brittle fracture resistance.

Thermo-mechanical processing in the form of rolling and aging played an important role in microstructure and mechanical property design of the alloys. Rolling led to the reduction in sheet thickness, which led to an increase in the dislocation density along with the formation of deformation-induced defects. This influenced the subsequent aging process by providing more nucleation sites for precipitates. The combination of rolling and aging resulted in a synergistic influence on the mechanical behavior, with both augmented strength and improved ductility being observed in the aged samples.

The Ag content was a controlling factor in the strength of the alloys, with strength rising with increasing content of Ag. Aging time and temperature also controlled the precipitation kinetics and the resulting microstructure, and thereby the mechanical behavior.

Fractography of the Al-Mg-1% Ag alloy reveals distinct failure mechanisms for the different processing conditions, providing an understanding of the deformation behavior of the material. The samples in the O-condition, as seen from photos (a) and (b), have a predominantly ductile fracture surface with deep and well-defined dimples of the same size. This morphology, visible at both low and high magnifications, is indicative of extensive plastic deformation at failure and is in agreement with the enhanced ductility apparent in the mechanical test results.

In contrast, the as-received condition, illustrated in photos (c) and (d), has a more complex fracture surface with an inhomogeneous dimple size distribution. The surface topography is seen to contain a combination of small and medium-sized dimples, together with well-developed secondary cracks and tear ridges. The hybrid morphology is characteristic of a balanced competition between ductile and quasi-brittle fracture processes, and is responsible for the intermediate mechanical behavior of this condition.

The rolled state, as revealed in photos (e) and (f), displays an extremely dissimilar fracture surface with considerably finer and shallower dimples. The high-magnification photo illustrates sharp features and well-defined shear zones, along with numerous secondary cracks and cleavage-like regions. This morphology is indicative of a material with high strength but limited ductility, perfectly aligning with the mechanical behavior observed in the stress-strain curves of the rolled samples.

The progression from O-condition to rolled state shows a clear transition in fracture characteristics, with dimple size and depth decreasing notably. This transitional pattern strongly correlates with the mechanical properties, where the O-condition's larger dimples correspond to higher ductility, the as-received condition's mixed features reflect balanced properties, and the rolled condition's fine features and quasi-cleavage appearance indicate high strength with reduced ductility.

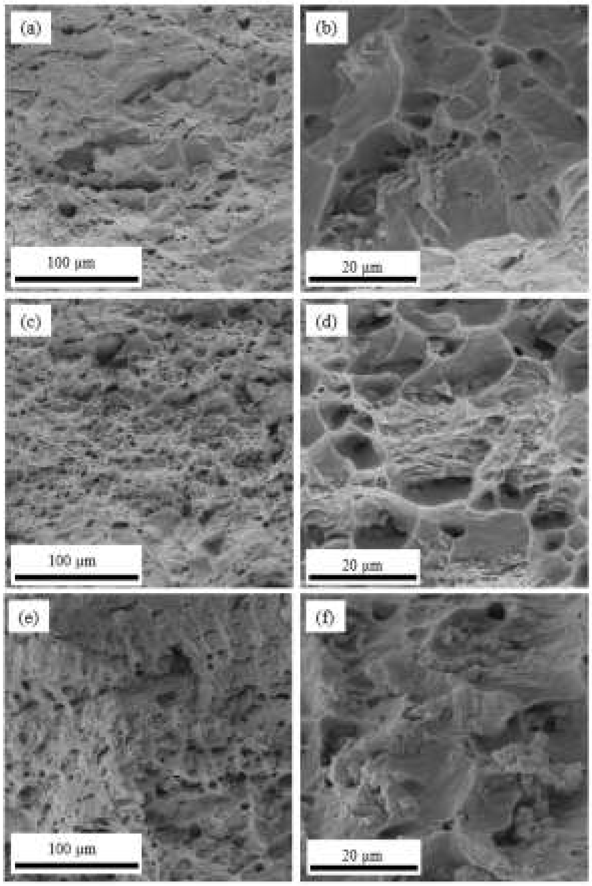

Figure 6. Fracture surfaces of the samples in low and high magnifications for (a and b) 1% Ag O-condition, (c and d) 1% Ag as-received, and (e and f) 1% Ag rolled.

Also, as shown in Fig. 7, the fracture morphology analysis of the Al-Mg-Ag alloy samples illustrates distinctive failure mechanisms that correlate strongly with their composition, aging conditions, and mechanical properties. The sample containing 1.5% Ag aged at 150°C for 24 hours, shown in images (a) and (b), exhibits a predominantly ductile fracture characterized by well-developed, equiaxed dimples of varying sizes. The high-magnification image (b) clearly displays these deep dimples with pronounced rims, indicating significant plastic deformation before failure. This morphology aligns perfectly with the superior strength and ductility observed in the tensile test results for this condition.

Moving to the 1% Ag sample aged at 150°C for 12 hours, depicted in images (c) and (d), the fracture surface shows a transition toward more brittle behavior. Low-magnification photo (c) shows a relatively flat topography with smaller, shallower dimples, while the high-magnification photo (d) shows quasi-cleavage features and tear ridges. Some regions show minimal plastic deformation, which agrees with the low ductility observed in mechanical testing of this condition.

The 1% Ag sample aged 24 h at 150°C, visible in figures (e) and (f), has an interesting intermediate fracture morphology. The surface has both ductile dimples and quasi-brittle characteristics, suggesting a mixed-mode failure mechanism. The high-magnification image (f) reveals areas of both ductile tearing and dimple formation and areas of more brittle behavior, with sharper features and more irregular topography. It is in line with the optimally balanced tensile mechanical characteristics revealed through the tensile tests.

These fractographic images are informative in their presentation of the interrelationship between processing conditions and failure modes of these alloys. The transition from predominantly ductile behavior in the 1.5% Ag sample to increasingly more brittle behavior in the 1% Ag samples, and finally to a mixed-mode failure, demonstrate the significance of small compositional and aging condition changes on the deformation and fracture behavior of these materials.

Overall, the findings indicate that tensile strength of Al-Mg alloys can be significantly enhanced by Ag addition through Orowan strengthening mechanisms. Thermo-mechanical processing techniques, i.e., rolling and aging, in combination, further optimized the mechanical properties of the alloys. Fracture morphologies showed the brittle-to-ductile transition because of microstructural changes as a result of Ag addition and thermo-mechanical processing. These findings contribute to an understanding of the effect of silver on the Orowan strengthening of Al-Mg-Ag alloys after thermo-mechanical processing.

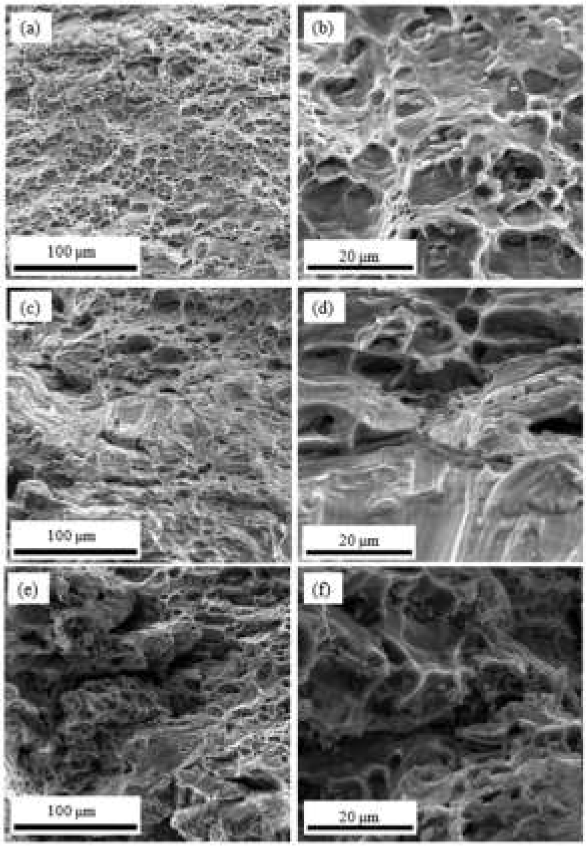

Figure 7. Fracture surfaces of the samples in low and high magnifications for (a and b) 1.5% Ag-150C-24h, (c and d) 1% Ag-150C-12h, and (e and f) 1% Ag-150C-24h.

4. Conclusions

This detailed investigation into the effect of silver content and thermo-mechanical processing on Al-Mg-Ag alloys has yielded a number of significant outcomes. The silver addition, particularly at the 1.5 wt% level, significantly enhanced the tensile strength through effective Orowan strengthening mechanisms. Silver addition to aluminum-magnesium alloys reveals a good strategy for enhancing mechanical properties through the precipitation hardening and microstructural refinement.

This strengthening was optimized when combined with the appropriate thermo-mechanical processing conditions, i.e., aging at 150°C for 24 hours, to achieve a peak strength of 310 MPa. The study revealed that lower aging temperatures (150°C) provided improved strength consistently compared to higher temperatures (180°C and 210°C), due to the formation of finer and more uniformly distributed precipitates.

The fracture morphology analysis provided crucial insights into the deformation mechanisms, showing a clear transition from brittle to ductile behavior depending on the processing conditions.

Rolled samples exhibited characteristic brittle fracture surfaces with facets, while solution-treated and aged samples showed predominantly ductile fracture features with well-defined dimples. This correlation between processing parameters and fracture behavior demonstrates the ability to tailor mechanical properties through controlled thermo-mechanical processing.

Future work should focus on several key areas:

1. Investigation of the precipitate evolution using advanced characterization techniques such as TEM and atom probe tomography to better understand the strengthening mechanisms.

2. Exploration of the effect of minor alloying additions (such as Zr or Sc) in combination with silver to potentially enhance grain refinement and thermal stability.

3. Development of optimized processing routes for specific industrial applications, particularly in aerospace and automotive sectors.

4. Study of the material's behavior under dynamic loading conditions and fatigue performance.

Acknowledgment

The authors would like to thank University of Babylon/Iraq, Tikrit University/Iraq, Al-Mustaqbal University/Iraq and University of Technology/Iraq for their invaluable support throughout this research. The guidance and resources provided by the faculty and staff were essential in shaping this work and enhancing our understanding of the subject.

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