Međunarodna naučno-stručna konferencija
„Savremeni materijali i tehnologije u poslovanju kompanija na području Zapadnog Balkana“, Zenica, BiH, 02. i 3. Oktobar 2025

LAKI STRUKTURNI MATERIJALI ZA AUTOMOBILSKU I SVEMIRSKU INDUSTRIJU - DIZAJN, SVOJSTVA I ODRŽIVOST

LIGHTWEIGHT STRUCTURAL MATERIALS FOR AUTOMOTIVE AND AEROSPACE INDUSTRY - DESIGN, PROPERTIES AND SUSTAINABILITY

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REZIME

Razvoj aluminijskih legura s dodatkom litija i magnezija (Al-Mg-Li) privlači pažnju zbog njihove niske gustoće, povećane krutosti i specifične čvrstoće, što ih čini pogodnima za primjenu u automobilskoj, zrakoplovnoj i svemirskoj industriji. Cilj ovog istraživanja bio je ispitati utjecaj uvjeta sinteze taline te omjera Li/Mg na razvoj mikrostrukture, mehanička svojstva i ponašanje legura u degradacijskom okruženju. Sinteza je provedena u različitim zaštitnim atmosferama (argon, argon s djelomičnim ili potpunim pokrovom lonca te vakuum), pri čemu su dobivene legure s različitim sadržajem Li i Mg te dodatkom mikrolegirajućih elemenata (npr. Zr, AlTi5B1). Analizirani su kemijski sastav, mikrostruktura, tlačna čvrstoća te degradacijska otpornost ispitana elektrokemijskom i uranjajućom metodom u uvjetima koji simuliraju radne uvjete u transportnoj industrije. Rezultati pokazuju da je najveća gustoća od 2,49 g/cm³ postignuta pri taljenju u zaštitnoj atmosferi argona s djelomičnim pokrovom, dok je najniža gustoća (2,27 g/cm³) zabilježena pri vakuumskom taljenju. Najniža vrijednost može se povezati s prisutnošću vakuumske poroznosti. Legure s uravnoteženim omjerom Li/Mg pokazale su najveće vrijednosti tlačne čvrstoće i dobru stabilnost nakon toplinske obrade, dok su legure s visokim udjelom litija imale nižu gustoću, ali i smanjenu duktilnost. Elektrokemijska degradacija u lijevanom stanju iznosila je 17,01 mm/god, dok je nakon toplinske obrade otapajućim žarenjem značajno porasla na 51,24 mm/god, što ukazuje na osjetljivost mikrostrukture na toplinsku obradu. Sveukupno, rezultati jasno pokazuju da zaštitna atmosfera argona omogućuje gušće i homogenije legure, dok uravnotežen Li/Mg omjer osigurava optimalnu kombinaciju čvrstoće, krutosti i otpornosti na degradaciju. Dobiveni rezultati potvrđuju veliki potencijal Al-Mg-Li legura za primjenu u nosivim i sekundarnim konstrukcijama zrakoplova, satelita i automobila, uz mogućnost daljnje optimizacije termomehaničkom obradom i mikrolegiranjem.

Ključne riječi: Al-Mg-Li legure, procesni parametri, sinteza taline, Li/Mg omjer, mikrostruktura, tlačna čvrstoća, zaštitna atmosfera, degradacijska otpornost

SUMMARY

The development of aluminum alloys with the addition of lithium and magnesium (Al-Mg-Li) has attracted considerable attention due to their low density, increased stiffness, and specific strength, making them suitable for applications in the automotive and aerospace industries. The aim of this research was to examine the influence of melt synthesis conditions and the Li/Mg ratio on the evolution of microstructure, mechanical properties, and alloy behaviour in a degradation

environment. Synthesis was performed under a different protective atmospheres (argon, argon with partial or full crucible cover, and vacuum), resulting in alloys with varying Li and Mg contents and with the addition of microalloying elements (e.g., Zr, AlTi5B1). The chemical composition, microstructure, compressive strength and degradation resistance were analysed. The degradation resistance was tested by electrochemical and immersion methods under conditions simulating the working environment of the transport industry. The results show that the highest density of 2.49 g/cm³ was achieved during melting in an argon protective atmosphere with a partial cover, while the lowest density (2.27 g/cm³) was recorded during vacuum melting. The lowest value can be attributed to the presence of vacuum porosity. Alloys with a Li/Mg ratio close to 1 exhibited the highest compressive strength values and good stability after heat treatment, while alloys with a high lithium content had lower density but reduced ductility. Electrochemical degradation in the as-cast condition amounted to 17.01 mm/year, whereas after solution heat treatment it significantly increased to 51.24 mm/year, indicating the sensitivity of the alloy to heat treatment. Overall, the results clearly demonstrate that an argon protective atmosphere produces denser and more homogeneous alloys, while a Li/Mg ratio close to 1 ensures an optimal combination of strength, stiffness, and degradation resistance. The findings confirm the great potential of Al-Mg-Li alloys for application in primary and secondary structures of aircraft, satellites, and automobiles, with the possibility of further optimization through thermomechanical processing and microalloying.

Keywords: Al-Mg-Li alloys, process parameters, alloy synthesis, Li/Mg ratio, microstructure, compressive strength, synthesis conditions, degradation resistance

1. INTRODUCTION

The demand for lightweight and efficient structural materials remains one of the key challenges in modern transport systems. In the automotive, aviation, and aerospace industries, reducing vehicle mass improves energy efficiency, lowers emissions, and enhances overall performance [1,2].

Aluminium (Al) alloys are widely used as structural materials due to their low density, good mechanical properties, and corrosion resistance. They are utilized in automotive, aerospace, and space structures where lightweight design is essential for achieving improved performance and reliability [3,4].

The development of aluminium–lithium (Al–Li) alloys was driven by the need for further reduction in density and improvement in specific properties. The addition of lithium reduces density and increases stiffness and specific strength. However, early generations of Al–Li alloys showed sensitivity to processing conditions, resulting in anisotropy of microstructure and mechanical properties, reduced fracture toughness, and increased sensitivity to stress corrosion cracking [5,6]. To overcome these limitations, alloy systems were further modified by the addition of elements such as copper (Cu), magnesium (Mg), silver (Ag), and zirconium (Zr), along with the development of advanced thermo-mechanical processing [7,8]. These developments highlight the importance of chemical composition and processing conditions, which define microstructure and the resulting functional properties of the alloy.

In this context, Al–Mg–Li alloys represent a simplified and practical alloy system, where the combined addition of Li and Mg enables density reduction and the formation of a suitable microstructure. Lithium primarily reduces density and contributes to stiffness through the formation of strengthening phases, while magnesium provides solid solution strengthening and influences the formation and distribution of Li-based intermetallic phases. The resulting microstructure, formed during solidification and subsequent processing, directly determines the functional behaviour of the alloy [2,3].

This work presents a practical approach to the design and development of Al–Mg–Li alloys by linking chemical composition, processing, microstructure, and functional properties for lightweight engineering applications.

2. APPROACH TO Al–Mg–Li ALLOY DESIGN AND DEVELOPMENT

The primary objective of this work is to reduce alloy density while maintaining the functional properties required for structural applications. This aim is driven by the increasing demand for lightweight materials in the transportation industry.

The approach assumes that chemical composition and processing conditions determine microstructure, which in turn defines the functional properties of the alloy. Figure 1 illustrates this relationship and shows how changes in alloy design and processing are reflected in the resulting material behaviour.

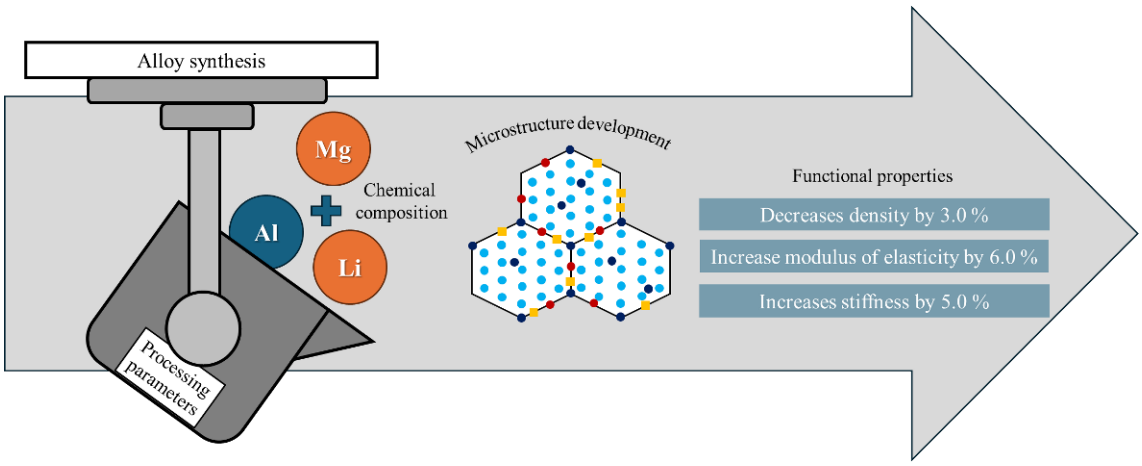


Figure 1. The alloy design approach

In this context, lithium primarily contributes to density reduction and increased stiffness through the formation of strengthening phases. Magnesium is added to provide solid solution strengthening and to influence the formation and distribution of Li-based intermetallic phases. The Li/Mg ratio plays a key role in defining the resulting microstructure [2,3]. The combined addition of Li and Mg enables the development of alloys with a suitable balance of density and functional properties.

Figure 2 presents the development route from initial alloy design to final property evaluation and highlights the influence of processing conditions on solidification sequence and microstructure formation.

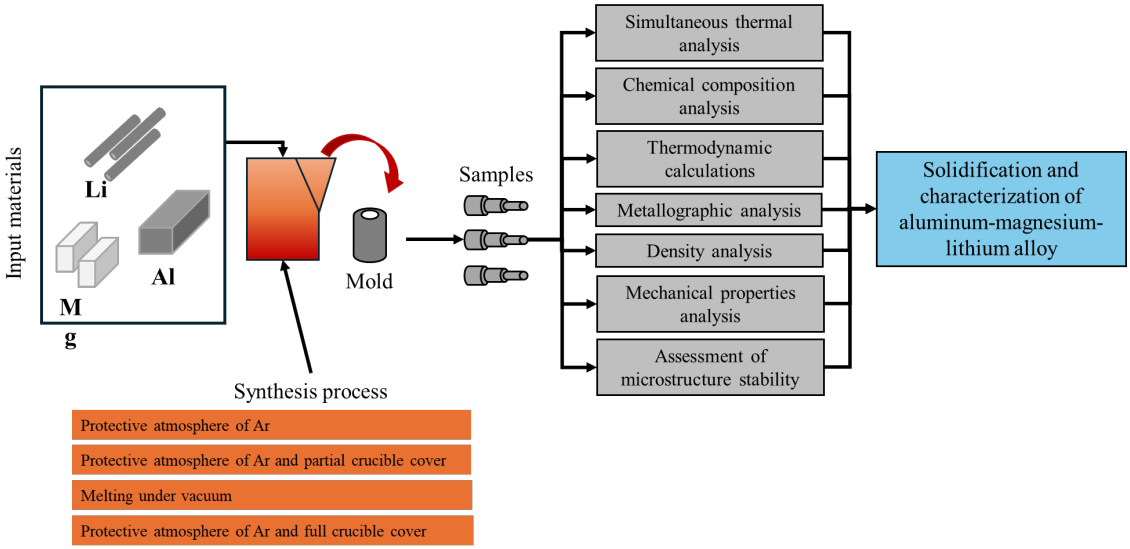


Figure 2. The alloy development

For traceability and reproducibility, the development of Al–Mg–Li alloys follow a clearly defined sequence of steps. The process includes:

- chemical composition redesign,
- alloy synthesis under controlled processing conditions,
- chemical composition analysis,
- microstructural characterisation,
- evaluation of functional properties.

The key advantage of this approach is its applicability, as it enables systematic alloy development through a clear and reproducible procedure.

3. CHEMICAL COMPOSITION REDESIGN

The redesign of the chemical composition is based on current trends in the development and use of aluminium alloys in the transportation industry, as well as advancements in aluminium–lithium (Al–Li) systems. Conventional aluminium alloys used in vehicle production include both cast and wrought systems (figure 3).

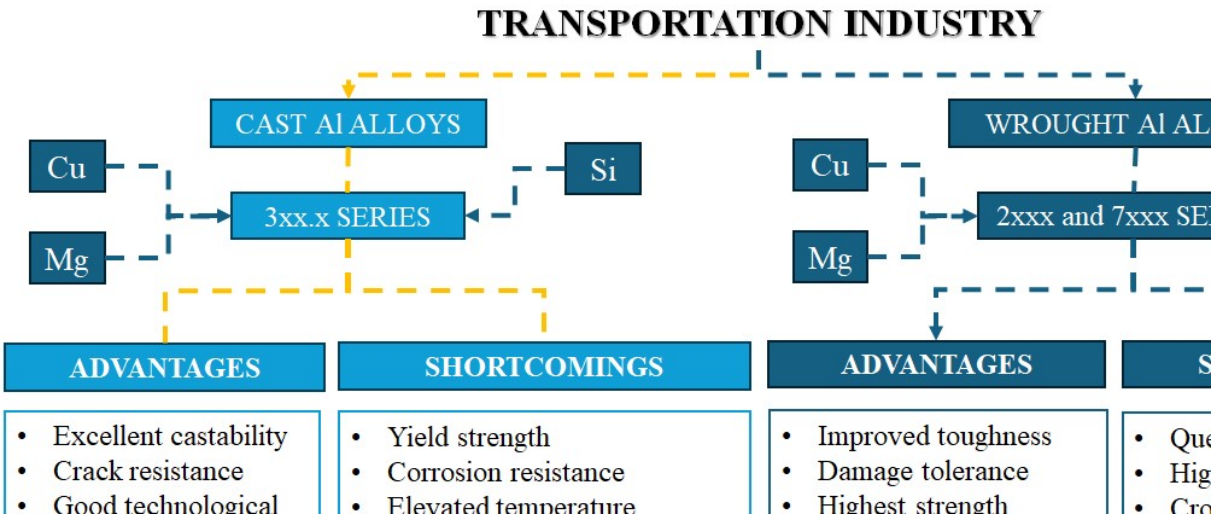


Figure 3. The cast and wrought aluminum alloys used in transportation industry

Cast Al–Si-based alloys (3xx.x series) are widely used for engine components, transmission housings, suspension parts, and wheels due to their excellent castability and resistance to hot cracking. However, their microstructure, formed during solidification, contains a combination of eutectic and intermetallic phases that can limit mechanical properties and stability at elevated temperatures. Wrought aluminium alloys, particularly Al–Cu (2xxx) and Al–Zn–Mg (7xxx) systems, are used for structural components in aerospace and transportation applications due to their high strength and good tensile properties. However, their microstructure development involves complex sequences of precipitation reactions with multiple stable and metastable phases, which can reduce fracture toughness, increase sensitivity to corrosion and heat treatment, and limit weldability and dimensional stability. Despite their widespread use in structural applications, the limitations of these alloys drive the development of new aluminium alloy systems with improved performance [9-11].

The introduction of lithium marks a significant advancement in aluminium alloy development, enabling further weight reduction and improvement in specific properties. The

development of Al–Li alloys has progressed through several generations, with chemical composition and processing conditions as the key factors controlling their performance. Early alloy designs used higher lithium additions (typically 2.0–3.0 wt.% Li) to maximise density reduction and stiffness, but this resulted in increased anisotropy and reduced ductility. Subsequent development focused on lowering lithium content (generally below 2.0 wt.% Li and often close to 1.3 wt.% Li) and introducing additional alloying elements such as Cu, Mg, Ag, and Zr to improve mechanical properties, fracture toughness, and processing stability. Based on these developments, the effect of lithium content on density and mechanical properties can be quantitatively described [12]. Each addition of 1.0 wt.% Li reduces density by approximately 3.0%, increases the modulus of elasticity by about 6.0%, and improves stiffness for additions up to 4.2 wt.% Li. However, increasing the lithium content above about 1.3 wt.% results in a decrease in yield and tensile strength, indicating that lithium additions close to this value are more suitable for achieving a favourable combination of properties [13].

The Al–Mg–Li alloy system is recognised as a suitable basis for alloy redesign and development due to its potential to reduce density while maintaining favourable functional properties. Magnesium contributes to solid solution strengthening and further reduces alloy density, while also influencing the formation and distribution of lithium-based intermetallic phases. The combined addition of Li and Mg modifies the solidification sequence and resulting microstructure.

A key parameter in this system is the Li/Mg ratio, which determines the type and distribution of phases formed during solidification. The microstructure development based on Li/Mg ratio can be expressed by equations 1 and 2 [14]:

For high Li/Mg ratio $$\alpha_{Al} \rightarrow Al_3Li\ (\delta') \rightarrow AlLi\ (\delta) \quad (1)$$

For low Li/Mg ratio $$\alpha_{Al} \rightarrow Al_3Li\ (\delta') \rightarrow Al_2LiMg\ (T) \quad (2)$$

For Li/Mg > 1, the formation of Li-rich phases such as Al_3Li (δ') is promoted, while for Li/Mg < 1, the formation of mixed Li–Mg phases such as Al_2LiMg becomes more pronounced. These differences in phase formation influence microstructure morphology and the distribution of strengthening constituents. Li/Mg ratios close to 1, corresponding to similar additions of Li and Mg, are commonly associated with more uniform microstructure development and a more stable material response [2,4,14].

The present alloy design focuses on the Al-rich corner of the Al–Mg–Li ternary system. This approach limits the total addition of alloying elements and allows better control of solidification behaviour and the resulting microstructure. Lithium and magnesium are highly reactive elements, making alloy preparation sensitive to melt processing conditions. High reactivity can cause element loss, compositional deviations, and microstructure variations if process parameters are not properly controlled.

The redesign of chemical composition is therefore a compromise between the desired microstructure, targeted functional properties, and melt synthesis conditions. By combining controlled Li and Mg additions with an appropriate Li/Mg ratio, the alloy design remains suitable for practical implementation while enabling reproducible microstructure development.

This approach provides a basis for further evaluation of microstructure and functional properties presented in the following sections.

4. ALLOY SYNTHESIS

The Al–Mg–Li alloys were prepared using various melt synthesis methods to minimise the loss of alloying elements, prevent melt contamination, and produce a chemically homogeneous melt. Due to the high reactivity of Li and Mg, particular attention was paid to the protective atmosphere, alloying temperature, and the type of refractory materials and coatings used [15].

The alloys were synthesised under various conditions, including melting in an argon protective atmosphere, an argon atmosphere with a partial or full crucible cover, and under vacuum. These conditions were chosen to limit oxidation due to the high reactivity of the alloying elements and to compare the effectiveness of different levels of melt protection. Melt contamination was further minimised by applying a protective coating to the crucible and tools used during alloy preparation. Lithium and magnesium were added simultaneously, wrapped in aluminium foil, and introduced into the melt using a steel bell to improve dissolution and reduce oxidation losses. Grain refinement was applied in selected cases using an AlTi5B1 master alloy to improve microstructure uniformity and reduce grain size [15]. Different approaches to alloy synthesis are shown in Figure 4.

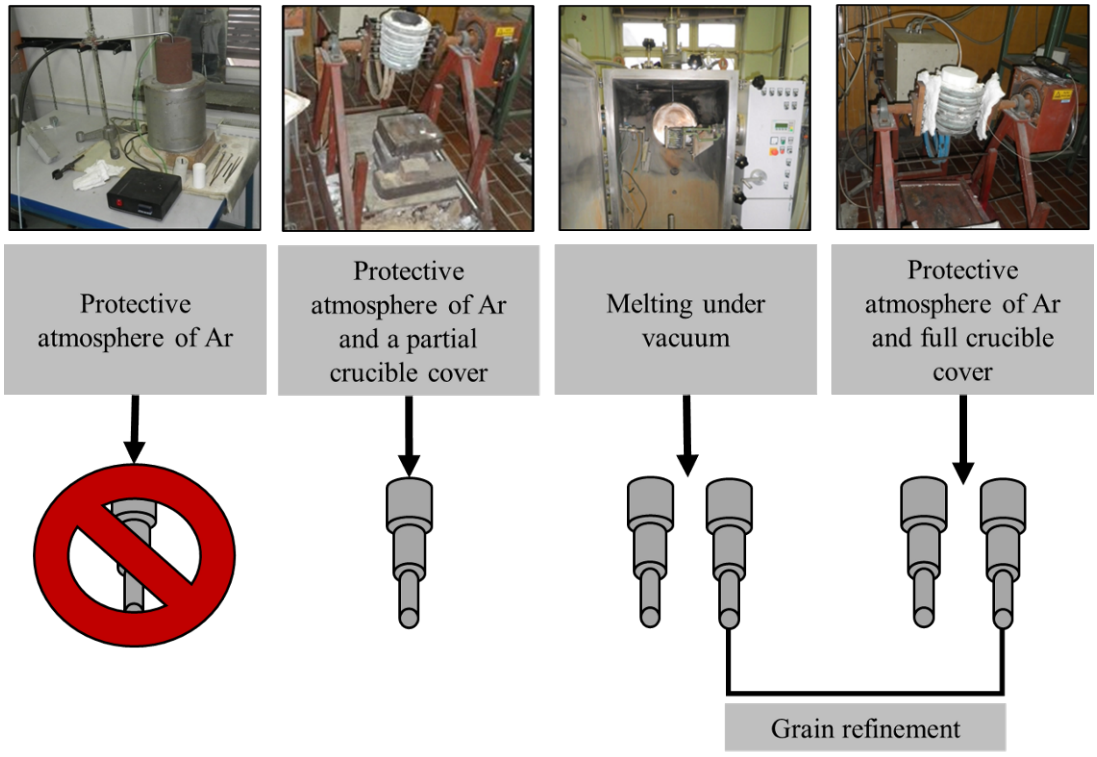


Figure 4. Different approaches to alloy synthesis with indicated samples [15]

In total, five alloys were synthesised: one sample prepared under argon atmosphere with partial crucible cover, two samples under vacuum, and two samples under argon atmosphere with full crucible cover. The attempt to synthesise the alloy under an argon atmosphere without a crucible cover was unsuccessful, and no sample was obtained (figure 4).

The obtained alloys showed a clear dependence of element loss on processing conditions. Average losses of lithium and magnesium were of similar magnitude (approximately 18% for Li and approximately 13% for Mg), indicating comparable sensitivity of both elements to melt processing conditions. The highest losses were observed under vacuum conditions, while improved melt protection in an argon atmosphere reduced element loss and enabled better compositional control. These trends confirm that melt protection is essential for maintaining the target composition [15].

5. CHARACTERIZATION OF SYNTHESIZED ALLOYS

The characterization of synthesized Al–Mg–Li alloys was performed to estimate the effects of chemical composition and melt processing conditions on the produced alloy. Attention was given to the achieved composition, microstructure development, and the corresponding functional properties. In addition, the aim of the characterisation was to assess the suitability of the developed alloys for use in the transportation industry.

5.1. Chemical composition

The chemical composition of the synthesised alloys was designed within the Al-rich corner of the Al–Mg–Li ternary system. The target compositions were generally achieved, although deviations in lithium and magnesium content were observed. A broad range of Li/Mg ratios was obtained, from approximately 0.88 in alloys synthesised under argon atmosphere with a fully covered crucible to 5.68 in the sample prepared under argon atmosphere with a partially covered crucible. These differences in chemical composition and Li/Mg ratio are a direct consequence of the melt synthesis method. Based on the achieved Li/Mg ratios, differences in phase formation during solidification are expected. For high Li/Mg ratios, the solidification sequence will involve the formation of Li-containing phases (equation 1), while for low Li/Mg ratios, the sequence shifts towards the formation of Li–Mg phases (equation 2) [15].

5.2. Density measurements

The measured density of the synthesised alloys ranged from approximately 2.37 g/cm³ to 2.84 g/cm³, depending on the achieved chemical composition. The lowest density was observed in alloys with higher Li/Mg ratios, while higher densities corresponded to lower Li/Mg ratios, reflecting the opposing contributions of lithium and magnesium to the overall density [15].
Figure 5 compares the average density of the synthesised alloys with that of commercially used alloys.

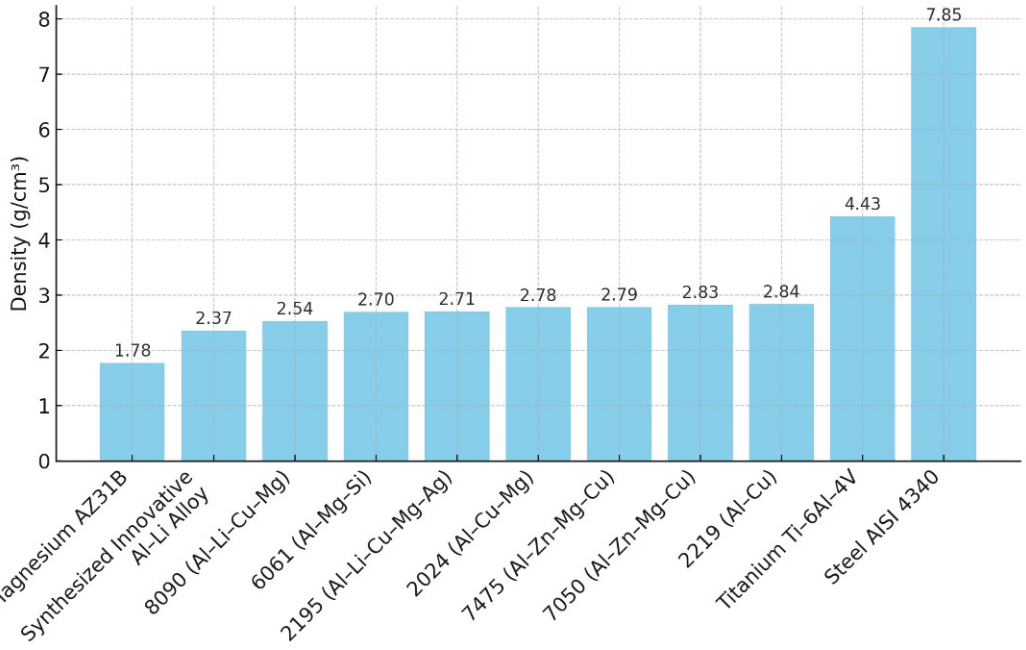


Figure 5. Comparison of the average density of the synthesised alloys with commercially used alloys

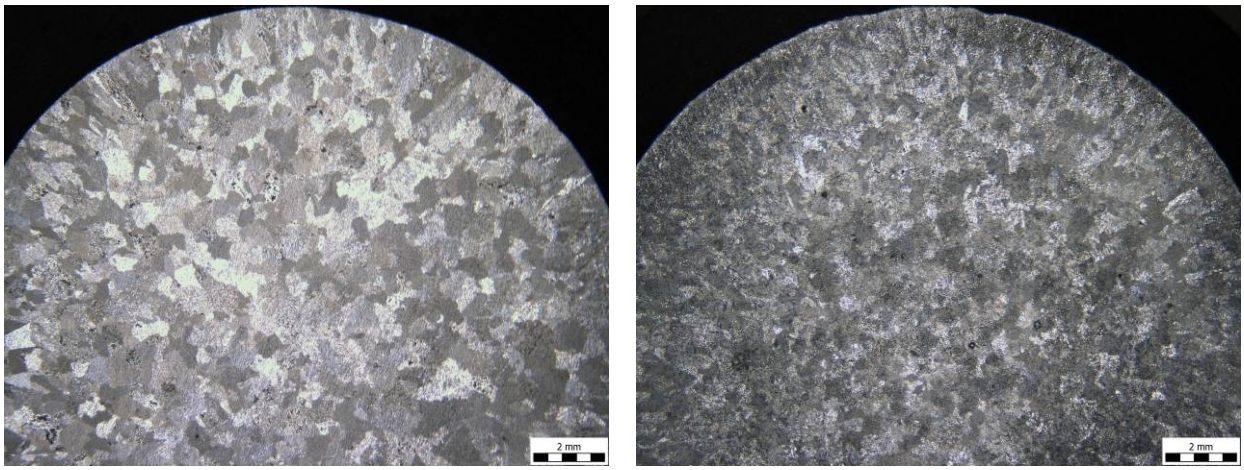
The average density of the synthesised alloys was approximately 2.37 g/cm³, which is lower than that of conventional wrought aluminium alloys such as the 2xxx and 7xxx series (≈2.7–

2.8 g/cm³). The average density also remains well below that of other materials used in the transportation industry, such as titanium alloys (≈4.43 g/cm³) and steels (≈7.85 g/cm³).

5.3. Microstructure characterization

The microstructure of the synthesised alloys was characterised using various methods to enable qualitative and quantitative analysis of macrostructural and microstructural constituents.

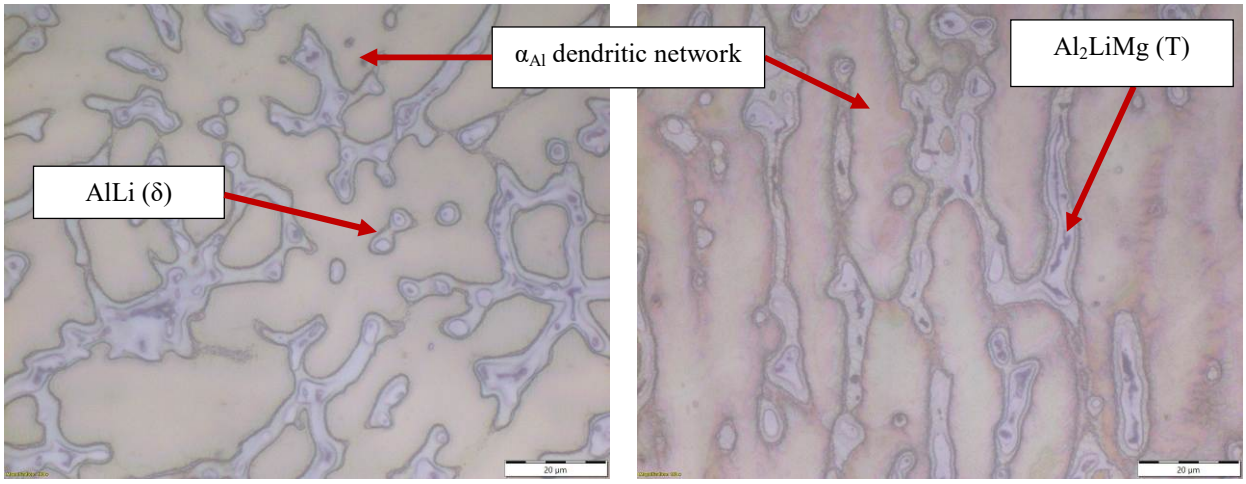
The samples display a macrostructure typical of alloy solidification in a permanent mould, with visible chill, columnar, and equiaxed crystal zones (figure 6 a). Grain refinement resulted in a uniform grain size and morphology across the cross-section (figure 6 b).



a) *b)*

Figure 6. Macrostructure of the alloy with Li/Mg = 0.9: (a) without grain refinement; (b) with grain refinement using AlTi5B1 [15]

The microstructure of the synthesised alloys consists of an α_{Al} matrix with intermetallic phases distributed in the interdendritic regions. The type and distribution of these phases are strongly influenced by the Li/Mg ratio. Alloys with higher Li/Mg ratios are characterised by the presence of Li-rich phases, primarily Al_3Li (δ′) and AlLi (δ) (figure 7 a), while lower ratios promote the formation of Li–Mg phases such as Al_2LiMg (T), along with Mg-rich phases such as Al_8Mg_5 (β) (figure 7 b).



a) *b)*

Figure 7. Microstructure of the synthesized alloys with: a) Li/Mg = 5.6, b) Li/Mg=0.9

From the standpoint of mechanical performance, a finer and more uniformly distributed δ′ phase is considered favourable, while the presence of coarse and continuous Li–Mg and Mg-rich phases may lead to reduced ductility and lower fracture toughness. Accordingly, variations in the Li/Mg ratio result in different microstructures and expected mechanical behaviour of the synthesised alloys [15].

5.4. Mechanical properties

The mechanical properties of the synthesised alloys were evaluated using compression testing, hardness and microhardness measurements, and determination of the elastic modulus. These methods were used to assess the influence of chemical composition and microstructure on the strength, local mechanical properties, and elastic behaviour of the alloys.

The compression results show that the deformation behaviour of the alloys is closely linked to the observed microstructure. Metallographic analysis after compression revealed that alloys with a more uniform phase distribution exhibit more homogeneous deformation, while alloys with pronounced phase heterogeneity display localised deformation and strain concentration in interdendritic regions. In alloys with Li/Mg ratios close to 1, deformation is more evenly distributed across the α_{Al} matrix, whereas the presence of coarse and continuous Li–Mg and Mg-rich phases promote crack initiation and propagation during compression (figure 8). These findings confirm that microstructure morphology and phase distribution are key factors in determining the compressive behaviour of the synthesised alloys [15,16].

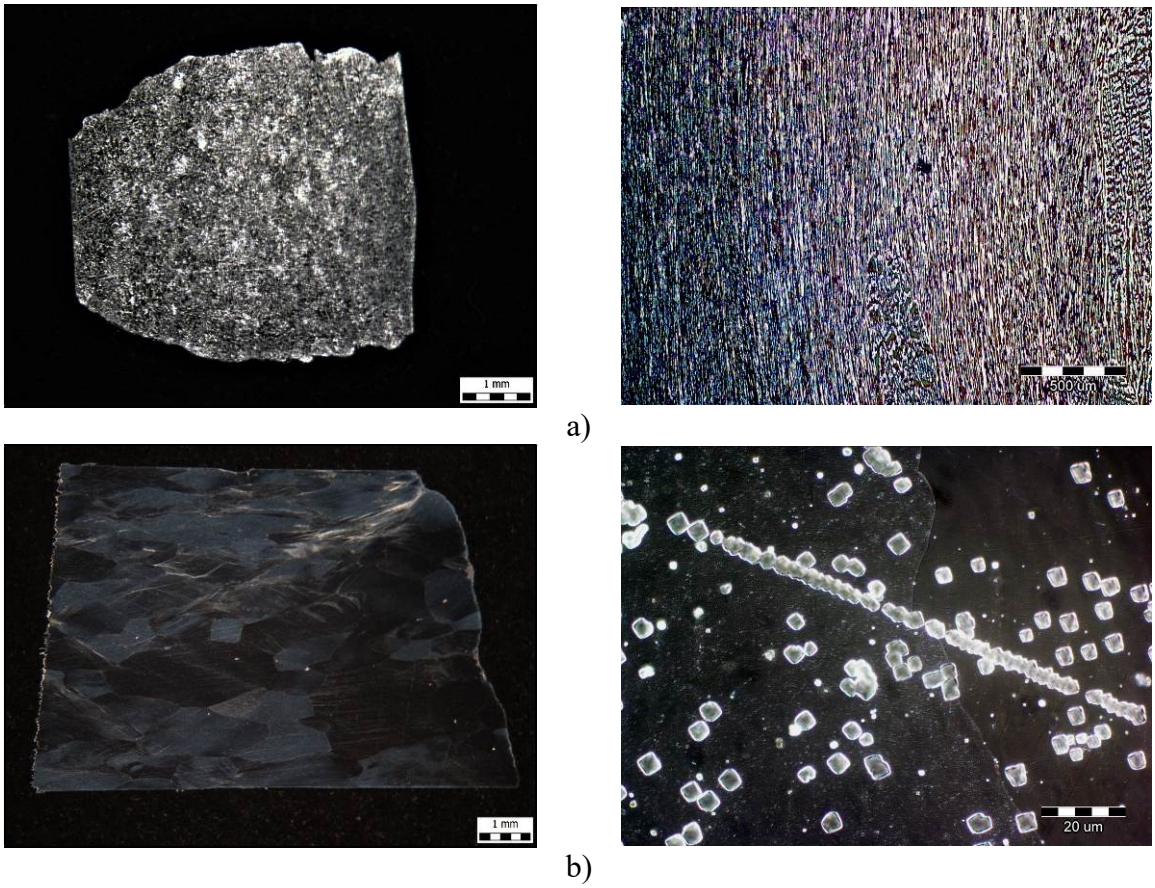


Figure 8. The cross-sectional microstructure of typical deformation behaviours: a) unequal deformation and barrelling effect (sample 21 as-cast condition), b) materials' flow line formation and free movement of dislocations (sample 1 solutionized condition)

Hardness and microhardness measurements reflect the influence of phase composition and distribution on the mechanical response of the synthesised alloys. The highest hardness and microhardness values were recorded in alloys with Li/Mg ratios close to 1, where a more uniform distribution of strengthening phases is expected. In these alloys, the presence of finely dispersed δ′ (Al_3Li) phase contributes to increased resistance to plastic deformation.
In contrast, alloys with higher or lower Li/Mg ratios exhibit lower hardness values, which can be attributed to a more heterogeneous phase distribution and the presence of coarser Li–Mg and Mg-rich phases. Microhardness measurements also reveal local variations in phase distribution, particularly in interdendritic regions, confirming the influence of microstructural heterogeneity on the local mechanical response [15].
The elastic modulus exhibits relatively little variation compared to strength-related properties. The highest values were observed in alloys with higher Li/Mg ratios, reflecting the contribution of lithium to increased stiffness. In alloys with lower Li/Mg ratios, slightly lower values were recorded due to the reduced influence of lithium.
Overall, the results indicate that the elastic modulus is primarily determined by lithium content, with microstructure having a less pronounced influence.

5.5. Degradation resistance

The degradation behaviour was evaluated on a selected alloy using immersion testing in EXCO solution (pH ≈ 0.4) for exposure times of 5, 24, 48, and 72 hours. This environment represents aggressive service conditions relevant to transportation applications and enables assessment of material stability under acidic chloride conditions [15,17,18].
The results show that mass loss increases with exposure time, while the degradation rate decreases, indicating that the process is most pronounced at the initial stage. The highest degradation rate was observed after 5 hours of exposure, followed by a gradual decrease over time. This behaviour is consistent with the observed increase in solution pH, which remains acidic but rises significantly during exposure, leading to reduced degradation intensity.
Metallographic analysis revealed that degradation initiates along grain boundaries and propagates through interdendritic regions. In the as-cast condition, preferential dissolution of Al_8Mg_5 (β) and Al_2LiMg (T) phases was observed, resulting in cavity formation and localised degradation. With increasing exposure time, degradation extends to surrounding intermetallic regions [17,18].
These observations indicate that degradation is strongly influenced by microstructure, with Li–Mg and Mg-rich phases exhibiting higher susceptibility.

6. CONCLUSIONS

This study confirms that the design and development of Al–Mg–Li alloys can be effectively guided by the relationship between chemical composition, processing conditions, microstructure, and functional properties.

- Melt synthesis conditions significantly affect the chemical composition of Al–Mg–Li alloys. Improved melt protection in an argon atmosphere reduces element loss and allows better control of the Li/Mg ratio.
- The Li/Mg ratio governs phase formation during solidification and determines the resulting microstructure. Higher ratios promote Li-rich phases, while lower ratios favour the formation of Li–Mg and Mg-rich phases.
- Microstructure directly influences mechanical behaviour. Alloys with Li/Mg ratios close to 1 show the most favourable combination of compressive strength and hardness, while heterogeneous phase distribution leads to localised deformation and reduced performance.

- The synthesised alloys have lower density than conventional aluminium alloys, confirming their suitability for lightweight applications.
- Degradation behaviour is controlled by microstructure, with preferential dissolution of Li–Mg and Mg-rich phases and a decrease in degradation rate over time.
- The results indicate that controlled melt synthesis and an appropriate Li/Mg ratio enable the development of Al–Mg–Li alloys with a balanced combination of properties, making them suitable for lightweight structural applications in the automotive and aerospace industries.

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8. ACKNOWLEDGMENT

The investigation was carried out as part of the Institutional Research Project the "Design and characterisation of innovative engineering alloys/products (KIIL)" financed by the EU – Next Generation EU. The views and opinions expressed are those of the author and do not necessarily reflect the official positions of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. The investigation was performed on equipment within the infrastructural scientific projects: Center for Founding - SIMET (Code: KK.01.1.1.02.0020); and the VIRTULAB - Integrated Laboratory for Primary and Secondary Raw Materials (Code: KK.01.1.1.02.0022).