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Effect of Magnesium Variation on Microstructure and Mechanical Properties of Aluminum Recycled Alloys

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Abstract

The use of recycled aluminum (scrap) as a lightweight material in the automotive industry continues to increase; however, its quality is often limited by technical issues such as impurity contamination, oxidation, and chemical composition variability, which adversely affect mechanical performance. One effective approach to overcoming these limitations is the addition of magnesium as an alloying element to enhance the strength and hardness of recycled aluminum. This study investigates the effect of magnesium additions of 5 wt% and 10 wt% on the mechanical properties and microstructure of aluminum produced from scrap melting using the sand casting method at a temperature of 707 °C.The results show that magnesium addition significantly improves hardness, increasing from 39.4 HV to 94.6 HV, as well as tensile strength, which rises from 49.5 MPa to 181.5 MPa. Microstructural analysis reveals the formation of Mg-rich phases that are more dominant and more homogeneously distributed within the aluminum matrix, contributing to the enhanced mechanical properties. The addition of 10 wt% Mg provides the most optimal performance, demonstrating that the quality limitations of recycled aluminum caused by impurities and compositional variability can be effectively mitigated through appropriate alloying strategies. These findings confirm the strong potential of recycled aluminum to be developed into a high value-added engineering material.

Keywords: aluminum; magnesium; mechanical properties; recycling.

Abstrak

Penggunaan aluminium daur ulang (scrap) sebagai material ringan dalam industri otomotif terus berkembang, namun kualitasnya sering dibatasi oleh permasalahan teknis seperti keberadaan impuritas, oksidasi, serta variasi komposisi kimia yang berdampak pada penurunan sifat mekanik. Salah satu pendekatan untuk mengatasi keterbatasan tersebut adalah melalui penambahan unsur paduan magnesium guna meningkatkan kekuatan dan kekerasan material hasil daur ulang. Penelitian ini menganalisis pengaruh penambahan magnesium sebesar 5 wt% dan 10 wt% terhadap sifat mekanik dan struktur mikro aluminium hasil peleburan scrap menggunakan metode sand casting pada temperatur 707 °C. Hasil pengujian menunjukkan bahwa penambahan magnesium mampu meningkatkan nilai kekerasan dari 39,4 HV menjadi 94,6 HV, serta kekuatan tarik dari 49,5 MPa menjadi 181,5 MPa. Analisis mikrostruktur memperlihatkan terbentuknya fasa kaya magnesium yang lebih dominan dan terdistribusi lebih homogen dalam matriks aluminium, yang berkontribusi terhadap peningkatan sifat mekanik. Penambahan magnesium sebesar 10 wt% memberikan hasil paling optimal, menunjukkan bahwa keterbatasan kualitas aluminium daur ulang akibat impuritas dan variabilitas komposisi dapat diminimalkan melalui pemaduan yang tepat, sehingga material daur ulang berpotensi dikembangkan sebagai material teknik bernilai tambah tinggi.

Kata kunci: alumunium; daur ulang; magnesium; sifat mekanik.

1. Introduction

The increasing demand for lightweight and sustainable materials has intensified interest in the utilization of recycled aluminum (scrap), particularly for automotive and manufacturing applications. Aluminum offers advantages such as low density, good corrosion resistance, and high recyclability; however, aluminum produced from secondary sources often exhibits inferior and inconsistent properties compared to primary aluminum alloys. As a result, the application of recycled aluminum remains largely restricted to non-structural or low value-added components [1].

A major challenge associated with recycled aluminum arises from chemical composition variability and impurity contamination, which are inherent to scrap-based feedstock. Aluminum scrap originating from the machining of 1xxx series alloys generally possesses a high aluminum content (>99 wt%), yet it inevitably contains impurities such as Fe and

Si, as well as oxide inclusions formed during machining, storage, and repeated melting. These impurities promote the formation of brittle intermetallic phases, increase porosity, and degrade mechanical performance, thereby limiting the structural applicability of recycled aluminum alloys. Previous studies have attempted to enhance the mechanical properties of recycled aluminum through alloying strategies, particularly by introducing magnesium as a strengthening element. Magnesium is known to improve mechanical performance through solid-solution strengthening and the formation of Mg-rich phases within the aluminum matrix. Nevertheless, most existing studies have focused on low to moderate Mg additions (typically below 5 wt%), primarily to maintain process stability and minimize oxidation-related losses. Consequently, the potential of high magnesium additions to compensate for impurity-related degradation in recycled aluminum has not been comprehensively investigated [2]

The use of magnesium at elevated concentrations (≥5 wt%) represents a promising yet scientifically challenging approach. While higher Mg content may significantly enhance strength and hardness, it also introduces critical concerns, including increased oxidation susceptibility, gas porosity formation, and microstructural instability during melting and casting. To date, systematic experimental studies addressing these competing effects in recycled aluminum, particularly under conventional casting conditions, remain limited. This gap underscores the need for a detailed investigation into the feasibility and performance limits of high-Mg recycled aluminum alloys. In this context, the present study focuses on aluminum scrap derived from machining processes of the 1xxx series alloys, characterized by high aluminum purity but accompanied by unavoidable impurities. Magnesium additions of 5 wt% and 10 wt% were deliberately selected to represent the transition from moderate to high alloying levels, enabling an evaluation of the effectiveness of aggressive alloying in overcoming the inherent limitations of recycled aluminum. This approach aims to establish a clearer understanding of the relationship between Mg content, microstructural evolution, and mechanical performance [3]

The objective of this study is to quantitatively evaluate the effects of 5 wt% and 10 wt% magnesium additions on the mechanical properties (hardness and tensile strength) and microstructural characteristics of recycled aluminum produced via sand casting at a melting temperature of 707 °C. The findings are expected to provide fundamental insights into alloy design strategies for high-performance recycled aluminum, supporting its development as a value-added engineering material for lightweight structural applications [4], [5].

2. Material and Method

This study aims to analyze the impact of magnesium (Mg) addition on the mechanical properties and microstructure of recycled aluminum (scrap Al) smelting results. The methods used include the melting process, casting using the sand casting method, and testing including chemical composition analysis, hardness test, tensile test, and microstructure examination.

2.1. Materials and Material Preparation

The basic materials are 1XXX series aluminum scrap from machining process and pure magnesium in flake form. Magnesium composition was varied as 5 wt% and 10 wt%.

- Scrap Alumunium

The weighing documentation shows in figure no 1, where three pieces of aluminum scrap on a digital scale. One piece weighing 700 grams was used as pure aluminum, while the other two pieces weighing 591 and 594 grams were used for the 5Wt% and 10Wt% Al-Mg mixtures.

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Figure 1. Aluminum Scrap Composition

- Magnesium

Figure 2. Magnesium Composition

Visual documentation shows two magnesium containers on a digital balance weighing 38 and 59 grams, representing the Mg additions to produce 5% and 10% Al-Mg alloys, as described in Table 1.

Table 1. Composition of Scrap Al and Mg

Variation	Composition (gr)		Total Weight (gr)
	Scrap Al	Mg	
Scrap Alumunium	700	-	707
Al-Mg 5Wt%	591	29,55	620,55
Al-Mg 10Wt%	594	59,4	653,4

The table shows the composition of Al and Mg mixtures for variations in weight percentage (Wt%) of Mg. 707 grams of pure aluminum scrap without the addition of Mg. For the 5Wt% Al-Mg variation, 591 grams of Al and 29.55 grams of Mg were used, totaling 620.55 grams. In the 10Wt% Al-Mg variation, the mixture consisted of 594 grams of Al and 59.4 grams of Mg with a total weight of 653.4 grams.

- Wood Pattern

Figure 3. Wood Pattern

The following shows the steps for calculating the total volume and mass of cast material required. Wood pattern volume.

$$V = p \times l \times t = cm^3 \quad (1)$$

Wood pattern mass

$$m = V \times \rho \tag{2}$$

Crucible Furnace, a furnace for melting metal using charcoal burning and a blower, Blower, to provide the air needed for charcoal combustion and maintain furnace temperature. Charcoal for furnace combustion. Mold, a silica sand mold that holds molten metal.

2.2. Smelting Process

After the furnace temperature reaches 707°C, the aluminum pieces are put into the crucible and allowed to melt completely.

Figure 3. Melting Furnace

Mold making starts with preparing a wooden pattern according to the shape of the object to be molded, then the pattern is inserted into silica sand that has been mixed with a binder. The sand is compacted around the pattern to form a mold cavity, then the wooden pattern is carefully removed. After the molten aluminum is mixed with Mg, the molten metal is poured into the sand mold shown in figure 5. The molten metal is cooled to solidify, then the sand mold is opened to remove the casting. After the casting is removed, the surface is cleaned of any remaining sand using a wire brush for a smoother finish.

Figure 4. Final Mold Making

Table 2. Casting Result

Variation	Casting Result
Scrap Al	
Al-Mg 5Wt%	
Al-Mg 10Wt%	

Figure 5. Liquid Metal Pouring

2.3. Spectrocopy testing (chemical composition)

The spectrocopy testing process refers to the ASTM E1251 standard. Making specimens for spectroscopy tests is done by preparing tools and materials such as hand saws, ragums, and casting pieces. After understanding the working drawings, the specimen is marked with a cut mark according to the standard size, clamped on the ragum, then cut using a hand saw according to the predetermined limits.

Figure 6. Laying Out Spectrocopy Specimens

The test is carried out by firing the first point on the surface of the specimen, then the handle is shifted by 5 mm and locked back in a new position. This process is repeated until three firing points are completed on the specimen.

2.4. Metallographic Testing and Hardness Testing

The process of making specimens for hardness tests and microstructure observations was carried out based on ASTM E3-95 standards (Standard Practice for Preparation of Metallographic Specimens)[6]. The preparation stage begins with cutting the sample using a hand saw, then proceeds with a gradual sanding process using a rotary grinder with a level of sandpaper roughness of 1000, 1500, and 2000 grit respectively until the specimen surface becomes flat and smooth.

Figure 7. Metallography and Hardness Specimens

After the sanding process is complete, the specimen is dried using a dryer machine and then observed using an Olympus BX51M optical microscope at 5x to 100x magnification to ensure surface flatness. Sand and polish the specimen until smooth using alumina paste.

- Etching Process Steps

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Prepare an etching solution for the material with the Keller's Reagent method referring to ASTM E407, in the form of 2.5ml HNO3, 1.5ml HCl, and 1ml HF and 95ml distilled water. Figure 9 is the preparation of the etching solution. After the bubbles are no longer visible, the specimen is dried using a dryer.

Figure 8. Etching Process

- Hardness Test Process Steps

Hardness testing is carried out by preparing samples according to standards, then using the micro Vickers method with a diamond pyramid-shaped indenter and loading of 0.2 kgf.

Figure 9. Hardness Testing

2.5. Preparation of Tensile Test Specimens

Making tensile test specimens begins with preparing tools and understanding the work drawings, then giving cut marks according to ASTM E8 standards. The cutting process is carried out using a milling machine with a Ø 20 mm cutter, and the specimen is clamped using clamps and parallel pads to be flat.

Figure 10. Tensile Test Specimen

3. Results and Discussion

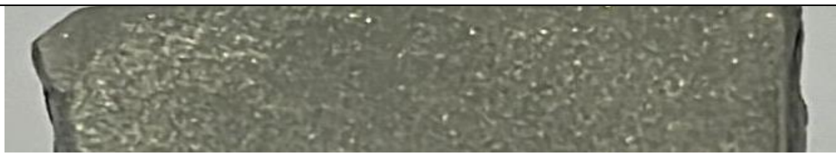
3.1. Visual Observation Results

Visual observation of the specimens that have gone through the casting process with the sand casting method shows differences in surface quality and homogeneity. The observation results are shown in Table 3.The melting of aluminum scrap was conducted with magnesium additions of 5 wt% and 10 wt% at a constant melting temperature of 707 °C. The outcomes of the melting and sand casting processes for the base scrap aluminum and the Al–Mg alloys are summarized in Table 3

Visual inspection of the cast specimens (Table 3) revealed distinct differences in surface quality and casting homogeneity. The specimen produced from aluminum scrap without magnesium addition exhibited the highest visual quality, characterized by a smooth surface, minimal inclusions or cracks, and a relatively uniform internal structure.
In contrast, the addition of magnesium altered the casting characteristics. The Al–5 wt% Mg alloy displayed a higher density of surface defects and inclusions, accompanied by increased surface roughness. However, a further increase in magnesium content to 10 wt% did not result in a proportional increase in visual defects, indicating a non-linear relationship between Mg content and surface quality [7].

These variations are attributed to changes in melt behavior and solidification dynamics induced by magnesium addition. Elevated Mg content is known to increase oxidation tendency and dross formation during melting and pouring, which may promote inclusions and surface irregularities. Nevertheless, the absence of a direct correlation between higher Mg content and defect severity suggests that casting quality is governed by the combined effects of alloy composition, melt handling, oxidation control, and solidification kinetics [8]. Overall, while aluminum scrap without magnesium addition yields the best visual casting quality, the presence of magnesium does not inherently lead to increased surface defects, highlighting the importance of process control in high-Mg recycled aluminum alloys.

Table 3. Sand Casting Result

Composition	Visual Observation Result
Scrap Al	
Al-Mg 5Wt%	
Al-Mg 10Wt%	

3.2. Chemical Composition Testing Results

Chemical composition tests were performed on the specimens to ensure that the material used matched the required aluminum series.

Table 4. Spectroscopic Analysis Results of Aluminum Scrap

Chemical Composition	1	2	3	**Average**
Al	98.55	98.61	98.57	98.58
Si	<1.00	<1.00	<1.00	<1.00
Fe	0.308	0.256	0.302	0.289
Cu	0.0037	0.0034	0.0041	0.0037
Mn	0.0050	0.0048	0.0047	0.0048

Mg	0.0240	0.0187	0.0204	0.0210
Zn	<0.0020	<0.0020	<0.0020	<0.0020

Based on the spectroscopic composition analysis of the aluminum scrap presented in Table 4, aluminum is identified as the primary constituent, with an average content of 98.58%, indicating the high purity of the recycled material. Silicon is present at 0.99%, while the remaining 0.43% consists of minor uncontrolled elements. The analysis further reveals a very low magnesium content of only 0.0210%, confirming that the aluminum scrap is essentially Mg-free. This compositional condition makes the material particularly suitable for intentional magnesium addition as an alloying element to enhance mechanical properties, such as hardness and tensile strength [9].

Based on the spectroscopic analysis presented in Table 5 the sample contains 95.63% aluminum and 3.64% magnesium. Compared with the chemical composition of the aluminum scrap prior to magnesium addition, this represents an increase in magnesium content of 3.61%. These results indicate that the aluminum alloy produced through melting with a 5 wt% Mg addition can be classified within the 5xxx series aluminum alloys. One representative alloy in this series is AA5052, which is widely recognized for its moderate strength, good corrosion resistance, and excellent weldability. At this concentration, magnesium contributes significantly to the enhancement of mechanical strength and corrosion resistance of the alloy [10].

Table 5. Spectroscopic Analysis Results of Al-Mg 5%

Chemical composition	1	2	3	**Average**
Al	95,54%	95,77%	95,59%	95,63%
Si	0,147	0,136	0,148	0,144
Fe	0.436	0.417	0.416	0.423
Cu	0.0249	0.0238	0.0249	0.0245
Mn	0.0178	0.0164	0.0169	0.0170
Mg	3.71	3.53	3.69	3.64
Zn	0.0584	0.0554	0.0628	0.0589

In addition to the primary alloying elements, approximately 0.73% of other elements were detected but not specifically identified. These elements are likely present as trace elements or contaminants originating from the melting process and are difficult to fully control during scrap-based recycling operations.

Table 6. Spectroscopic Analysis Results of Al-Mg 10%

Chemical Composition	1	2	3	**Average**
Al	92,32	92,32%	92,29%	92,31%
Si	<1,00	<1,00	<1,00	<1,00
Fe	0.391	0.380	0.355	0.375
Cu	0.0781	0.0798	0.0729	0.0769
Mn	0.0330	0.0329	0.0318	0.0326
Mg	>5,00	>5,00	>5,00	>5,00
Zn	0.115	0.120	0.109	00.115

Referring to the spectroscopic results presented in Table 6, the sample contains 92.31% aluminum and 6.69% magnesium. Compared with the initial composition of the aluminum scrap prior to magnesium addition, this corresponds to an increase in magnesium content of 6.66%. These results indicate that the alloy produced by melting aluminum scrap with a 10 wt% Mg addition falls within the category of 5xxx series aluminum alloys. A representative alloy within this series is AA5083, which is well known for its medium-to-high strength, excellent corrosion resistance, and good weldability. At this magnesium level, Mg contributes significantly to the enhancement of mechanical properties and resistance to corrosive environments.

In addition to the primary alloying elements, approximately 1% of other elements were detected but could not be specifically identified. These elements are likely present as trace elements or contaminants introduced during the melting process and are difficult to fully control in scrap-based recycling operations.

3.3. Microstructure Observation Results

Microstructure observations using optical microscopy showed changes in grain morphology and Mg phase

3.3.1 Microstructure Scrap Al

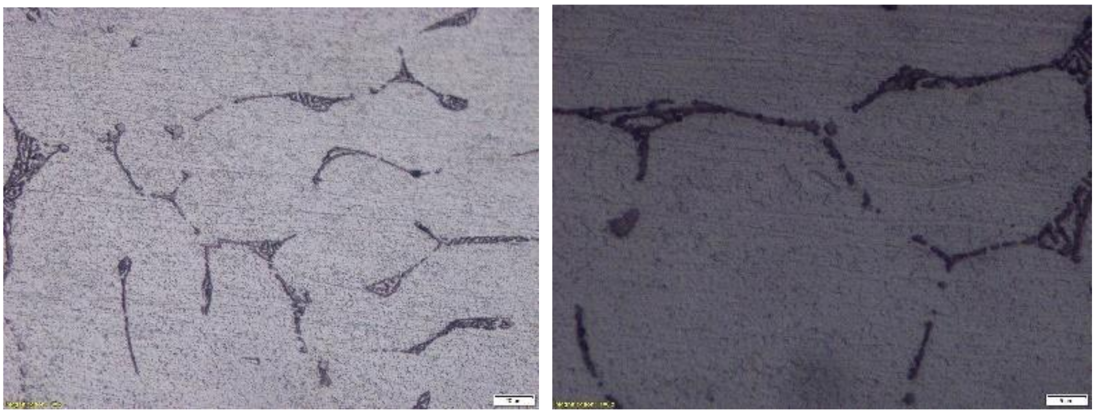


Figure 12. Microstructure of Scrap Aluminum Specimen

Based on the microscopic observations shown in Figure 6, the aluminum microstructure consists of relatively large, irregular polygonal grains. Clearly defined grain boundaries are observed, indicating distinct separation between individual crystals within the metallic structure. As the examined material is predominantly pure aluminum, the microstructure exhibits dark intermetallic phases that are non-uniformly dispersed within the aluminum matrix. The grain orientation appears random, suggesting the absence of any preferred crystallographic texture resulting from deformation. Overall, this microstructural morphology is consistent with the typical characteristics of high-purity aluminum materials [11].

3.3.2 Microstructure Scrap Al-Mg 5%

Based on the observations in Figure 13, the microstructure of aluminum scrap cast with a 5 wt% magnesium addition exhibits pronounced changes compared to aluminum without magnesium. Dark particles are observed to be non-uniformly distributed within the metal matrix and are identified as Mg-rich intermetallic phases, formed as a result of the reaction between aluminum and magnesium during solidification [12].

In addition, dark, rounded inclusions are present, which are attributed to gas entrapment during the casting process. These inclusions likely originate from entrapped gases or oxide particles that were unable to rise to the melt surface prior to solidification. Consequently, they remain trapped within the solidified structure, forming closed pores that are clearly visible in the microstructural images [13].

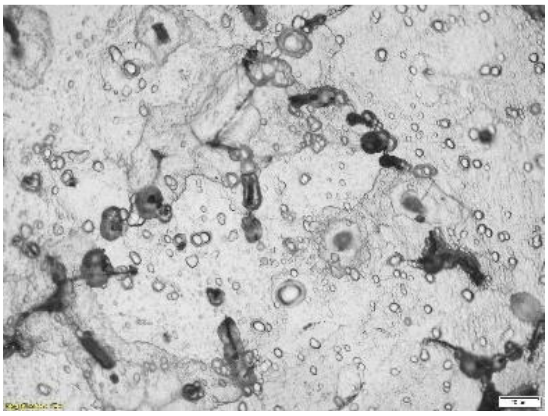


Figure 13. Microstructure of Al–Mg 5 wt% Alloy

3.3.3 Microstructure Scrap Al-Mg10%

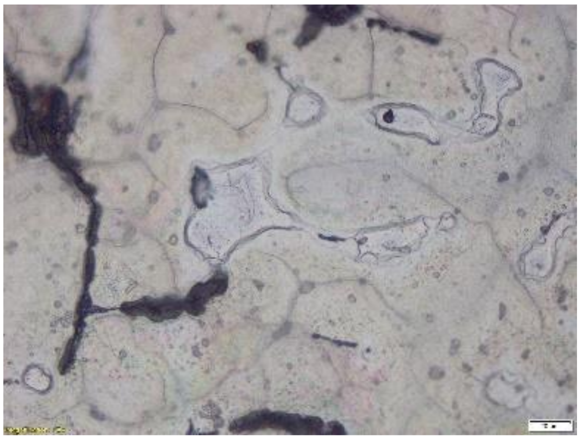


Figure 14. Microstructure of Al–Mg 10 wt% Alloy

Referring to Figure14, the microstructure of aluminum scrap cast with a 10 wt% magnesium addition exhibits a more complex and heterogeneous morphology. Aluminum grains (α-Al phase) are surrounded by darker intermetallic phases formed through the reaction between aluminum and magnesium during solidification. These Mg-rich intermetallic phases are predominantly distributed along grain boundaries, indicating intensive elemental interaction during the solidification process [14].

Furthermore, eutectic structures are observed in several regions, suggesting more pronounced magnesium segregation with increasing Mg content. This behavior indicates a tendency for magnesium to concentrate locally within the microstructure, forming characteristic networks along grain boundaries (11).

Irregularly shaped dark regions are also detected & identified as inclusions. These inclusions are most likely associated with entrapped gases, oxides, or solid particles that failed to escape from the molten metal prior to solidification. As a result, internal defects are formed, which may adversely affect the mechanical properties of the alloy [15].

Overall, the addition of magnesium up to 10 wt% leads to an increased volume fraction and wider distribution of intermetallic phases within the microstructure. While this microstructural evolution can contribute to enhanced alloy strength, it may simultaneously reduce ductility and increase susceptibility to brittleness in the material (13).

3.4. Vickers Hardness Testing Results

The hardness test results using the Vickers method show a significant increase in hardness values as the magnesium content in the aluminum alloy increases. The following table presents the hardness test results:

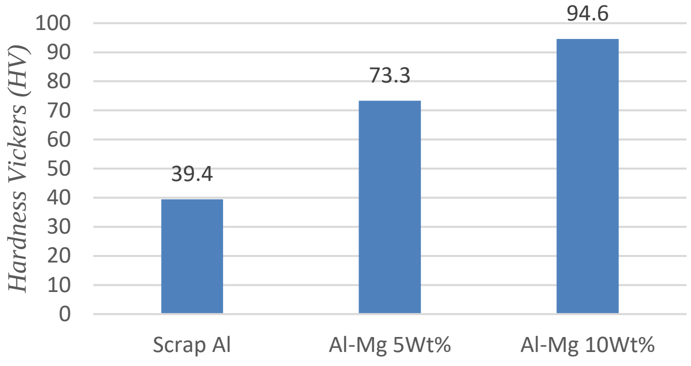


Figure 11. Hardness Value Comparison Chart

This increase in hardness is due to the formation of intermetallic phases between Al and Mg, which strengthen the metal structure through solid solution strengthening mechanisms and the formation of fine precipitates. At 10 wt% Mg, more reinforcing phases are formed resulting in the highest hardness (94.6 HV), almost 2.4 times higher than that of aluminum without magnesium addition (39.4 HV).

3.5. Tensile Strength Testing Results

Tensile testing is done to measure the maximum strength that a metal can withstand before undergoing plastic deformation. The results are presented in the following table: Based on the tensile test results, pure aluminum scrap exhibits the lowest mechanical performance, with an ultimate tensile strength of 49.5 MPa and a yield strength of 46.03 MPa, indicating a soft material that undergoes plastic deformation easily. The addition of 5 wt% magnesium results in a significant improvement, with the tensile strength increasing to 145.5 MPa and the yield strength to 132 MPa, demonstrating the effectiveness of magnesium in strengthening the aluminum crystal structure.

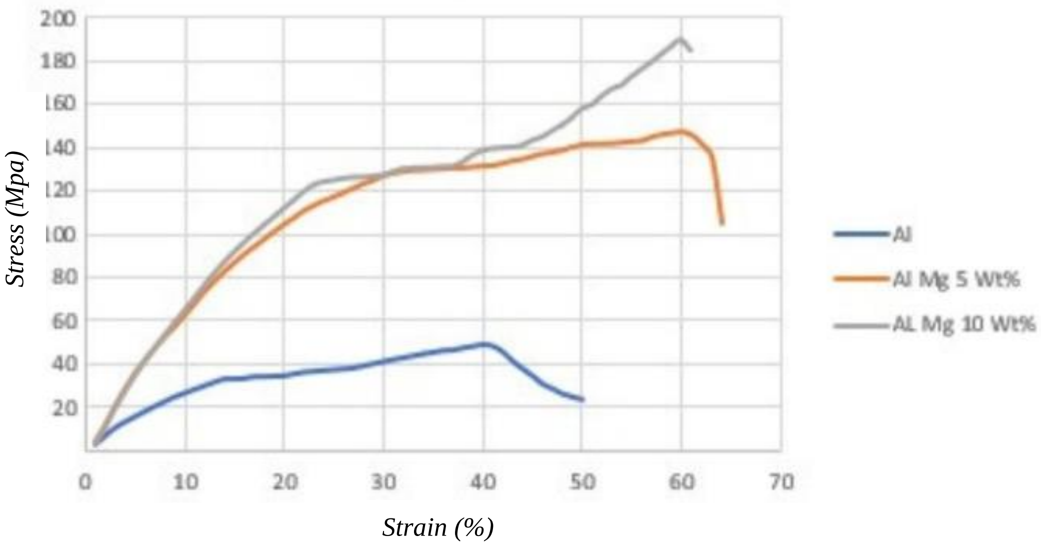


Figure 12. Stress Strain Graph

With a further increase in magnesium content to 10 wt%, the tensile strength rises to 181.5 MPa, representing an additional increase of 36 MPa compared to the 5 wt% Mg alloy. Overall, magnesium addition enhances the tensile strength by more than threefold relative to pure aluminum scrap, confirming its substantial strengthening effect in recycled aluminum alloys.

Table 7. Tensile Test Fracture Results

Content	Tensile Test Result Fracture
Scrap Al	
Al-Mg 5Wt%	
Al-Mg 10Wt%	

Tensile test results showed that aluminum scrap fractured ductilely, Al-Mg 5Wt% experienced slight necking with increased strength and ductility, while Al-Mg 10Wt% showed coarse fracture and tended to be brittle.

4. Conclusion

This study demonstrates that the mechanical performance of recycled aluminum scrap can be significantly enhanced through controlled magnesium alloying. The initial aluminum scrap, characterized by high aluminum purity but limited mechanical strength, exhibits substantial improvements in hardness, yield strength, and tensile strength following magnesium addition. Specifically, the introduction of 5 wt% Mg results in a pronounced increase in strength due to solid-solution strengthening and the formation of Mg-rich intermetallic phases. Further increasing the magnesium content to 10 wt% leads to additional improvements in tensile strength, reaching 181.5 MPa, which is more than three times higher than that of the unalloyed aluminum scrap. Microstructural observations reveal a higher volume fraction and wider distribution of Mg-rich intermetallic phases, predominantly along grain boundaries, accompanied by localized eutectic structures. While these microstructural features contribute to strength enhancement, they also indicate a potential trade-off in terms of ductility and susceptibility to brittleness at higher magnesium levels. Overall, the results confirm that the inherent limitations of recycled aluminum—such as compositional variability and impurity effects—can be effectively mitigated through appropriate magnesium alloying. The findings highlight the feasibility of producing high value-added, lightweight aluminum alloys from recycled scrap using conventional sand casting processes, thereby supporting sustainable materials development and broader industrial adoption of recycled aluminum for structural application

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