Faculty of Industrial and Manufacturing Technology and Engineering

EFFECT OF MAGNESIUM (MG) CONTENT AND ARTIFICIAL AGING ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF HOMOGENIZED AL-SI-CU ALLOY

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DEDICATION

To my beloved mother, siblings and wife who encourage and support me with full effort without hesitated until thesis completion. My most profound appreciation goes Assoc. Prof. Ir. Ts. Dr. Mohd Shukor bin Salleh as my supervisor and mentors, for his time, effort, and understanding in helping me succeed in my studies. His vast wisdom and wealth of experience have inspired me throughout my studies. I like to express my gratitude to everyone in the program classmate of Manufacturing Engineering including assistant engineer who support and assist me during studies. Thanks to their generosity and encouragement, my time spent studying and getting beneficial discussion throughout project really made my knowledeg improved.As conclusion, I like to thank to Allah SWT, my parents, my wife, and my children. It would have been impossible to finish my studies without their unwavering support over the past few years.

ABSTRACT

The study of the effect of magnesium (Mg) content and artificial aging on the microstructure and mechanical properties of homogenized Al-Si-Cu alloys was critical for advancing the development of lightweight, high-strength materials for automotive and aerospace applications. Several studies on the modification and addition of alloying elements conducted previously reported positive improvements to enhance the mechanical properties of Al-Si-Cu alloys, including the addition of Magnesium (Mg) content, Copper (Cu), Silicon (Si), and other alloying elements. However, there was a lack of technical data that correlated both the effect of magnesium added and artificial aging as T6 Heat treatment into Al-Si-Cu alloy. Despite extensive research on Al-Si-Cu alloys, the specific impact of varying Mg concentrations on their homogenized microstructure and resultant mechanical properties remained inadequately understood. This research aimed to fill this gap by systematically investigating the influence of 0.5%wt, 0.8%wt, and 1.2%wt of Magnesium (Mg) contents on A356 alloys under 1, 3, and 5 hours of artificial aging after casting through permanent mold casting and thixoforming process. To achieve the project objectives, nine (9) combination of Taguchi method runs for A356 alloy samples with varying Mg concentrations and different artificial aging were prepared through Permanent Mold and Thixoforming casting process. As a results, the microstructural characteristics were analyzed using Optical microscopy (OM), Scanning electron microscopy (SEM) incuding energy-dispersive X-ray spectroscopy (EDS) for elemental mapping for specific area. Hence, a mechanical properties evaluation was performed, including tensile strength (E8M) and Vicker microhardness (E92), through standardized ASTM testing procedures. The results revealed that increasing Mg content significantly refined the microstructure, enhancing the dispersion of secondary phases and reducing the size of primary Si particles. This refinement of microstructure led to notable improvements in mechanical properties. Specifically, alloys with higher Mg content exhibited increased yield strength (YS) and ultimate tensile strength (UTS) while reducing the elongation to fractures. In addition, artificial aging also tends to increase yield strength (YS) and ultimate tensile strength (UTS). Other than that, the hardness results show an increasing trend with a longer artificial aging period while reducing Vickers Hardness (HV) value under the influence of the increment of Mg addition into the alloying system. These findings highlighted the critical role of Mg and artificial aging in optimizing the performance of Al-Si-Cu alloys and provided valuable insights for their application in high-performance engineering components. This study not only elucidated the relationship between Mg content and the microstructure-mechanical property interplay in homogenized Al-Si-Cu alloys but also offered a pathway for designing advanced materials with superior properties for industrial applications.

ABSTRAK

Kajian tentang kesan kandungan magnesium (Mg) dan tempoh penuaan buatan ke atas struktur mikro dan sifat mekanikal aloi Al-Si-Cu terhomogen adalah kritikal untuk memajukan pembangunan bahan ringan, berkekuatan tinggi untuk aplikasi automotif dan aeroangkasa. Beberapa kajian mengenai pengubahsuaian dan penambahan unsur aloi yang dijalankan sebelum ini melaporkan peningkatan positif untuk meningkatkan sifat mekanikal aloi Al-Si-Cu, termasuk penambahan kandungan Magnesium (Mg), Kuprum (Cu), Silikon (Si), dan lain-lain unsur pengaloian. Walau bagaimanapun, terdapat kekurangan maklumat data teknikal yang mengaitkan kedua-dua kesan penambahan magnesium dan penuaan buatan daripada Rawatan haba jenis T6 ke atas aloi Al-Si-Cu. Walaupun penyelidikan meluas ke atas aloi Al-Si-Cu, kesan khusus kepekatan Mg yang berbeza-beza dengan penuaan berlainan pada struktur mikro homogen dan sifat mekanikal yang terhasil masih tidak difahami dengan secukupnya. Penyelidikan ini bertujuan untuk mengisi jurang ini dengan menyiasat secara sistematik bagi pengaruh kandungan Magnesium (Mg) 0.5%wt, 0.8%wt, dan 1.2%wt Magnesium (Mg) pada aloi A356 di bawah pengaruh selama 1, 3, dan 5 jam penuaan buatan selepas penuangan melalui proses penuangan acuan kekal dan acuan pembentukan thixo. Untuk mencapai objektif projek, sembilan (9) kombinasi melalui keadah Taguchi bagi sampel aloi A356 dengan kepekatan Mg yang berbeza-beza dan penuaan berlainan telah disediakan melalui proses tuangan Acuan kekal dan acuan pembentukan thixo dengan tertakluk kepada penghomogenan dari penuaan buatan berbeza beza. Hasilnya, ciri-ciri mikrostruktur telah dianalisis menggunakan mikroskop optik (OM), Mikroskopi elektron pengimbasan (SEM) termasuk spektroskopi sinar-X (EDS) penyebaran tenaga untuk pemetaan unsur bagi kawasan tertentu. Oleh itu, penilaian sifat mekanikal telah dilakukan, termasuk kekuatan tegangan (E8M) dan kekerasan mikro Vicker (E92), melalui prosedur ujian piawaian ASTM. Hasilnya menunjukkan bahawa peningkatan kandungan Mg telah menapis struktur mikro dengan ketara, meningkatkan penyebaran fasa sekunder dan mengurangkan saiz zarah Si primer. Penambahbaikan struktur mikro ini membawa kepada peningkatan ketara dalam sifat mekanikal. Khususnya, aloi dengan kandungan Mg yang lebih tinggi menunjukkan peningkatan kekuatan hasil (YS) dan kekuatan tegangan muktamad (UTS) sambil mengurangkan pemanjangan patah putus. Selain itu, penuaan buatan juga cenderung untuk meningkatkan kekuatan hasil (YS) dan kekuatan tegangan muktamad (UTS). Selain daripada itu, keputusan kekerasan menunjukkan trend yang meningkat dengan tempoh penuaan buatan yang lebih lama sambil mengurangkan nilai Kekerasan Vicker (HV) di bawah pengaruh penambahan Mg ke dalam sistem pengaloian. Penemuan ini menyerlahkan peranan kritikal rawatan haba Mg dan T6 dalam mengoptimumkan prestasi aloi Al-Si-Cu dan memberikan pandangan berharga untuk aplikasinya dalam komponen kejuruteraan berprestasi tinggi. Kajian ini bukan sahaja menjelaskan hubungan antara kandungan Mg dan interaksi sifat mikrostruktur-mekanikal dalam aloi Al-Si-Cu yang dihomogenkan tetapi juga menawarkan laluan untuk mereka bentuk bahan termaju dengan sifat unggul untuk aplikasi industri.

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LIST OF ABBREVIATIONS

YS	-	Yield Strength
UTS	-	Ultimate Tensile Strength
CS	-	Cooling slope
OM	-	Optical Microscopy
DSC	-	Different Scanning Calorimetry
XRD	-	X-Ray Diffraction
SEM	-	Scanning Electron Microscopy
UTM	-	Universal Testing Machine
HV	-	Hardness Vicker
HB	-	Hardness Brinell
FCC	-	Face-Centered Cubic
SHT	-	Solution Heat Treatment
SSM	-	Semi Solid Metal
DOE	-	Design Of Experiment
TM	-	Melting Temperature
TG	-	Glass Temperature

LIST OF SYMBOLS

Q'	-	Quaternary phases in alloys (Stable)
A	-	Alpha
β	-	Beta
P	-	Pressure
T	-	Temperature
%	-	Percentage
ρ	-	Density
π	-	Pi = 3.412
wt	-	Weight percentage

CHAPTER 1

INTRODUCTION

1.1 Overview

Cast aluminum alloys are significant Aluminum (Al) alloy classes with a wide range of automotive and aeronautics applications because of their established casting, shaping capability, low density, high specific strength, good toughness, and excellent corrosion resistance. Several studies on the modification and addition of alloying elements conducted previously reported positive improvements to enhance the mechanical properties of Al-Si-Cu alloys, including the addition of Magnesium (Mg) content, Copper (Cu), Silicon (Si), and other alloying elements. Recently, a lot of development approaches of Al-Si-Cu alloy studies had performed to improve the microstructure capability through several technical methods such as microstructure grain refinery, alteration of atomic scale, alloying casting technique, and others provide more possibility to improve the alloy strength, microhardness value and more stable phase transition during alloy formability.

Processing these Al-Si-Cu alloys such as A356 to improve their mechanical properties requires homogenization treatment, which is an essential step for ensuring the alloy performance quality. The accepted practice closely monitors homogenization temperatures to prevent the early melting of Mg-rich phases at high temperatures. One of the crucial alloying elements that possibly enhances Al-Si-Cu alloy mechanical properties is Magnesium (Mg), which was proven by Salleh et. al. (2015a), who concluded that the size of the a-Al globule and eutectic silicon in the microstructure of the thixoformed samples had been marginally refined by the addition of magnesium to Al–5%Si–Cu. Other than that, the function of Magnesium (Mg) in Al-Si-Cu alloy is to increase the strength by forming different types of precipitates, such as β' (Mg_2Si-type), Q' ($Al_5Cu_2Mg_8Si_6$-type), and S'(Al_2CuMg-type) according to the amount of element addition as per stated by Zang et. al. (2022). Other than that, thixoforming processing is a sophisticated manufacturing technology that shapes metals while they are in a semi-solid state, exhibiting properties of both liquids and solids that offers notable benefits in terms of mechanical qualities, near-net form possibilities, and material utilisation as per mentioned by Husain et. al. (2017) .

The strength of the modified alloy was enhanced by the creation of the compact π-$Al_8FeMg_3Si_6$ phase and the reduction of the β-Al_5FeSi phase's sharp and plate-like structure, which was caused by an increase in the Mg content as per reported by Arif et. al. (2020a). Recently, Son et. al. (2023) have shown an increased interest in the alteration of homogenous heat treatment by changing their process temperature and aging time as per reported. The improved mechanical properties of the heat treated Al-Si-Cu alloy with high melt-holding temperature were attributed to several microstructural changes, including microstructure refinement and acceleration of precipitation kinetics caused by enhanced second-phase dissolution. Different constituent particles, such as Mg_2Si, Al_2Cu, $Al_5Cu_2Mg_8Si_6$, b-Al_5FeSi, $Al_8Mg_3FeSi_6$, and $Al_{15}(MnFe)_3Si_2$, were formed during solidification under different conditions. T6 heat treatment is used to enhance the mechanical properties of alloys containing magnesium was proof by Salleh et. al. (2015a).

In general, the microstructure of as-cast alloys under standard solidification conditions is composed of coarse Si flakes in the eutectic phase and a dendritic structure, which encourages brittle behavior. Brittle behavior is characterized by low strength and ductility during its application. In order to reduce the dendritic arm in the microstructure of Al-Si-Cu alloy, Samat et. al. (2022a) suggest that one of the suitable casting methods is a thixotropic process, which employs semi-solid state behavior and reduces macrosegregation, microporosity, and forming applied force during the forming process.

In this study, the research task was to evaluate microstructural features and mechanical properties of thixoformed Al–Si–Cu alloys with different Mg contents (0.5 % wt, 0.8 % wt, and 1.2 % wt) with different artificial aging duration period started with 1,3 and 5 hours at 180ºCas reheating temperature. The Different Scanning Calorimetry (DSC) used to determine the optimum thermal behaviour changes before the suitable processing temperature used for the selected process. Other than that, X-Ray Diffraction (XRD) is utilized to find the related all aluminum homogenized element by study the crystallographic structure, chemical composition, and physical properties of materials. Scanning Electron Microscopy (SEM) and Optical Microscope (OM) were utilized to observe and visualize dendritic microstructures and interdendritic channels of the Al-Si-Cu eutectic region. For mechanical properties testing such as tensile and hardness were carried out to evaluate and compare their theoretical value. Adding Magnesium (Mg) is expected to significantly improve all the tensile and hardness material values with better intermetallic compounds transition phase. For future benefit, exploring more opportunities for optimum magnesium levels of amount addition as alloying for the high strength of Al-Si-Cu alloy is essential.

1.2 Problem Statements

A material's microstructure with microstructural constituents precipitating during the solidification phase determines the alloying performance, including its mechanical properties. These alloying elements are linked to the material's composition and process technology selection. Nowadays, new alloying material requirements are crucial to be utilized in the automotive body panel industry and some of the aerospace applications which require high-strength material with excellent properties such as high tensile yield strength (YS), high ultimate tensile strength (UTS), good chemical resistance, excellent corrosion resistance, lightweight and excellent impact strength.

However, most of aluminium alloys have less than 250 MPa of ultimate tensile strength. Therefore, there is a need to improve the mechanical properties of the Al-Si-Cu alloys to comply with the material current requirement. Recently, investigated developing application of Al-Si-Cu for Aluminum alloy which effected by Magnesium (Mg) which is still limited by their low strength even though it has been improved by the casting method with T6 temper condition. In addition, Aluminium alloys and other lightweight materials can be used to create lightweight cars, with a potential weight reduction of 30% to 40% when compared to steel. The precipitation hardening process can be enhance with better mechanical properties by adding alloying elements such as magnesium (Mg). Other than that, Salleh et. al. (2015b) concluded through his study that significant improvement is obtained from the hardening during artificial aging caused by the cooperative precipitation of the Mg_2Si and Al_2Cu phases in the alloy's mechanical characteristics compared to alloys that have not been heated.

By adding magnesium (Mg) into Al-Si-Cu alloying system, the grain becomes more refined and more uniform microstructure, as justified by Alhawari where semi-solid processing allows for the production of aluminum-silicon alloys with fine microstructures, reduced coarse phase segregation, and uniform distribution of second phases with addition of Mg. The coarse Mg_2Si phase needs to be changed to guarantee appropriate mechanical strength and ductility, as mentioned by Alhawari et. al. (2017).

Additionally, the thixoforming method was used in this study. There are insufficient data on the thixoforming fabrication method that utilizes the material studies on alloying elements added into the casting process such as Cobalt (Co), Copper (Cu), Ferum (Fe), Silicon (Si), including Magnesium (Mg) which require more information and investigation results for mechanical properties enhancement. Through the material characterization on Magnesium (Mg), the homogenization of various intermetallic phases can be further explored and analyzed. This study is supported by research by Arif et al. (2020), which proves that the alloy's microstructure consists of a solid spheroidal structure in a liquid matrix during processing with compromised mechanical properties. The method of experimental design used to analyze the data is lacking through the Taguchi method approach, where more detailed explanation using several direct factors as best optimization solution for better mechanical properties.

Technically, the difference was attributed to the lowering of solidus lines in alloys with higher Mg content, increasing the solid solubility of these alloying elements. Furthermore, alloys with higher Mg contents also presented faster responses to aging treatments. According to Salim et. al. (2023), The addition of more magnesium content has the potential to significantly enhance the hardness of the thixoformed samples, with a maximum increase of 73%. Increasing the Mg concentration up to 2 wt.% enhances the hardness, rising from 43 HRB to 74 HRB.

Many studies have extensively documented the impact of adding Mg to the traditional casting of aluminum alloys. However, there is still a scarcity of information regarding the influence of varying Mg content on thixoformed alloys. Hence, this study assessed the impact of different magnesium concentrations in thixoformed with Taguchi method for Al–Si–Cu alloys on both the microstructure and mechanical properties. The alloys were produced using the permanent mold casting with continuous stirrer up to 5 minutes to achieve a non-dendritic structure and subsequently thixoformed using a hydraulic press. Following a T6 heat-treatment procedure with 1,3 and 5 hours of artificial aging, an examination was conducted to analyze the microstructure and mechanical properties of the samples.

1.3 Research Objectives

The objectives and purpose of this study are:

1. To determine the optimum content of magnesium elements for maximizing mechanical properties of thixoformed Aluminum alloys through Taguchi method.

2. To examine the effect of magnesium content for microstructural evolution of Thixoformed A356 aluminium alloy.

3. To investigate the mechanical properties of different Magnesium (Mg) content for Thixoformed A356 aluminium alloys during artificial aging duration of T6 heat treatment.

1.4 Scope of the study

This study investigated the effects of different amounts of magnesium (Mg) added into A356 alloy based on the microstructures and mechanical properties using the thixoformed process with various artificial aging T6 conditions. Three different alloys containing various amounts of Mg (0.5, 0.8 and 1.2 % wt) were prepared through the permanent mold casting technique before they were thixoformed using a compression press machine. Initial samples were taken using Different scanning calorimetry (DSC) equipment to evaluate heat flow required. Then, the samples were categorized according to the Taguchi method approach where two factors with three levels were used (L9) for formulation optimization. Several of the thixoformed samples were then treated with a T6 heat treatment and immersed into solution treatment at 540 ºC for 8 hours, quenching in normal water at 25 ºC, followed by aging at different artificial aging conditions started with 1,3 and 5 hours at 180ºC. After that, the sample was cut, etched, polished, and prepared before proceeding with the subsequent microstructure evaluation and mechanical testing. All samples were characterized by using optical microscopy (OM) and scanning electron microscopy (SEM) for microstructure evaluation study. The cast A356 Aluminum sample also performed an X-ray diffraction (XRD) analysis to determine the optimum phase observed after precipitation. For the mechanical properties evaluation of Al alloy, tensile tests were performed for each weight ratio of magnesium content using a universal testing machine (UTM), and a microhardness test was conducted through a Vickers tester for each sample.

CHAPTER 2

LITERATURE REVIEW

2.1 Aluminum alloy

Aluminium is a malleable metal that can form alloys with various elements such as copper, magnesium, silicon, zinc, and manganese, thereby modifying its mechanical and physical properties. These metals are added in precise ratios to attain the desired characteristics for a particular use. Combining magnesium with Aluminium yields a robust and lightweight alloy that is exceptionally suitable for application in the aerospace and automotive sectors. Also, aluminum alloys are widely utilized in various industries due to their low density, corrosion resistance, and thermal conductivity. According to the review publication by Raj et al. (2021), Aluminum alloys are utilized to produce various items, such as consumer electronics, automobiles, and aircraft.

In addition, aluminum alloys possess low densities, rendering them lightweight and well-suited for situations where weight is crucial. Aluminum alloys have inherent corrosion resistance due to the formation of a protective oxide layer on their surfaces, effectively shielding them from corrosion in various environments. Moreover, Aluminum alloys possess a high strength-to-weight ratio, meaning they are both strong and durable despite their relatively low mass. Raj et al. (2021) mentioned that This characteristic makes them highly valuable in a wide range of applications where the careful balance between strength and weight is crucial. Aluminum alloys exhibit excellent malleability and ductility, rendering them highly adaptable for various manufacturing procedures.

Moreover, aluminum alloys are extensively utilized in the Automotive and Aerospace industries due to their ability to undergo heat treatment, improving their exceptional strength, workability, thermal and electrical conductivity, and corrosion resistance, all while maintaining a low weight. The heat treatment processes used for Aluminium alloys include homogenization, annealing, and precipitation hardening. These processes involve solution treatment, quenching, and aging, which can be done at either room temperature (natural aging) or at a higher temperature (artificial aging). In order to ensure uniformity in the temperature-time cycle, Palanisamy et.al. (2018) reported that it is necessary to carry out heat treatment processes in properly equipped furnaces, adhering to the appropriate thermal conditions. In recent studies of Aluminum alloy, Niu et. al. (2023) also suggest that an increase the upper limit of Fe element content tolerance in casting aluminum alloys is viewed as a viable method to encourage the use of recycled aluminum production.

This aluminum alloy material provides more benefit to the current product application. For instance, aluminium metal matrix composites find application in various functional, non-structural, and structural roles within the industrial and engineering sectors. Novel materials with reduced density, enhanced stiffness, and increased strength are required to surpass the limitations of currently utilized alloys. Two approaches to achieve this are enhancing the strength-to-weight ratio or reducing the weight of the composite. Materials must be produced to achieve greater stiffness, lower density, greater ultimate tensile strength, and higher yield strength as per reported by Deshmukh et. al. (2023).

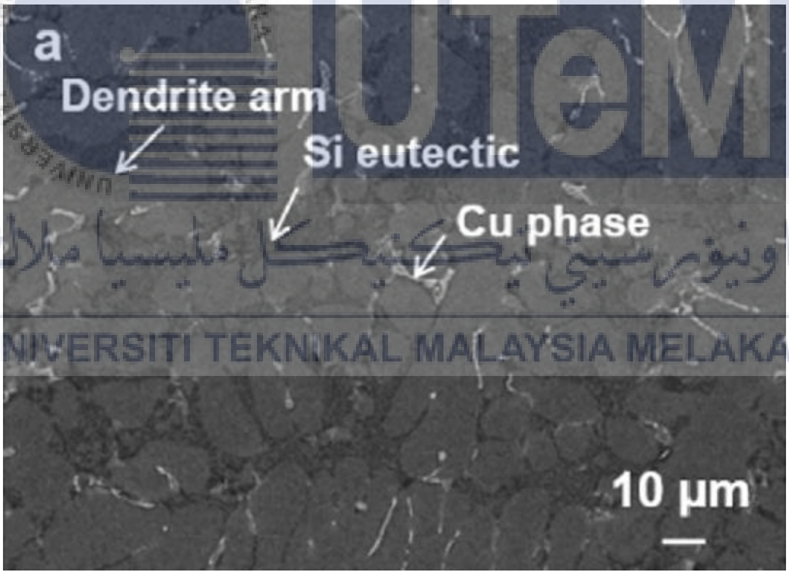

Figure 2.1: As-cast microstructure showing dendritic microstructure

(Sadeghi et. al., 2017)

In 2017, Sadeghi et. al. (2017) performed studies about the roughness of the microstructure is determined by the solidification rate, which in turn is influenced by the rate at which the material cools from its solidifying temperature. The $Al_{17}(Fe_{3.2}Mn_{0.8})Si_2$ structure is characterized by needle-like shapes, which have a negative impact on its mechanical properties. Additionally, the structure also exhibits a more rounded skeleton-like appearance, as shown in Figure 2.1.

Based on experiment by Ravi & Wolverton (2004), the degree of strengthening is contingent upon the microstructural morphology of the precipitates, which was determined by the interfacial and strain energies of the precipitate/matrix system. The interfacial and strain energies was influenced by the specific crystal structure of the precipitate phases, the matrix phase, and the interface connecting them. Consequently, significant research has been dedicated to comprehending the precipitation kinetics and crystal structure of precipitate phases in alloys containing Aluminium, magnesium, silicon, and possibly copper. On the other hand, the particles were structured by stacking two rows of Mg and one row of Si alternately on the lattice planes of the matrix, specifically the (011) planes, as shown in Figure 2.2. The growth of these particles occurs along the [100] direction. When the GP zone model was expanded in all three dimensions, it forms a complete bulk crystal structure known as Mg_2Si stacking of (011) planes. This arrangement of atoms corresponds to an orthorhombic structure based on the face-centered cubic (FCC) lattice, similar to the $MoPt_2$-type structure.

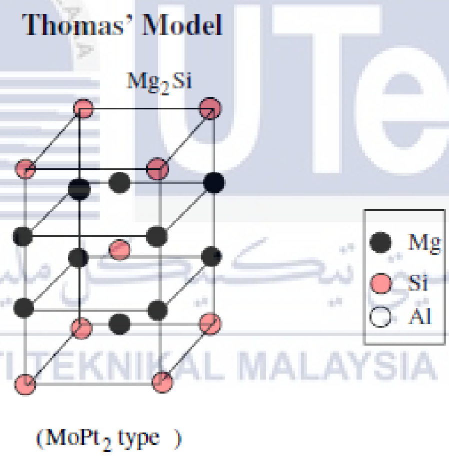

Figure 2.2: Bulk structural models of GP zones proposed in Al–Mg–Si alloys. The orthorhombic fcc superstructure was proposed by Thomas (Ravi & Wolverton, 2004)

2.1.1 Aluminum alloy - A356

An aluminum alloy is a distinctive amalgamation of various metallic elements that exhibits heightened strength and durability. This aluminum is conventionally known for its low weight and exceptional ability to resist corrosion. These alloys are created through the amalgamation of liquid/molten aluminum with other elements, which undergoes cooling and solidification, forming a uniform solid material. When combined with aluminum to create these alloys, the other constituents can account for as much as 15 percent of the overall mass. Some examples of these additional elements are Zinc (Zn), Iron (Fe), Magnesium (Mg), Copper (Cu), and Silicon (Si). Other than that, these elements in aluminum result in an alloy that exhibits improved electrical conductivity, corrosion resistance, workability, and strength compared to pure metallic elements. Significant disparities exist between cast and wrought aluminum alloys. According to the Emmanuel et. al. (2021), the primary categories of aluminum alloys are cast alloys and wrought alloys.

Furthermore, many types of Aluminum alloy exist for certain applications, including A356 made from the casting process. This A356 aluminum is commonly used in casting alloy collection, particularly for aircraft applications. A distinct nomenclature system, unlike wrought alloys, characterizes cast aluminum. Additionally, aluminum die casting for various industries produces A356 aluminum casting parts of exceptional quality. Moreover, A356 is a specific aluminum alloy used for the process of casting. According to Paul et. al. (2014), the cast aluminum alloy designation system consists of nine series: 1xx.x, 2xx.x, 3xx.x, 4xx.x, 5xx.x, 6xx.x, 7xx.x, 8xx.x, and 9xx.x. The 3xx.x series indicates that the primary alloying element is silicon, along with the addition of copper and magnesium. Hence, the second and third digits indicate the minimum aluminum content as a percentage. In terms of the decimal number of the Alumnium code, the decimal digit after the point denotes whether the alloy is in the form of a casting (designated as .0) or an ingot (set as .1 or .2). The prefix "A" preceding an alloy designation indicates a refined and more pure form of the chemical composition. The material from the Aluminum Association (AA) was designated as A356.0. Plus, the A356 aluminum die-casting alloy exhibits excellent casting and machining characteristics, making it well-suited for applications in aircraft, pump housings, impellers, high-velocity blowers, and other structural castings that demand exceptional strength. From reviewed by Li et.al. (2023), A356 aluminum is frequently employed to produce intricate and complex aluminum castings due to its lightweight nature, ability to withstand pressure,