International Journal of Innovative Scientific & Engineering
Technologies Research 11(3):36-49, July-Sept, 2023

© SEAHI PUBLICATIONS, 2023 www.seahipaj.org ISSN: 2360-896X

Assessing the Mechanical Properties of an Aluminum-Copper-Magnesium Alloy

[1]Ugwuoke, N. F., [2]Onyia P. E., [3]Onyia T. M., [4]Nwogbu C. C., [5]Iyida L. O., [6]Agboeze N. A.

[1,2,3,4&5] Department of Metallurgical and Materials Engineering,
Enugu State University of Science and Technology, Enugu, Nigeria.
***Corresponding Author Contacts; +2348103551255, ugwuoke.nnamdi@esut.edu.ng**

ABSTRACT

This study aims to evaluate the mechanical behavior of Aluminum-Copper-Magnesium Alloy signifying the effect of adding magnesium to an alloy of Al-Cu to determine its potential for engineering applications. The research involved a series of processes, including melting the materials using a crucible furnace, followed by casting, machining, heat treatment, and subsequent testing. Five samples of the alloy were produced, with one serving as the control sample (96wt% Al + 4wt% Cu), and the remaining samples containing increasing percentages of magnesium ranging from 0.5wt% to 2wt%. Various mechanical tests, such as hardness, impact, flexural, and tensile tests, were conducted, along with microstructural analysis. The result revealed that adding magnesium to the base alloy (96wt% Al-4wt% Cu) increased the hardness of the aluminum alloy as the magnesium content increased. Additionally, the resistance to flexural force also demonstrated an upward trend with increasing magnesium content, up to 2wt%. However, analysis of the fracture surface indicated a decrease in ductility as the magnesium percentage increased. Furthermore, the material exhibited improved tensile strength, reaching its peak of 176.84N/mm^2 at 2wt% Mg while the lowest of 79.578N/mm^2 and 123.79N/mm^2 at 0wt% Mg (control) and 0.5wt%Mg respectively. Microstructural analysis unveiled that at 2wt% magnesium, the precipitation of magnesium occurred along the grain boundaries, forming flakes. Conversely, magnesium was uniformly distributed within the grains at lower magnesium percentages. These findings suggest that the addition of magnesium to Al-Cu alloy will greatly increase mechanical properties like hardness, tensile strength, and resistance to flexural force while decreasing ductility. The fractured surface in line with the microstructural analysis gives insight into mechanical failure and root cause through the composition and diffusion. Thus, magnesium proves positive for strength addition in Al-Cu alloy which is potentially can mitigate creeping-related issues.

Keywords: Aluminum, Copper, Magnesium, Alloy, Hardness, Flexural, Bend, Impact, Mechanical Properties, Microstructure, Microstructural Analysis, Alloy Composition, Aluminum Alloy, Al-Cu-Mg

INTRODUCTION

Materials selection plays a crucial role in engineering, surpassing the significance of the final product. Understanding the behavior of materials is imperative for their successful application. This study focuses on investigating the mechanical properties of an aluminum-copper-magnesium alloy for potential application in the automobile industry, castings, structural engineering, and high-strength, low-weight applications. While aluminum is widely available and possesses desirable characteristics such as ductility, malleability, corrosion resistance, and good thermal and electrical conductivity, it is often inadequate for certain structural and engineering applications. Therefore, it is essential to examine the behavior of aluminum alloys.

Alloys, which are metallic materials formed by combining two or more elements in a homogeneous composition (French, 2018), offer distinct advantages over pure metals. While pure metals consist of individual metal crystals that are malleable, soft, and possess high electrical conductivity, they are limited in their applications. On the other hand, alloys exhibit improved corrosion resistance and are less susceptible to changes in atmospheric conditions. Furthermore, the hardness of alloys can be modified through specific heat treatments, and their conductivities can vary depending on the weight percentage of the constituent elements.

Previous research by Kaufman (2008) mentioned that Aluminum-magnesium alloys offer the advantage of being lighter compared to other aluminum alloys and are less prone to flammability issues associated with high-magnesium alloys, however, this did not give in detail the compositions of these elements and their mechanical orientations for diverse applications which this research is essential to bring to light. The addition of copper to aluminum alloys contributes to significant strength improvements and enables precipitation hardening (Raqaya et al, 2015), however, the inclusion of copper in aluminum can reduce ductility and corrosion resistance. Definitely, the alloy of Al-Mg and Al-Cu will produce a new material that needs the mechanical characteristics to be understood based on the percentage of the constituent elements.

When selecting an appropriate alloy for a specific application, various factors come into play, including tensile strength, density, ductility, formability, workability, weldability, and corrosion resistance (Safranski and Gall, 2017). Therefore, it becomes essential to study the properties and effects of different alloying elements and their quantities. Due to their high strength-to-weight ratio, aluminum alloys find extensive use in aircraft (Stojanovic et al, 2018). Conversely, pure aluminum is too soft for such applications and lacks the necessary tensile strength required for airplanes and helicopters. Hence, alloying elements are added to aluminum to enhance its mechanical properties, and knowing the effect of these elements and the amount of composition that will effect this desired change is necessary, thus the significance of this study. Recent advancements in aluminum alloys have broadened the scope of applications for wrought aluminum, replacing traditional aluminum castings.

The microstructures and mechanical properties of wrought aluminum alloys are highly influenced by different working processes and thermal treatments according to Ny Khudair (2017), hence there is a vital need to understudy the microstructural orientation of alloy and the effect of heat treatment and how it's going to affect the mechanical properties. The introduction of alloying elements has further enhanced the mechanical properties of aluminum alloys, expanding their potential applications, particularly in the aerospace and automotive industries (Ying et al, 2016). This progress signifies a significant step towards utilizing wrought aluminum alloys in various engineering fields.

Through extensive research, engineers have made significant advancements in creating a wide range of aluminum alloys aimed at enhancing their mechanical properties. Among the various alloying elements utilized, copper and magnesium have emerged as particularly valuable. These elements possess distinct properties that contribute to the improvement of aluminum's mechanical characteristics, thereby increasing the likelihood of selecting aluminum alloys for diverse applications during the material selection process. These metals possess distinct characteristics that contribute to their uniqueness and importance in this research. Aluminum alloys offer economic advantages in numerous applications, as mentioned by D Féron (2017), and have a diverse range of uses. However, some elements used in aluminum alloys can be costly, and the preparation methods can be expensive due to the need for precision during production.

In contrast, magnesium, another essential component in the study, is known to be inflammable in its powdered form, and care must be taken during the casting stage to avoid oxides inclusions. These inclusions can lead to changes in the properties of the final product, as highlighted by Vinojitha (2012). Understanding and addressing these unique characteristics are crucial for the successful utilization of these metals in various applications, hence, another significance of this study.

Molten magnesium tends to oxidize and burn unless care is taken to protect its surface against oxidation. Unlike aluminum alloys which tend to form a continuous, impervious oxide skin on the molten bath limiting further oxidation, magnesium alloys form a loose, permeable oxide coating on the molten metal surface. This allows oxygen to pass through and support burning below the oxide at the surface. Protection of the molten alloy using either a flux or a protective gas cover to exclude oxygen is therefore necessary. There are basically two main systems, flux, and flux less, for the melt protection of magnesium alloys (Alil et al, 2015).

Considering the properties we are set to determine, hardness is the resistance of a material to localized plastic deformation, ranging from super hard materials like diamonds to soft metals and plastics. Other properties like toughness and strength also play a role, as hard materials may have low toughness and be prone to fracture. Hardness can be assessed through indentation, scratch, and rebound hardness measurements.

Strength is a material's ability to withstand applied loads without failure or plastic deformation. Al-Cu-Mg alloy exhibits good mechanical strength and can be precipitation hardened to achieve strengths similar to steel. Toughness, on the other hand, refers to a metal's ability to deform plastically and absorb energy before fracture. A combination of strength and ductility contributes to toughness. It can be measured by calculating the area under the stress-strain curve from a tensile test. When comparing the strength of Al-Cu-Mg alloy with its weight, it is discovered that the ratio of strength to weight is always high (Joseph, 2011).

Ultimate tensile strength (UTS) represents a material's maximum resistance to fracture under simple tension. It is an important measure for assessing a material's performance in applications. It’s therefore very useful that this work will help influence decision-making on the choice of material in particular Al-Cu-Mg alloy for a given application and the work performance of these materials can be predicted to give the desired performance upon application. These will also help the producers during production to understand the unique properties of each composition.

2.0 MATERIALS AND METHODS

2.1 Materials

- Aluminum billets of 98.9% purity.
- Copper powder of 98.5% purity.
- Manganese powder of 99.8 purity
- Crucible furnace.
- Permanent mold.
- Weighing balance.
- Universal tensile strength testing machine.
- Charpy Impact testing machine.
- Digital Rockwell hardness tester.
- Optical microscope

2.2 Methods

2.2.1 Samples Preparation

Materials used for this experiment include commercially available aluminum of 98.9 % purity in the form of bundles of wires, 98.5 % pure copper, and 99.8% pure magnesium both in powdered metal form.

A permanent mold was specifically designed to manufacture standardized samples of an Al-Cu alloy. The composition of the alloy consisted of 4 wt% copper and 96 wt% aluminum. Initially, the alloy was produced as a billet with dimensions 40 mm in gauge diameter and 150 mm in gauge length, and upon solidification, a precisely measured portion was selected for alloying with magnesium. The magnesium content was incrementally increased from 0.5 wt% to 2 wt% while maintaining the aluminum-copper alloy's overall percentage.

Table 1 Chemical compositions of the Al-Cu-Mg alloy developed

S/N	Type of sample	Wt% of AlCu	Wt% of Mg
1	$Al_{96}Cu_4$ Control sample	100	0
2	$AlCu_{99.5}Mg_{0.5}$ Sample 1	99.5	0.5
3	$AlCu_{99}Mg_1$ Sample 2	99	1
4	$AlCu_{98.5}Mg_{1.5}$ Sample 3	98.5	1.5
5	$AlCu_{98}Mg_2$ Sample 4	98	2

To produce the desired samples, a total of 6000g of the alloy was required. An additional 600g was added to account for casting risers, gating, and tolerance against waste. For measuring the alloy constituents, a portable digital weighing machine was utilized, providing accurate measurements. The aluminum was obtained in wire form, which was then cut into smaller pieces to facilitate efficient melting and ease of measurement.

The crucible furnace used for melting the alloy was preheated to 200°C to eliminate any moisture content. The melting temperature was carefully controlled and varied between 450°C to 1100°C, considering the preheating, heat required for melting all constituents, and the homogenization process of the alloy mixture.

To achieve proper homogenization, the constituents were charged into the crucible in a specific order based on their melting point temperature and quantity. Al-Cu alloy was introduced first, followed by the addition of Mg. It is important to note that precautions were taken during the addition of Mg to prevent contact with atmospheric oxygen, as Mg readily reacts and is flammable. A pipe was used as a guide to ensure the safe introduction of Mg into the alloy without exposure to oxygen.

In the experiment, a mold designed to accommodate 1200g of the alloy per charge was utilized, allowing for the production of three samples in a single pour. The final test samples were cast in a steel pipe with an internal diameter of 15mm and a gauge length of 200mm.

2.2.2 Method of Testing

Hardness tests were conducted using a Digital Rockwell hardness tester, 15mm sections were cut from each sample, followed by grinding and polishing of the surface. Three indentations were made on each sample, and the average value of the hardness was calculated from these three measurements. This approach ensures a more accurate representation of the sample's hardness properties and minimizes the potential impact of alloying element segregation.

A Charpy Impact testing machine was used to conduct the impact test, the samples were notched with a 3mm cut, with the notched side facing the direction of the impact force of 50 Joules.

For the flexural test, the triple point flexural test method was employed, with a span length of 55mm using a Universal material tester. The flexural strength was read from the calibrated scale on the machine. These tests assess the samples' ability to resist bending moments and provide essential data on their toughness and resilience.

For the tensile test, the samples were machined to a gauge length of 70mm, a gauge diameter of 6mm, and a gripping diameter was 13mm to fit into the Universal tensile testing machine. The ductility of the material was calculated using the data from the tensile test as follows:

$$\text{Percentage elongation (ductility)} = \frac{increase\ in\ length}{original\ length} \times \frac{100}{1}$$

For the microstructural study, the sample underwent the following preparation steps:

- Cutting: The sample was cut to the desired size for examination.
- Grinding: The cut sample was carefully ground to achieve a smooth and flat surface.
- Polishing: After grinding, the sample was polished to further refine the surface and remove any surface imperfections.
- Etching: Kroll's solution, consisting of 25ml of HCl acid, 25ml of nitric acid, and 2ml of HF acid, was used as the etchant. The sample was immersed in this solution for a specific duration of time to reveal the microstructure.
- Rinsing: Once the etching process was complete, the sample was thoroughly rinsed to remove any residual etchant.
- Drying: After rinsing, the sample was carefully dried to prevent any contamination.

Examination: The prepared sample was then examined using a Laboratory Electro-Optical Microscope. This microscope allows for detailed observation and analysis of the sample's microstructure, providing valuable information about its internal features, grain boundaries, and any defects present.

3.0 RESULTS

3.1 Hardness Variation of the Aluminum Alloy, Samples

Table 2 Readings of the hardness tests of the samples in HRC (Rockwell)

Samples	**1st reading**	**2nd reading**	**3rd reading**	**Average**
Control	45.6	32.6	50.4	42.87
0.5%	38.7	52.6	49.2	46.83
1%	57.7	51.9	66.5	58.7
1.5%	70.6	68.8	70.2	69.9
2%	74.6	72.8	72.4	73.26

Analysis of the readings taken from different parts of the polished face of the test samples reveals a clear trend in hardness. The control sample, which contains 0% magnesium, exhibits the lowest average hardness value. As the percentage of magnesium increases, the hardness of the samples also increases. Notably, the sample with 2wt% magnesium demonstrates the highest hardness value, indicating that it is the hardest among the tested samples. This observation suggests that the addition of magnesium contributes to the enhancement of hardness in the alloy.

3.2 Fracture (Impact) Variation of the Aluminum Alloy Samples

Table 3 Readings of the impact test of the samples

Samples (%Mg)	**Energy Absorbed (J)**
Control	58
0.5%	61
1%	37.5
1.5%	18
2%	11

During the experiment, a total of 300 joules of energy was directed at the material, and the amount of energy absorbed by the test samples was measured and recorded. The results, displayed on the right-hand side of the table, indicate that the control sample absorbed 58 joules of energy. Surprisingly, the sample with 0.5% magnesium absorbed the highest energy, measuring 61 joules, slightly higher than the control sample. However, as the percentage of magnesium increases in the alloy, the energy absorbed by the samples decreases. The sample with 2% magnesium exhibited the lowest absorbed energy despite having the highest magnesium content. These findings indicate that the presence of magnesium in the aluminum-copper alloy reduces its toughness, with the sample containing 2% magnesium demonstrating the lowest toughness. However, it is interesting to note that the sample with 0.5% magnesium defies this trend by exhibiting higher toughness than the control sample. This suggests that even a small amount of magnesium, as low as 0.5%, can strengthen the material. Another notable observation made during the test was the behavior of the materials and their failure modes. Both the control sample and the 0.5% magnesium sample exhibited high ductility, as they did not break but rather bent even with the presence of a notch. In contrast, the samples with 1%, 1.5%, and 2% magnesium showed a brittle effect in their failure modes, indicating reduced ductility.

3.3 Flexural Test Behavior of the Samples

Table 4 shows the Flexural test result of the control sample

FORCE (KN)	BEND (mm)
4	2
5	4
6	6
6.75	8
7.5	9

The Flexural strength (F_s) can be calculated using the formula below

$F_s = \frac{3PL}{2b\,d^2}$

Where F_s = flexural strength of the material

P = load (force)

L = length of the span

b = thickness

d = width

From the experiment, our Length of span L is equal to 55mm, the width is equal to the thickness which is equal to the diameter of the cylindrical test samples 15mm.

Therefore, $Fs = \frac{3 \times 7.5 \times 10^3 \times 55}{2 \times 15 \times 15^2}$ = **183.3N/mm^2**

This is the maximum bending strength the control sample can withstand under flexural loading. Above this, the material will start exhibiting a rapid increment in extension which will lead to failure.

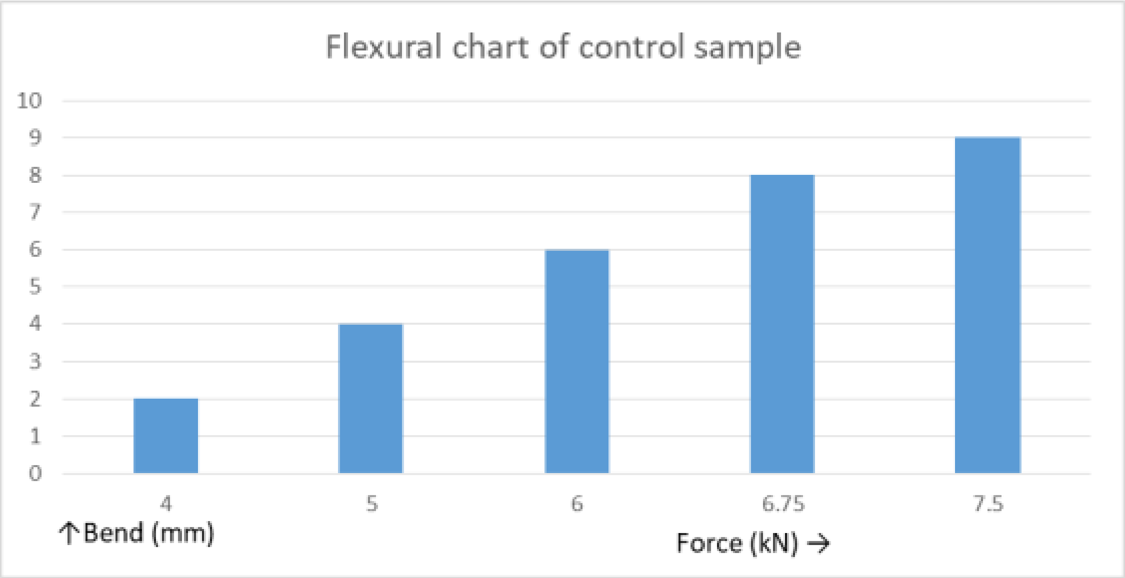


Fig 1: Flexural chart of the control sample

Table 5 Flexural test result of 0.5wt% Mg

Force (KN)	**Bend (mm)**
5	1
6.5	2
7.5	2.5
8	5
8.5	7

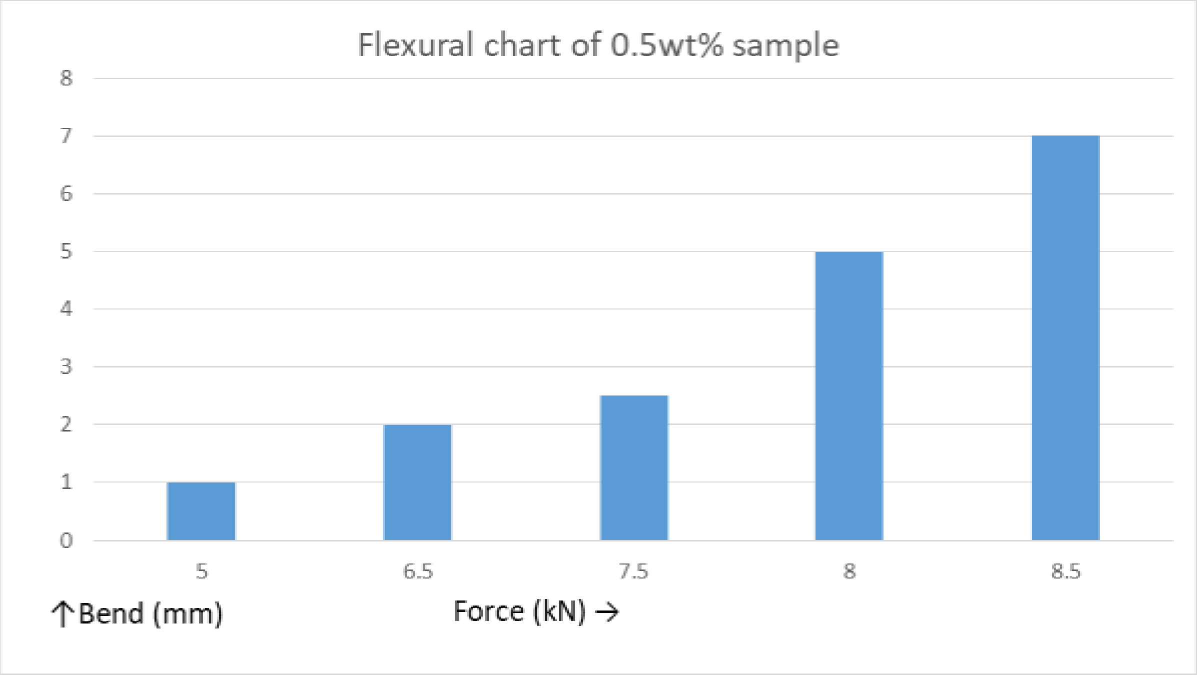


Fig 2: Flexural chart of 0.5wt% sample

The Flexural Strength F_s can be calculated using the formula below

$$Fs = \frac{3PL}{2b\,d^2}$$

P=8.5kN

Substituting the values of the parameters, we have:

$$Fs = \frac{3 \times 8.5 \times 10^3 \times 55}{2 \times 15 \times 15^2} = \mathbf{207.78N/mm^2}$$

The 0.5wt% can withstand a bending stress of 207.78N/mm^2 above which the material will tend to fail. Comparing the result of this with the control above, it can be seen that 0.5% can withstand more bending force than the control.

Table 6. The flexural result of the 1wt% Mg sample

Force (KN)	Bend (mm)
5	2
5.5	3
6.5	3.5
7	4
7.25	6
8	8

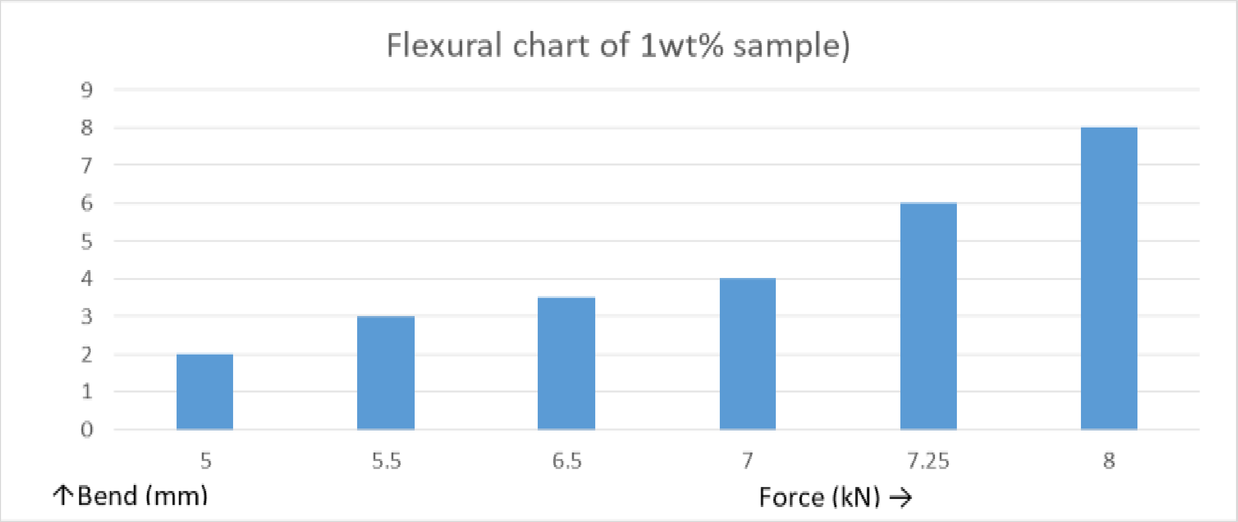


Fig 3: Flexural chart of 1wt% sample

$$fs = \frac{3PL}{2bd^2}$$

$F_s = \frac{3 \times 8 \times 10^3 \times 55}{2 \times 15 \times 15^2}$= **195.55N/mm^2**

The maximum flexural strength is 195.55N/mm^2 which is above the control sample but a little bit smaller than the 0.5wt% sample.

Table 7. Flexural test result of the 1.5wt%Mg sample.

Force (KN)	Bend (mm)
5	2
7	4
8.5	7
8.75	11

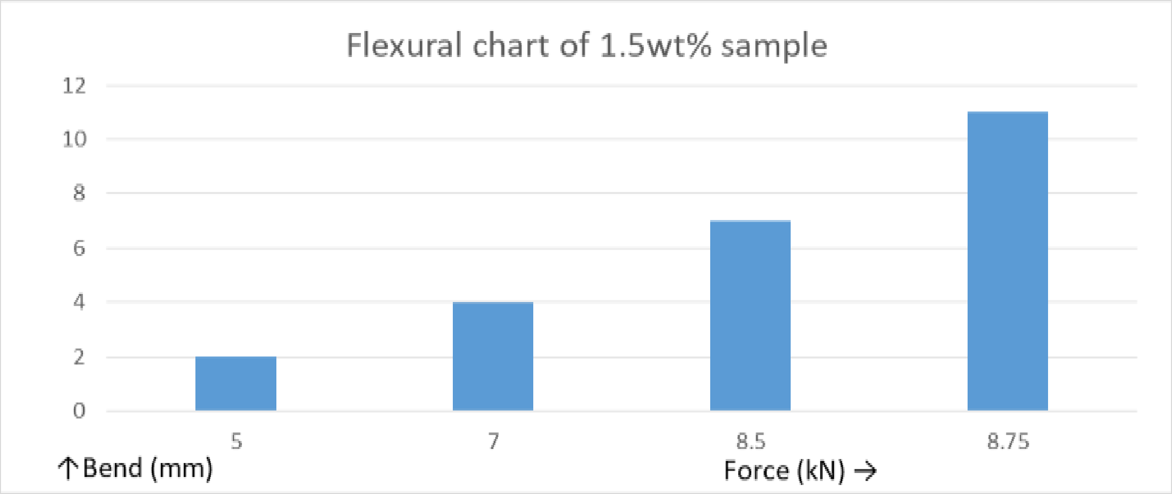


Fig 4: Flexural chart of 1.5wt% sample

$F_s = \frac{3\times8.75\times10^3\times55}{2\times15\times15^2}$ = **213.9N/mm²**

This sample shows a lot of flexural strength according to the value above. The flexural strength exceeded the previous values gotten from the other samples.

Table 8 shows the flexural test result of the 2wt%Mg sample.

Force (KN)	**Bend (mm)**
5	2
6.75	4
7.75	6
8	7.5
9	10

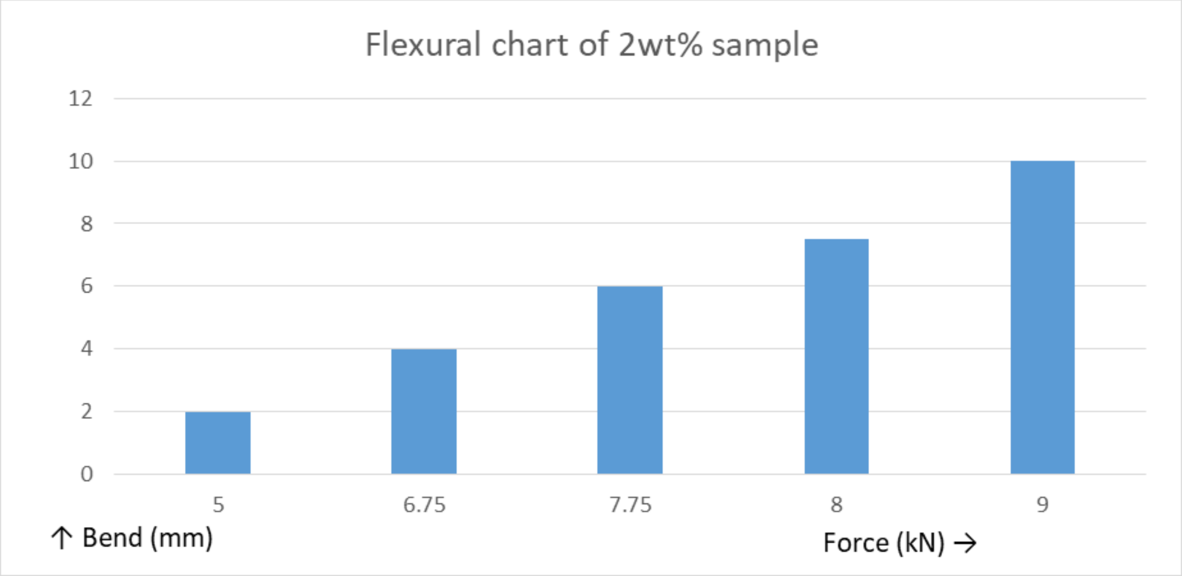


Fig 5: Flexural chart of 2wt% sample

Calculating the flexural strength using the formula $Fs = \frac{3PL}{2bd2}$ we have:

Since the maximum force is 9kN

Therefore, Fs = $\frac{3\times9\times10^3\times55}{2\times15\times15^2}$= **220N/mm²**

The maximum flexural strength of the material is 220N/mm². This is the material with the most flexural strength. This material happens to be the one with the highest percentage of magnesium. Therefore, the presence of magnesium in the alloy increases the resistance to bending force and also the rate of bending before failure as the maximum extension is 10mm.

3.4 Tensile Test Of The Aluminum Alloy Samples

Table 9. Tensile test result of the control sample.

Force (KN)	Extension
1.25	0.15
1.5	0.30
2	0.90
2.25	1.05
1.5	1.15

From the table above, we can calculate the Stress σ, Strain ε, and the plot of Stress against Strain.
Stress, σ =F/A

Where: F is the force

A is unit Area.

Knowing the diameter to be 6mm, the area can be calculated using πd²/4 which is equal to 28.274mm²

Therefore, $\sigma1 = 1.25 \times \frac{10^3}{28.274} = \frac{44.21N}{mm^3}$

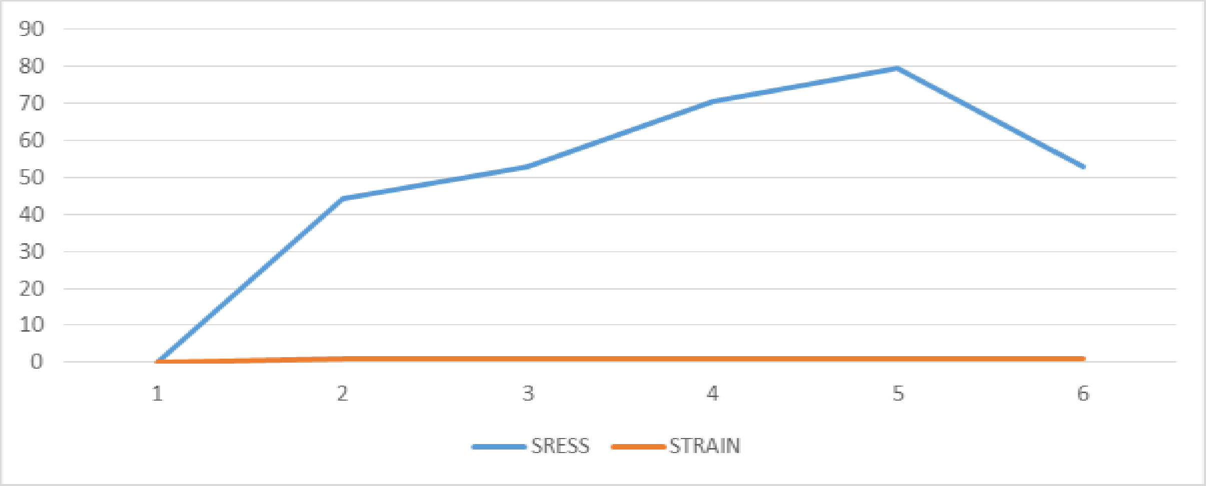
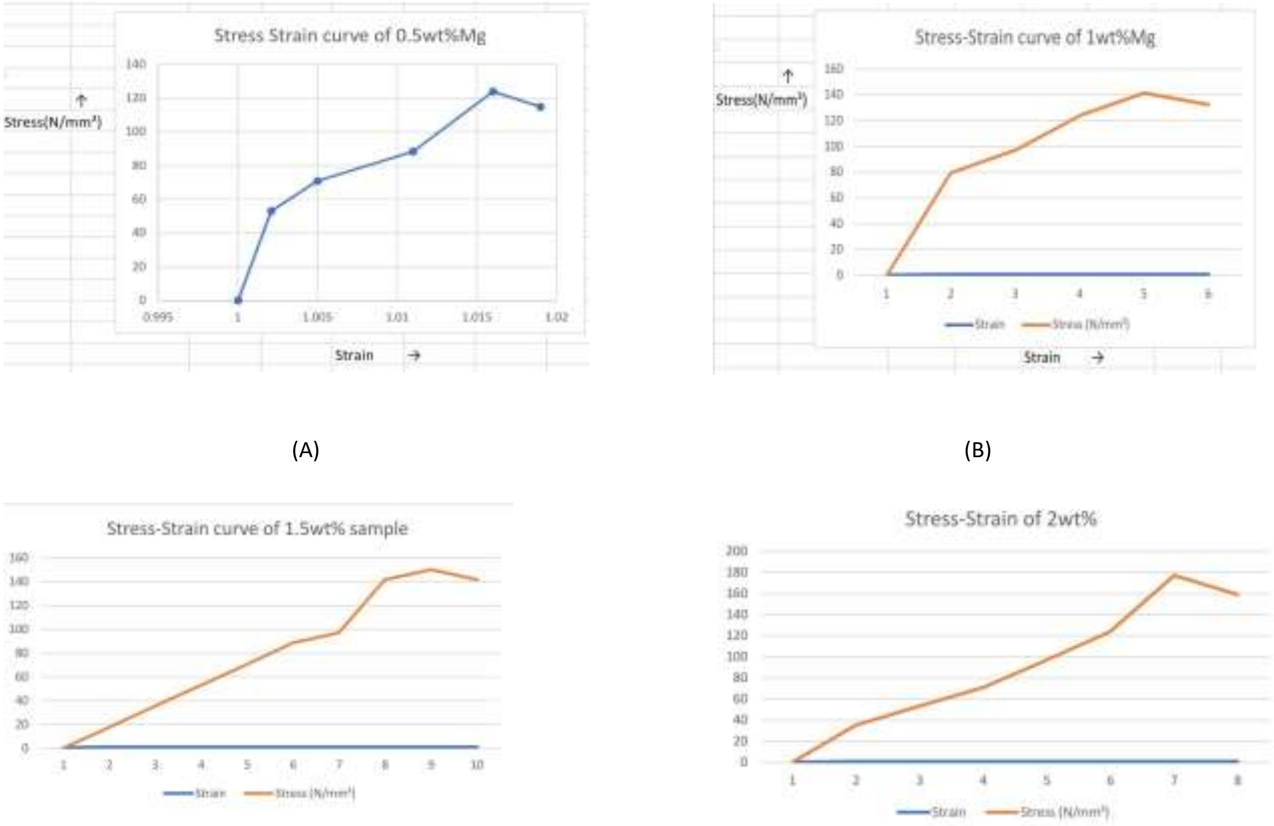


Fig 6: Stress, Strain curve of the control sample

Table 10. The tensile test result of the 0.5wt%Mg sample.

Force (KN)	Extension
1.5	0.5
2	0.35
2.5	0.75
3.5	1.15
3.25	1.35



(A) (B)

(C) (D)

Fig 7: A, B, C D; graph of 0.5wt%, 1wt%, 1.5wt% and 2wt% stress-strain curve respectively

From the graph of the control sample above, the material exhibits an elastic range deformation up to a Stress of 44.21N/mm² after which the plastic region begins. The material yield at the point of stress was equal to 53.05N/mm², however, the Ultimate stress extended to 79.578N/mm² before the fracture occurred at lower stress and higher strain of 53.06N/mm². For the 0.5wt% Mg, The UTS value is 123.79N/mm² which is the maximum tensile strength of the sample. After which the material failed at 114.94N/mm². This shows a very significant effect of magnesium on the alloy of aluminum and copper. The yield stress of 1wt% Mg and that of 1.5wt% happen to be the same value but looking at the UTS value, you discover that the 1.5wt% is higher thereby proving that 1wt% would withhold less force than 1.5wt%. The 1.5wt% has a yield point of 97.26N/mm² and the Ultimate stress of 150.3N/mm², this can be described as the strain-hardened region.

One significant difference in the stress and strain curve for the 2wt% sample is that the material exhibited a very low elastic region, however, proceeded with a plastic region that looks almost like the elastic region. The plastic region is almost linear as that of the elastic. This significant change can be attributed to the behavior of the material due to the effect of the alloying element which created a strain-hardened region. It's as if the material is getting harder with the increase in stress. There's enough resistance the material has to offer to the increasing stress thereby giving it a longer time before failure will occur. Immediately after the Ultimate stress of 176.84N/mm^2, the material stress dropped and rupture occurred.

3.5 Comparison Of Ultimate Tensile Strength (UTS) Values

Looking at the tensile strength values, the highest value of stress in each of the samples represents the Ultimate tensile strength of the sample. The control sample has the least with UTS of 79.578N/mm^2, the UTS increases with increasing magnesium percentage to 176.84N/mm^2 for the 2wt% sample. It is therefore noted that 2wt% Mg has the highest strength coupled with hardness but shows more brittleness than the control sample and 1wt% sample.

3.6 Microstructural Analysis

The micrograph as was carried out using an optical microscope is shown below.

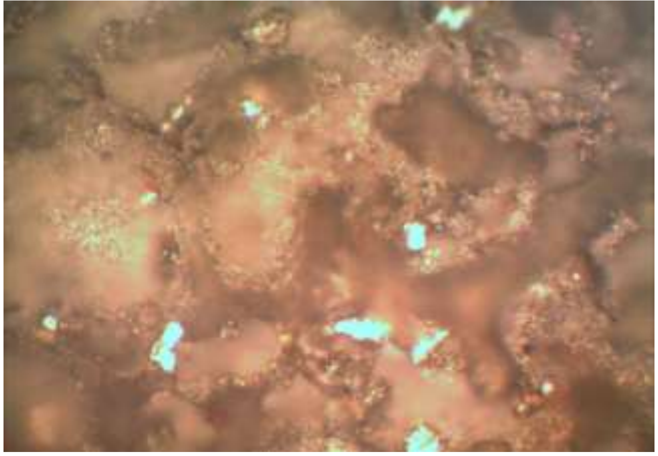


Fig 8: shows the microstructure of the control sample.

There are no phases of magnesium in the microstructure. The dark phase is an aluminum phase with copper scatterings.

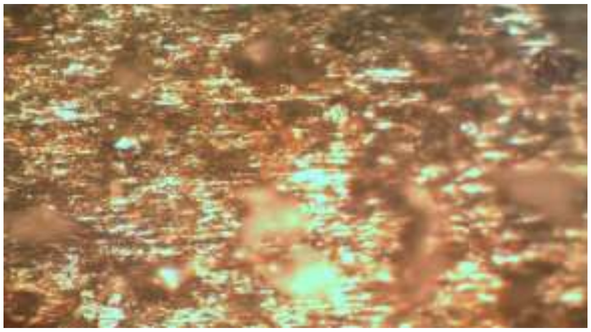


Fig 9: shows the micrograph of 0.5wt%Mg

There are scattered magnesium-containing phases. Also, copper segregation can be seen in the phases with aluminum. Some regions with dark shades cannot be categorically defined as it is beyond the scope of this work.

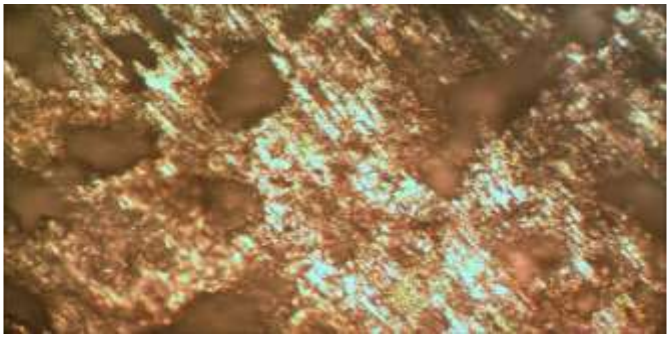


Fig 10: shows the micrograph of 1wt%Mg

In this graph, there are more magnesium-containing phases than in 0.5wt%Mg. These increasing phases can be seen in the hardness test as it increases the hardness property.

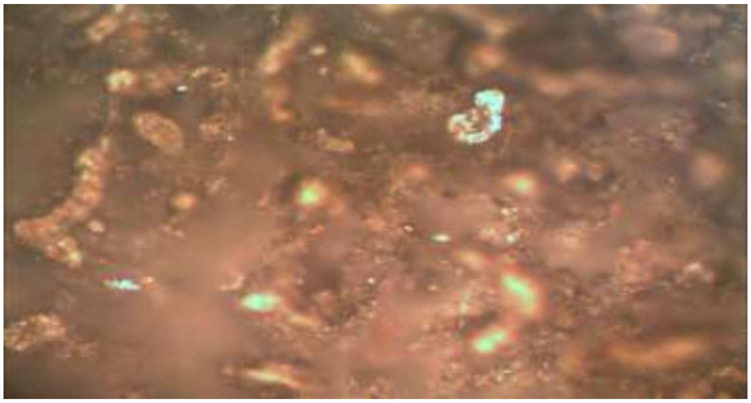


Fig 11: shows the micrograph of 1.5wt%Mg

Magnesium contains phases that can be seen forming flakes within the face of the sample.

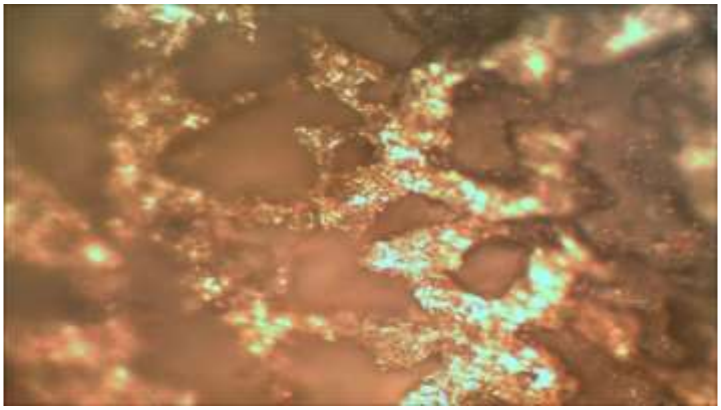


Fig 12: shows the micrograph of the 2wt%Mg sample

From the graph, we can see more magnesium flakes all over the face. The effect of magnesium contain phases resulted in the hardness increase, and the fractured face during impact, and the tensile test also shows the failure along the grain boundaries resulting in brittle-like failure.

4.1 CONCLUSION

In conclusion, this research confirmed that adding magnesium to aluminum-copper alloy increases strength and precipitation hardening. Magnesium flakes along grain boundaries contribute to material hardening but reduce ductility. These findings align with previous studies, validating magnesium's role in improving aluminum-based alloys.

4.2 RECOMMENDATION

At low magnesium percentages (0.5wt% to 2wt %), aluminum copper alloy retains sufficient ductility and strength. The balance between ductility and hardness in this range makes it suitable for advanced applications in the automobile industry, airplane skeletons, and other engineering requiring high strength and low weight. These alloys exhibit a high strength-to-weight ratio, making them ideal for structural engineering. Despite some weakness in intergranular corrosion due to copper, the alloying and heat treatment processes effectively distribute copper within the aluminum matrix, ensuring corrosion resistance. Limitations such as impurity inclusions and power outages during testing suggest the use of an electric furnace to avoid undesirable reactions. Additionally, these alloys offer superior heat dissipation, machinability, and magnetic shielding properties.

In addition to the above, a further study focusing on the creep orientation of the alloy samples needs to be studied.

REFERENCES

Alil A, M Popovic, T Radetic, M Zrilic (2015). Influence of annealing temperature on the baking response and corrosion properties of an Al – 4.6wt%Mg alloy with 0.54wt%Cu

Bhandari R., P Biswas, Mk Mondal, D mandal (2018). Finite element analysis of stress-strain localization and distribution in Al – 4.5Cu – 2Mg alloy.

D Féron (2017). Corrosion behavior and protection of copper and aluminum alloys in seawater.

French, H. J. (2018). Tensile Properties of Some Structural Alloy Steels at High Temperatures (Classic Reprint). United States: 1kg Limited

Joseph R. Davis (2011). ASM specialty handbook: Aluminum and Aluminum Alloys. ISBN 978- 0-87170-496-2

Kaufman, J. G. (2008). Parametric Analyses of High-temperature Data for Aluminum Alloys. United States: ASM International.

Michael Naboka, Jennifer Giordano (2011). Copper Alloys: preparations, properties and applications. ISBN 1612095046, 978162095042

N Nafsm, HMMA Rashed (2013). Effects of copper and magnesium on Microstructure and hardness of Al-Cu-Mg Alloys.

Ny Khudair (2017). Study the effect of magnesium addition on Microstructure, electrical conductivity and some mechanical properties of pure Aluminum.

Ruqaya A. Abdulkadhim, Muna Abbas (2015). Effect of precipitation hardening on mechanical properties of dissimilar friction stir welded AA2024 - T3 to AA7075 - T73 Aluminum Alloys. DOI:10.13140/RG.2.1.1840.6486.

Safranski, David & Laffoon, Stephen & Sycks, Dalton & Gall, Ken. (2017). Material Selection. 10.1016/B978-0-323-37797-3.00003-8.

Stojanovic B., (2018) Application of Aluminum and Aluminum Alloys in Engineering. Applied Engineering letters.

Vinojitha Raghavan (2012) Al-Cu-Mg-Zr (Aluminum – Copper – Magnesium – Zirconium) DOI: 10.1007/s11669-012-9988-0.

Ying Chen, Nong Gao, S Gang, Simon P. R. (2016). Microstructural evolution, strengthening and thermal stability of an ultrafine-grained Al-Cu-Mg Alloy. DOI: 10.1016/J.actamat.2016.02.050.