THE INVESTIGATION OF MECHANICAL PROPERTIES OF ANNEALED 5005AL ALLOYS AT DIFFERENT PARAMETERS

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Raghad Majeed Abdulkareem AL-MUSAWI

ABSTRACT

Master Thesis

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The constant increase in aluminum usage in the market is a testament to its indispensable role in modern industries. Aluminum's diverse uses are due to its inherent properties, including its remarkably light weight, exceptional formabilityand commendable resistance to mechanical stress. In order to adequately meet the constantly evolving demands of the market, it has become imperative to develop novel alloys that have the ability to impart different properties according to the specific needs of each. Heat treatments are widely recognized as a means of improving the mechanical properties, dimensional stability and corrosion resistance of various aluminum alloys. The present investigation aims to investigate the effects of different heat treatments on the Al-5005 alloy. Through and comprehensive study, the microstructural composition of the alloy was carefully examined using the techniques of optical microscopy and electron spectroscopy. With the aim of evaluating the alloy's performance, a comprehensive series of mechanical evaluations was carried out, which included tensile, fatigue and hardness tests. In addition, a comprehensive wear assessment was performed to carefully assess the complexfrictional properties of the material under study. The experimental results have provided essential and remarkable insights: through carefulmicrostructural analysis, it was found that the Al-5005 alloy has a special composition that is inherently fascinating. This intriguing composition reveals the presence of tiny ferrous particles complexly embedded in the very fabric of its structure. The use of scanning electron microscopy (SEM) imaging techniques has revealed an intriguing array of discernible microstructural changes induced by the application of different heat treatments. The particles studied were subjected to a state-of-the-art analysis technique called Scanning Electron Microscopy-Energy Dispersive X-ray Spectroscopy (SEM-EDX). This advanced method enabled the identification and characterization of the elemental composition within the particles. Remarkably, the SEM-EDX analysis revealed the presence of iron and silicon and shed light on the complex chemical composition of these particles. Experimental manipulation of the heat treatment temperature from 200 °C to 400 °C resulted in a marked decrease in measured tensile strength. Under the test conditions, exposing the material to a temperature of 200 ^{o}C for exactly 60 minutes, the most favorable tensile strength of an impressive 160.8 MPa was achieved. In contrast, the least desirable result was observed when the material was exposed to a significantly higher temperature of 400 ^{o}C.

Key Word : Al-5005 alloy, Heat treatment, Microstructure , Mechanical properties.

Science Code : **91518**

ÖZET

Yüksek Lisans Tezi

TAVLANMIŞ 5005 AL ALAŞIMLARININ MEKANİK ÖZELLİKLERİNİN FARKLI PARAMETRELERDE İNCELENMESİ

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Alüminyum kullanımının pazarda sürekli artması, modern endüstrilerdeki vazgeçilmez rolünün bir kanıtıdır. Alüminyumun çeşitli kullanımları, olağanüstü hafifliği, olağanüstü şekillendirilebilirliği ve mekanik strese karşı övgüye değer direnci dahil olmak üzere, doğal özelliklerinden kaynaklanmaktadır. Pazarın sürekli gelişen taleplerini yeterince karşılamak için, her birinin özel ihtiyaçlarına göre farklı özellikler kazandırma yeteneğine sahip yeni alaşımlar geliştirmek zorunlu hale geldi. Isıl işlemler, çeşitli alüminyum alaşımlarının mekanik özelliklerini, boyutsal kararlılığını ve korozyon direncini iyileştirmenin bir yolu olarak yaygın olarak kabul edilmektedir. Mevcut araştırma, farklı ısıl işlemlerin Al-5005 alaşımı üzerindeki etkilerini araştırmayı amaçlamaktadır. Kapsamlı ve kapsamlı bir çalışmayla, alaşımın mikroyapısal bileşimi, optik mikroskopi ve elektron spektroskopisi teknikleri kullanılarak dikkatlice incelendi. Alaşımın performansını değerlendirmek amacıyla, çekme, yorulma ve sertlik testlerini içeren kapsamlı bir dizi mekanik değerlendirme gerçekleştirildi. Ek olarak, incelenen malzemenin karmaşık sürtünme özelliklerini dikkatli bir şekilde değerlendirmek için kapsamlı bir aşınma değerlendirmesi yapılmıştır. Deneysel sonuçlar önemli ve dikkat çekici bilgiler sağladı: dikkatli mikroyapısal analizler sonucunda, Al-5005 alaşımının doğası gereği büyüleyici olan özel bir bileşime sahip olduğu bulundu. Bu ilgi çekici kompozisyon, yapısının dokusuna karmaşık bir şekilde gömülü olan küçük demir parçacıklarının varlığını ortaya koyuyor. Taramalı elektron mikroskobu (SEM) görüntüleme tekniklerinin kullanımı, farklı ısıl işlemlerin uygulanmasıyla indüklenen ilgi çekici bir dizi ayırt edilebilir mikroyapısal değişikliği ortaya çıkarmıştır. İncelenen parçacıklar, Taramalı Elektron Mikroskobu-Enerji Dağıtıcı X-ışını Spektroskopisi (SEM-EDX) adı verilen son teknoloji analiz tekniğine tabi tutuldu. Bu gelişmiş yöntem, parçacıklar içindeki temel bileşimin tanımlanmasını ve karakterizasyonunu sağladı. Dikkat çekici bir şekilde, SEM-EDX analizi demir ve silikonun varlığını ortaya çıkardı ve bu parçacıkların karmaşık kimyasal bileşimine ışık tuttu. Isıl işlem sıcaklığının 200 °C'den 400 °C'ye deneysel manipülasyonu, ölçülen gerilme mukavemetinde belirgin bir düşüşle sonuçlandı. Test koşulları altında, malzeme tam olarak 60 dakika boyunca 200 oC'lik bir sıcaklığa maruz bırakıldığında, etkileyici bir 160,8 MPa'lık en uygun gerilme mukavemeti elde edildi. Tersine, en az arzu edilen sonuç, malzeme 400 ^{o}C gibi önemli ölçüde daha yüksek bir sıcaklığa maruz bırakıldığında gözlemlendi.

Anahtar Sözcükler : Al-5005 alaşımı, Isıl işlem, Mikroyapı, Mekanik özellikler.
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SYMBOLS AND ABBREVIATIONS INDEX

SYMBOLS

α : Alpha

β : Beta

P : Density

Å : Angstrom

μm : Micrometer

℃ : Degrees Celsius

ABBREVIATIONS

HB : Brinell microhardness

ASTM : American Society for Testing and Materials

AA : Aluminium Alloy

OP : Optical microscope

EDS : Energy-Dispersive Spectrometry

Al-Mg : Aluminum-Magnesium

PART 1

INTRODUCTION

1.1 INTRODUCTION

Aluminum is one of the commonly used metals along with iron and steel in many industrial areas such as aerospace, marine and automotive. The most important reasons for the widespread use of aluminum are; In addition to being light in weight, its alloys have more strength, electrical and thermal conductivity and high light reflection properties than structural steels. Due to these superior properties, the use of aluminum as an engineering material has an increasing importance in many technological fields [1]. Despite this widespread use, there are many problems associated with the drilling of aluminum and its alloys, such as tool wear, burr formation and surface roughness. Although modern manufacturing methods such as ultrasonic, chemical, abrasive jet machining and laser cutting have a wide range of applications in the manufacturing industry, drilling with a drill is one of the most common manufacturing methods used today due to its economic and simplicity [2]. For this reason, it is very important to drill machine parts in the desired tolerance in many fields from the aerospace industry to the automotive industry. In the drilling process, the life of the cutting tool, the surface and microstructure properties of the processed material are the most important factors that determine the quality and cost of the product obtained. The machinability and efficiency of a workpiece; It depends on many factors such as the material of the workpiece, the machining method, the tool and the cutting parameters. Therefore, these parameters must be optimally selected in order to improve the machined surface quality. After the drilling process, burrs occur both at the entrance and exit areas of the holes as a result of plastic deformation. The larger dimensions of the output burrs than the inlet burrs affect the quality of the part more. It is very important to remove the burrs from the part because the burrs that occur after the drilling process can cause injuries due to the sensitivity and quality of the hole, because they are sharp, and make assembly difficult. Since deburring operations are usually carried out by hand or using fine machining tools, it causes time wastage and damage to the part. The cost of deburring increases with the shape and size of the burr, the precision of the hole, and the complexity of the part. It is very important to prevent or minimize burrs, especially since this situation leads to higher costs in mass production centers. One of the best methods for this is to optimally determine the drilling parameters that are more effective in burr formation. In order for such a study to be placed on a more solid ground and to be better understood, concepts such as literature research on this subject, aluminum and its alloys, modeling for burr height, thickness and burr sizes in drilling should be known. In this study, all these concepts are presented in the following sections, respectively.

In recent years, aluminum alloys have stood out due to characteristics related to their attractive combination of strength/weight, good formability, high corrosion resistance, high electrical and thermal conductivity, and infinite recyclability [3]. Because of such attractive characteristics, these alloys have been presented as a viable alternative for applications in the automotive industry and in other areas of engineering, such as the aerospace and telecommunications industries . In the automotive industry, the use of components or structural parts made of aluminum and its alloys has become a well-established practice that has been gaining prominence, mainly for applications in bus bodies, due to the possibility of reducing the weight of cars, resulting in the decrease in fuel costs and gas emissions[4] . A study carried out by Ducker WorldWide, at the request of the Aluminum Organization, indicates that in 2025 the forecast of use of aluminum and its alloys in automobiles in the United States will represent approximately 23, 62% of vehicle weight; i.e. 248 kg of total weight. Regarding the global market, the prospect is that the total amount of metal in cars will double by the same period, making the automotive sector the main market for aluminum[5]. However, the applications of aluminum alloys are still restricted due to their complex production technology and high cost when compared to the production of steels, four to five times higher [6]. The most commonly used method for manufacturing aluminum alloys in sheet form is based on the Direct Chill (DC) casting process. This process consists of casting molten aluminum and producing a plate. Due to the presence of an excessive layer of oxides on the surface of the cast slabs, a previous machining step (via milling) is necessary to remove this layer before proceeding with hot rolling. After milling, the plate goes to hot rolling, a process based on its passage, previously heated, between two cylinders rotating in opposite directions, allowing the reduction of the thickness of the material through plastic deformation. Then, the plate goes to cold rolling and subsequent heat treatment, if necessary.

The 5005 AI alloy is a non-heat treatable aluminum alloy that is commonly used in various industrial applications such as building facades, roofing, and cladding. While this alloy has good corrosion resistance and moderate strength, heat treatment can be used to further improve its mechanical properties.[7]

The mechanical properties of aluminum alloys are determined by their microstructure, which can be altered by heat treatment. The 5005 AI alloy is a non-heat treatable alloy, which means that its mechanical properties cannot be improved by traditional heat treatment methods such as precipitation hardening. However, it is possible to modify the microstructure of this alloy by annealing or other heat treatment methods, which can improve its mechanical properties[8].

Heat treatment is a process that involves heating the material to a specific temperature and holding it there for a certain amount of time before cooling it down. The aim of this process is to alter the microstructure of the material, which can improve its mechanical properties such as strength, ductility, and hardness[9].

There are different types of heat treatment that can be applied to aluminum alloys, such as solution heat treatment, precipitation hardening, and annealing. Each type of heat treatment has a different effect on the microstructure and mechanical properties of the alloy[10].

Annealing is a heat treatment process that involves heating the material to a specific temperature and holding it there for a certain amount of time before slowly cooling it down. This process can improve the ductility and toughness of the alloy by reducing the amount of internal stress and improving the grain structure of the material[11].

The research on the effect of heat treatment on the mechanical properties of 5005 AI alloys will involve conducting a series of experiments to determine the optimal heat treatment conditions for improving the mechanical properties of the alloy. These experiments may involve varying the temperature and duration of the heat treatment process to determine the most effective treatment for achieving the desired mechanical properties.

1.2 OBJECTIVE OF THE WORK

The thesis aims to investigate the effect of heat treatment on the mechanical properties of 5005 AI alloys. The 5005 AI alloy is a widely used aluminum alloy that is known for its excellent corrosion resistance and moderate strength. Heat treatment is a common technique used to improve the mechanical properties of aluminum alloys by altering their microstructure.

The research will involve conducting a series of experiments on samples of 5005 AI alloy to determine how different heat treatment conditions affect the mechanical properties of the alloy. The mechanical properties that will be studied include tensile strength, yield strength, ductility, and hardness.

The heat treatment process will involve heating the alloy to a specific temperature and holding it at that temperature for a predetermined amount of time before cooling it down. Different heat treatment conditions will be tested to determine the optimal treatment for improving the mechanical properties of the alloy.

The results of the experiments will be analyzed and discussed to determine the effect of heat treatment on the mechanical properties of 5005 AI alloys. The findings of this research can be useful in the development of new aluminum alloys with improved mechanical properties for various industrial applications.. The following steps can summarize this aim:

- Processing and characterizing of 5005 Al alloy via casting method to obtain materials suitable for applicable.
- Study the microstructure changes, physical and mechanical properties as a function of the heat treatment.

PART 2

THEORETICAL BACKGROUND

2.1 ALUMINUM AND ITS ALLOYS

Aluminum is a very abundant metal in the Earth's crust (8.1%) but it is not found in its pure state. Compared to other materials, aluminum is a relatively new metal, having only been known since the beginning of the 19th century, with Friedrich Wöhler being recognized for obtaining it in its pure state. Improvements in the process of obtaining aluminum from nature came to be improved in this century, mainly by the discoveries of Hall and Heroult, in 1886, of obtaining aluminum through the process of electrolysis of alumina dissolved in cryoline: the Hall-Peroult process .

The Bayer process, discovered in the same year, made it possible to obtain bauxite, used as a raw material to obtain alumina, through chemical leaching, contributing to the productive viability of aluminum [12] . The justification for the large and growing use of aluminum and its continued use in the manufacture of bicycle frames must be attributed to all its good properties.

Today, aluminum and its alloys have become one of the most important construction and engineering materials used in the industry due to their properties. While it has properties such as high thermal and electrical conductivity and corrosion resistance in its pure state, these properties spread to a much wider spectrum with alloying and have a widespread usage area. More than one hundred aluminum alloys are widely used in industry today. To list some important properties of aluminum;

Lightness: The specific weight of pure aluminum is about 2.7 gr/cm3. Its mass is 35% of iron and 9% of copper. This low weight feature is an important issue in the entire transportation industry, especially in the aircraft and automobile industries. - Mechanical properties: As a result of heat treatment of various aluminum alloys, strength, toughness, hardness and other mechanical properties can be improved as desired. Today, very high tensile strength values have been reached by heat treatment in aluminum alloys, whose strength is further increased by the addition of small amounts of Mg, Si, Cu, Zn. The fact that the mechanical properties can be changed in this way provides a great advantage and expands the usage areas. When aluminum surfaces are exposed to atmospheric corrosion, a very thin (20-25 Å) invisible oxide layer is formed immediately and this layer prevents further oxidation. This property of aluminum is the main reason for its high corrosion resistance. It shows the same resistance against many acids. However, some alkalis have the property of destroying this oxide layer. Galvanic corrosion may occur as a result of direct contact with some metals in electrolytic environments. In this case, paint or insulating tape should be applied.

- No toxicological reactions: Its non-toxicity has made it widely used in the food industry or kitchen supplies. Thanks to this feature, aluminum has a wide range of uses in the packaging of food and drugs, cigarettes and tea packaging.

- Thermal and electrical conductivity: Aluminum and its alloys conduct heat and electricity quite well. Its high thermal conductivity (6 times that of steel) has led to the widespread use of aluminum heat exchangers in the heating/cooling industries, food, chemical, petroleum, aerospace industries. Its electrical conductivity is around 37 (m/ohm.mm^2). Its electrical conductivity is on the order of 62% of copper. Considering that the density of copper is 8.9 and aluminum is 2.7 gr/cm3; Compared to weight, aluminum turns out to be a better conductor than copper. - High heat and light reflection: It is used in lighting with its light reflecting feature of more than 80%, and in roof coverings with its high heat reflectivity feature. Again, due to this feature, they are also used in the coating of light reflectors and back reflectivity of mirrors.

- Use in metallothermic reactions: Aluminum reduces oxides of other metals due to its affinity for oxygen. Due to this feature, powder aluminum chrome, It is used in the production of these metals by reducing metal oxides such as vanadium, barium and lithium. - Easy formability and workability: It can be cast easily, rolled thinner than paper (foil), drawn (wire, extrusions, profile), forged. Aluminum can be easily and quickly subjected to turning, milling, drilling operations.

- Weldability: Any joining method can be applied (welding, riveting). In addition, bonding applications are common in the aerospace and automotive industries. - Subject to a wide spectrum of surface treatments: In cases where a protective coating is not required, polishing, sandblasting or brushing are sufficient in most cases as mechanical surface treatments. As a protective coating, chemical and electrochemical paint applications, anodizing and electro coatings can be applied. In the vast majority of applications, two or more of the above-mentioned features come together and play a decisive role. For example, its lightness and strength are used in the aircraft industry, its corrosion resistance and thermal conductivity in the rail system transportation equipment in the chemical and petroleum industries, in addition to these features, its attractive appearance with its non-toxicity, resistance to atmospheric conditions and low maintenance costs in the construction industry with high reflectivity, excellent atmospheric resistance and lightness. It has made it widely used in roof coverings.

- Low cost: The economic advantage of aluminum compared to other metals increases its use rapidly. The main reason for this is that the cost of the unit unit is more economical than other metals. The fact that aluminum is lighter than other metals provides a great advantage in casting. It is possible to cast more than other metals of the same size. In addition, it is an important reason for preference due to its not very high melting temperature, less energy consumption during casting and less abrasion of the mold. Another advantage of aluminum and its alloys is that there is no need for coating due to high atmospheric corrosion resistance [13, 14].

Aluminum is only one third of the weight of a steel material of the same volume. All methods such as casting, forging, rolling, pressing, extrusion, drawing can be applied to shape aluminum. Aluminum offers suitable solutions for many usage areas with its average strength of 40-540 N/mm2. Aluminum used in the food and electrical industry is 99.99% pure. Aluminum pipes and sheets are 99.5% to 99.8%, sometimes 98-99% pure. The remaining parts are usually silicon and iron. If aluminum is annealed at 250-350°C, silicon in solid solution is separated from aluminum. Above 350°C, it becomes a solid solution again. With the separation of silicon, the strength of aluminum decreases. For this reason, it is necessary to pass this area quickly while it is cooling [15]. The basic physical properties for pure aluminum are presented in Table 2.1[16]. After welding, the seam should be cooled quickly by immersing it in water from 400°C.

Aluminum is produced in 99.0-99.5-99.7-99.8-99.9-99.99 purity. 99.99% pure aluminum is known as high quality aluminum. Here, the physical and mechanical properties manifest themselves in a certain way. High quality aluminum is soft, easily workable, reflects heat and light efficiently; It conducts heat and electricity well and is very resistant to corrosion [17]. The strength properties of aluminum depend on the purity of the material and the method of manufacture (Table 2.2). Pure aluminum dynamic strength is 0.4-0.5 times its static strength.

Table 2.1. Chemical and physical properties of pure aluminum [18-20].

Property	Value
Atomic number	13
Atomic Weight (gr/mol)	26.98
Lattice Structure	Face-centered cubic system
Density (20° C) (gr/ cm^3)	2.6989
Density (liquid at 660° C) (gr/ cm3)	2.37
Shear modulus, G (kp/mm^2)	2.7103
Elastic modulus, E (kp/mm^2)	7.2103
Melting temperature (°C)	660.24
Melting point (cal/gr)	94.6
Electrical conductivity (m/ohm.mm^2)	37.74

Aluminum alloys are used in many parts in the aircraft, rocket and space industries. (For example, in aircraft wings, engine, propellers, auxiliary parts and liquid fuel or oxidizer tanks). Aluminum is a material with high corrosion resistance and low density. The density of cast aluminum at 20°C is 2.65-2.69 gr/cm^3. Its melting point is 658°C, boiling point is 800°C. Aluminum is used as an aluminum alloy rather than in its pure form (Table 2.3) [21]. These alloys are divided into two main groups as wrought and cast alloys.

Table 2.2. Strength properties of aluminum [21].

Mechanical Properties	Casting	Rolling	Heat Treated
Aluminum Tensile strength (kg/mm^2)	9-12	18-28	7-11
Yield strength (kg/mm^2)	3-4	16-24	5-11
Elongation (%)	18-25	3-5	30-40
Shrinkage (%)	40-55	60-85	80-95
Hardness (Brinell)	24-32	45-60	80-95

Table 2.3. Components that make up pure aluminum (%) [21].

Fe	Cu	Si	Zn	Mg	Al
0.0005-0.002	0.0005-0.002	0.002-0.005	0.0005-0.002	0.001-0.002	Bal.

Wrought aluminum alloys have superior properties than cast aluminum alloys. This superiority is provided by forging, rolling, drawing and heat treatments. The mentioned processes refine the structure of aluminum and provide a more homogeneous structure. Fewer alloying elements are used in this type of alloys. Wrought aluminum alloys are obtained in three stages:

a) Large blocks are first obtained by casting.

b) Appropriate profiles are obtained by hot and cold rolling at temperatures of 300-500°C.

c) After the first two processes, they are subjected to heat treatments if necessary.

2.2 CLASSIFICATION OF ALUMINUM ALLOYS

Aluminum alloys are divided into two large groups, alloys for mechanical work and alloys for casting. Alloys for mechanical work are subdivided into eight families that are classified according to their main alloying elements. Alloys for mechanical work can be further classified into heat-treatable and non-heat-treatable alloys. The

Aluminum Association uses its nomenclature to design alloys for mechanical work, in which the first four digits specify the alloy and the following two characters specify the conditions of thermal or mechanical treatment. The first number indicates the alloy series, the second, when different from zero, indicates the change in the basic alloy, and the third and fourth numbers, except commercial aluminum, 1000, indicate the specific composition. Table 2.4 presents the alloys for mechanical work and their main alloying elements.

Table 2.4. Major alloying elements [22].

Series	Major Alloying Elements
1xxx	pure Al
2xxx	Cu
3xxx	Mn
4xxx	Si
5xxx	Mg
6xxx	Mg,Si
7xxx	Zn
8xxx	Li, Sn, Fe, Cu, M

The group of non-heat-treatable alloys includes the 1xxx, 3xxx, and 5xxx series alloys. These alloys increase their mechanical strength by cold plastic deformation, and the degree of deformation is specified by the letter H, which follows the four-digit chemical designation of the alloy. The 2xxx, 6xxx, and 7xxx series are included in the group of heat-treatable alloys whose mechanical resistance is increased through appropriate heat treatment. The process is designated by the letter T followed by one or more digits, which specify the heat treatment conditions, as shown in Table 2.5. Another type of heat treatment, called W, is attributed to alloys that harden by natural aging [23].

Table 2.5. Specifications of thermal treatments [24].

Type	First digit specification
T1	Partial solubilization and natural aging
T2	Annealing
T3	Total solubilization and cold deformation
T4	Total solubilization and natural aging
T5	Artificial aging only
T6	Total solubilization and artificial aging
T7	Solubilization and stabilization
T8	Solubilization, cold forming, and artificial aging
T9	Solubilization, artificial aging, and cold forming

- 2014 Alloy (4.5% Cu - 0.8% Si - 0.8% Mn - 0.4% Mg): It is used where high strength and related good machinability and hardness are required. It is widely used in the construction of aircraft equipment. Its density at 20ºC is 2.80 gr/cm³. It is kept at 412ºC for 2-3 hours for complete annealing. It is then cooled in the furnace at a cooling rate of 10ºC per hour [25].
- 2024 Alloy (4.5% Cu - 1.5% Mg - 0.6% Mn) [26]: It is used in aircraft structures, rivets, mixed shaped elements. Its density at 20ºC is 2.77 gr/cm³. After being kept at 413ºC for 2-3 hours in full annealing, it is cooled in the furnace with a cooling rate of 10ºC per hour. It can operate at temperatures between 260-480ºC.
- Alloy 5052 (2.5% Mg - 0.25% Cr)[27]: It is used in applications where average static strength, good operability, high fatigue strength, and excellent corrosion resistance are required. It is used in aircraft fuel, oil pipes, and fuel tanks. Its density at 20ºC is 2.68 gr/cm³. It can operate at temperatures between 260-510ºC. It is annealed at 345ºC. It is not necessary to keep it at this temperature. It can be cooled immediately.
- 6061 Alloy (1.0% Mg-0.6% Si-0.2% Cu-0.025% Cr): It is used where high strength, machinability, weldability, and good resistance to corrosion are required. Elements such as aircraft landing ladders have application areas. Its

density at 20ºC is 2.70 gr/cm³. It is used as a bare and clad alloy. It can operate at temperatures between 260-510ºC. Full annealing is done at 413ºC. After being kept at this temperature for 2-3 hours, it is cooled in the oven at 10º C per hour.

- 7075 Alloy (5.5% Zn - 2.5% Mn - 1.5% Cu - 0.3% Cr)[28]: It is used where high strength and good corrosion resistance are required. Most aircraft structural elements are made of 7075 alloys. Its density at 20ºC is 2.80 gr/cm³. Its modulus of stiffness is 14927 N/cm². Poisson's ratio is 0.33. Shear tensile strength is approximately 55% of tensile strength. It can work hot between 260-455ºC. Full annealing is done at 413ºC for 2-3 hours. It is then cooled in the air. If the material is to be stored for a period of time before use, it must be reheated at 232ºC.
- * 7079 Alloy (4.3% Zn - 3.3% Mg - 0.6% Cu - 0.2% Mn - 0.2% Cr)[29]: It is used in high-strength and heavy sections. It has an application area in aircraft structural elements. Its density is 2.74 gr/cm³ at 20ºC. Full annealing is done at 413ºC for 2-3 hours. It is cooled in the air. Air cooling is satisfactory if followed by 6 hours of stabilization annealing at 232°C.
- * Alloy 7178 (6.8% Zn - 2.7% Mg - 2.0% Cu - 0.3% Cr)[30]: Its density at 20º C is 2.82 gr/cm³. Shear, tensile strength is about 0.55 times the tensile strength. It can operate at temperatures between 260-455ºC. It is subjected to full annealing by keeping it at 413ºC for 2-3 hours. If it is subsequently subjected to a stabilization treatment at 232ºC for 6 hours, air cooling is sufficient.
- Cast aluminum alloys are alloys obtained by casting in sand or metal molds. Its properties vary depending on the casting form. Aluminum alloys with many metals. One of the essential alloying elements of aluminum is alloys made with silicon. Aluminum alloys with added silicon between 5% and 12.5% become fluid at casting temperature. As the amount of silicon increases, the casting becomes coarser. Silicon-Aluminum alloys are superior to Al-Cu alloys in corrosion resistance, toughness, malleability, and castability. Al-Si alloys are used in architecture, decoration, construction of marine engines' hulls and blocks, and engine parts, where sealing and corrosion resistance are required. It also makes alloys with aluminum, Zn, and Mg. Alloys of aluminum with Mg have superior corrosion resistance and are more durable than alloys with the

low silicon content. Alloys of aluminum with Zn are inexpensive and good in hardness. In contrast, it is heavy and has low corrosion resistance.

- 142 Alloy (4% Cu - 2% Ni - 1.5% Mg): It is used where very high-temperature resistance is required. It is used in aircraft generator housings, pistons, and air-cooled cylinder heads. Its density at 20ºC is 2.81 gr/cm³. Its modulus of elasticity is 14927.53, modulus of stiffness is 5579.7 N/cm². Poisson's ratio is 0.33. Sand casting types are annealed at 345 ºC. The casting temperature is between 677-788 ºC in sand casting. In continuous casting, casting is done in this temperature range. 142 alloy parts can be connected with rivets from 2117-T4 and 2017-T4 wrought aluminum alloys. Metal arc welding, carbon arc welding, and TIG welding in an argon shielding gas atmosphere can be performed with alloy 4043. No welding powder is required.
- 195 Alloy (4.5% Cu): It has application areas requiring high tensile properties and good machinability. It is used in aircraft wheels and connections. Its density at 20ºC is 2.81 gr/cm³. Its modulus of elasticity is 14492, modulus of stiffness is 5434 N/cm². It is annealed at 345ºC. It is kept at this temperature for 2-4 hours. Rivet connections can be made with 2117-T4 and 2017-T4 alloys. Atomic-hydrogen welding, metal arc welding, carbon arc welding, and TIG welding under an argon atmosphere can be performed with 4043 alloys.
- B195 Alloy (4.5% Cu - 2.5% Si): It is applied simultaneously when high tensile properties and good machinability are required. The application areas include aircraft connections, weapon control parts, and aircraft wheels.
- 220 Alloy (10% Mg): It is used when high strength and elongation, corrosion resistance, and excellent machinability are required. It is used in aircraft joints and mixed castings that require tensile and shock resistance. Its density at 20ºC is 2.57 gr/cm³. Tensile strength is 69.56, compressive tensile strength is 39.13, modulus of elasticity is 13768.1, and shear strength is 49.3 N/cm². The fatigue limit is 11.6 N/cm² after using 500 million turns. Rivet connections, spot, and butt welds can be made with 6053-T4 alloy.
- Alloy 355 (5% Si - 1.3% Cu - 0.5% Mg): Typical uses require good castability, weldability, and sealing under pressure. It is used in aircraft compressor coatings and liquid-cooled aircraft engine craters. Its density at 20ºC is 2.71

gr/cm³. The modulus of elasticity is 14782.6, modulus of stiffness is 5507 N/cm².

- Alloy 356 (7% Si - 0.3% Mg): It is used where excellent castability, weldability, tightness under pressure, and very high corrosion resistance are required. Aircraft pump parts, aircraft coupling, and control parts are typical uses. The density at 20ºC is 2.64 gr/cm³ [31, 32]. Aluminum is a metal that is used in many sectors because it is a metal that cools easily and absorbs heat, and it is soft and easy to process. While converting aluminum and its alloys from raw material to a certain shape, it is essential to carry out the production process by considering the geometric dimensions and surface properties suitable for the part drawing [14, 33]. This is the essential feature of the chip removal process.

2.3 ALUMINUM-MAGNESIUM ALLOYS

Aluminum-magnesium (Al-Mg) alloys are also known as the 5XXX series. The main alloying element is Magnesium. Magnesium can be found in the alloy between 0.6 and 5.5%. Increasing the Mg ratio gives the material strength and formability [34]. These alloys, albeit in small amounts, contain many elements, such as manganese, and contribute to the material's mechanical properties. Aluminum alloys in this series are in the group of alloys that cannot be heat treated, and no gain in strength can be achieved with this method. In order to change the strength properties of these alloys, the materials are reduced from specific thicknesses to thinner thicknesses by the rolling method. 5083, 5182, 5454, and 5754 alloys are mainly used as vehicle bodywork materials. The sheets' thickness in the body panels varies between 0.8 mm and 1.3 mm [35]. Figure 2.1 shows the estimated values of the use of aluminum-magnesium alloys in the automotive industry in the coming years.

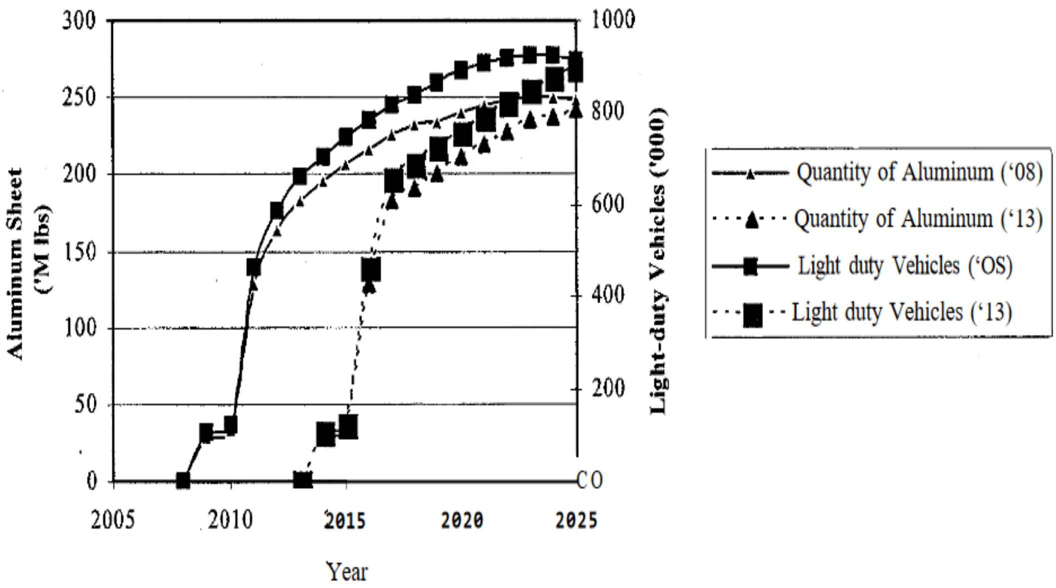


Figure 2.1. Estimation of the use of Al-Mg plates [36].

Due to the growing interest of the automotive and aerospace industries in vehicles with greater energy efficiency, aluminum alloys are presented as potential substitutes for steel in manufacturing components and structural parts. Among the options for the automotive sector, the most targeted are the 5XXX series alloys, which have magnesium as the primary alloying element.

Aluminum is approximately three times less dense than steel and 30% denser than magnesium. Such a relationship allows Al-Mg alloys to present exciting weight reduction and corrosion resistance characteristics, especially in saline environments [37]. In addition to exhibiting a great combination of fatigue resistance, formability, and weldability [38]. Aluminum-magnesium alloys form a single-phase binary system, as shown in Figure 2.2

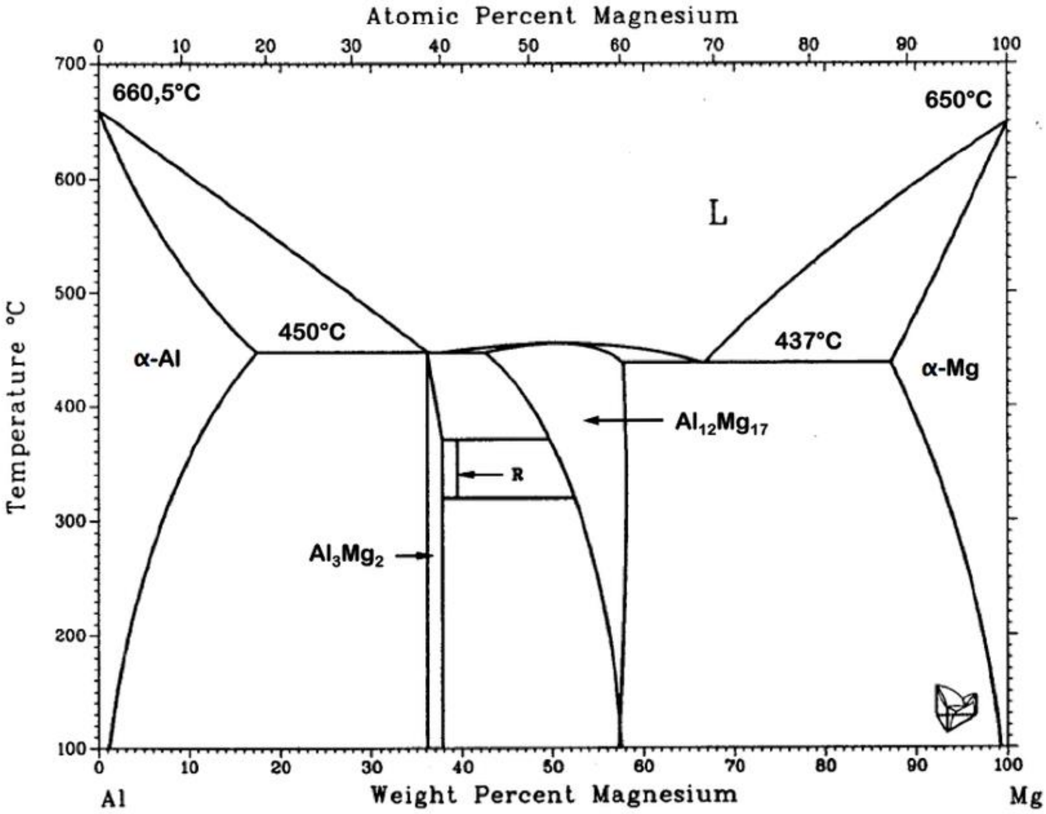


Figure 2.2. Al-Mg phase diagram [39].

Note the existence of a euthetic point, liquid → Al + Mg5Al8 (solid solution of Mg in Al with solubility from 15.4% to 35% of Mg), at a temperature of approximately 450 °C. Currently, the magnesium content present in the commercial leagues of the 5XXX series is defined according to the final application and may vary between 0.5 to 6.5% in mass. However, for theories above 3.5% of Mg and temperatures above 65 ºC, there are certain limitations for working these leagues in the cold, once due to exceeding the limit of solubility of magnesium due to the precipitation of the Al3Mg2 phases, Al3Mg5 or Al8Mg5. These intermetallic compounds formed preferentially precipitate in the grain contours, conferring greater susceptibility to intergranular fracture and stress corrosion[40] .

Table 2.6 shows the usage areas of the 5XXX series alloys, which are commonly used in automobiles. As can be seen from the chart, this series is mainly used as sheet metal in automobiles.

Table 2.6. Use of Al-Mg alloy plates in vehicles [41]

Alloy	Usage
AA5005	Body parts
AA5052	Interior panels, truck bumpers
AA5182	The interior panel, fender, A/C pans, and guards
AA5252	Body
AA5083	Welded tanks and unloading systems
AA5754	The inner panel, fender, heat shield, weldable parts, floor coverings

Alloys of the 5XXX series are hardened by solid solution and deformation (hardening), and it is impossible to obtain the desired mechanical properties through thermal treatments of solubilization and aging [42]. Al-Mg alloys, in the annealed condition, form Lüders lines when subjected to deformation. Alloys produced by forging, containing levels above 3% by mass of Mg, may present almost continuous intergranular precipitates of Al3Mg2 and a small fraction of precipitates inside the grains, which makes them susceptible to exfoliation [43]. The increase in magnesium content allows the mechanical strength of aluminum to be increased without the material's ductility being significantly affected. Thus, alloys with low magnesium content (< 5% by weight) are used in applications that aim at good formability and surface finish.

In the presence of silicon, magnesium associates form the Mg2Si phase, which helps harden the alloy, providing increased strength [44]. For applications in which high mechanical strength, fatigue strength, fracture resistance, and good weldability are key requirements, alloys with high magnesium content (> 5% by weight) are used [11]. Such alloys have Mg in solid solution or partially precipitated as Al3Mg2 particles uniformly dispersed throughout the matrix. These alloys also have high corrosion resistance in saline media and some alkaline solutions [45]. Due to their sensitivity to iron impurities, Al-Mg alloys' mechanical properties and corrosion resistance, especially when dealing with alloys with Mg contents between 4% and 6.5% by weight, can be affected.

In order to reduce the influence of iron 31 on alloy properties, the addition of manganese is a very common alternative [46]. However, compared to manganese, magnesium is more effective for hardening the alloy since adding about 0.8% Mg is similar to adding 1.25% Mn proportionally [47].

Among the most common alloys of the 5XXX series are 5005, 5049, 5251, 5154A, 5454, 5754, 5056, and 5083 [48]. In the case of applications in the civil construction, automotive, aerospace, and mechanical industries, alloys that combine Mg contents between 2.5 and 4% by weight, with low amounts of Mn and Cr are widely used, among them: 5454, 5754, and 5154A . The aluminum alloy (AA – Aluminum Alloy) 5052 has Mg as the only relevant alloying element, which has a content of 2.2% to 2.8% by weight, helping to form a solid solution of α and α phases. β [49, 50]. The mechanical strength of this alloy is obtained through cold working; therefore, the refinement of the recrystallized grains through cold rolling before the annealing heat treatment helps to obtain better mechanical properties [51]. Regarding the AA 5050C alloy, there is no information available in the literature since this was a compositional adaptation carried out by CBA from the AA 5052 alloy, so it would be possible to produce this material via a continuous casting process as this master's thesis is the first academic study conducted for this alloy in its final processing condition.

Due to the formation of Lüder bands (stretcher lines) on the plate surfaces during the shaping of these alloys at room temperatures, they are used in interior panels rather than exterior panels in vehicles. Because these errors are visible even after painting. The 5XXX series has high corrosion resistance and weldability due to its high Mg content. Especially in the welds made with aluminum-silicon alloys containing Si, such as the 6XXX series, the weld can be of good quality by increasing the Mg ratio of the weld area [52].

The presence of Mg in solid solution and second-phase particulates directly influences the density and distribution of dislocations in cold deformation, increasing the system's internal energy, which serves as a driving force for the subsequent heat treatment processes of recovery and recrystallization (annealing). The oldest Al-Mg alloys used commercially are 5052, 5154, and 5056. There are a few essentially binary Al-Mg alloys like 5005 and 5050 (with lower mechanical strength) since most contain elements forming dispersoids, such as chromium, manganese, and titanium. The Al-Mg alloy with the highest mechanical strength is 5456, followed by alloys 5083 and, at a lower level, 5086. Other alloys with lower mechanical strength are 5454, 5082, and 5182 . It is worth mentioning that the literature has already reported the effect of the Mg and Mn content on the temperature of the liquidus and solidus isotherms of commercial alloys of the Al-Mg-Mn system with low Si concentration, in which the workable alloys of the 5xxx series fit [53].

This material is characterized by its high mechanical resistance, high resistance to corrosion, and good weldability, which makes it widely used in the shipbuilding and transport industries. The properties of alloy 5xxx are widely explored in mechanical properties of laminates (formability) or even properties resulting from joining techniques of materials such as conventional and friction welding (Friction Stir Welding, FSW) . Still, despite not dealing directly with the commercial alloy in question, other works may well represent the behavior of systems whose main alloying element was investigated the unidirectional solidification in the transient regime of binary Al-3%Mg and ternary Al-3%Mg-1%Si alloy [37]. This work presents relevant results regarding microstructural characterization, a survey of relationships between thermal and microstructural parameters, and interrelationships between microstructure and mechanical properties. The results showed that for the Al-Mg binary alloy, the microstructure was formed mainly by α-Al matrix with dendritic morphology for cooling rates of 0.36 and 2.5 K/s (Figure 2.3) [54].

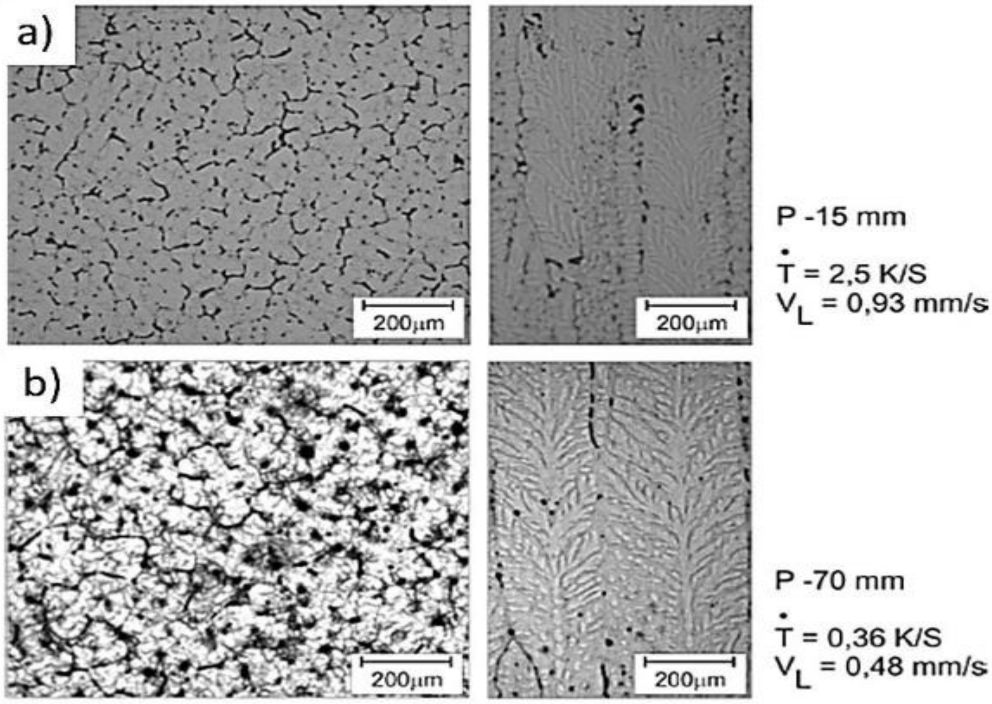


Figure 2.3. Predominantly dendritic microstructures showing the primary (left) and secondary (right) branches of the Al-3%Mg binary alloy resulting from upward unidirectional solidification, considering cooling rates a) 2.5K/s, and b) 0.36K/ s [54].

2.4 HEAT TREATMENTS APPLIED TO ALUMINUM ALLOYS

2.4.1 - Tempering

Tempering is applied to the metal or alloy through cold plastic deformation or heat treatment, providing structure and mechanical properties. Although the original strength can be increased by adding certain elements, the mechanical properties of alloys, except for some casting alloys, do not depend solely on their chemical composition. Similar to other metals, aluminum and its alloys harden and increase in strength when cold worked, such as cold rolled sheets. In addition, some aluminum alloys have the valuable characteristic of responding to heat treatment, acquiring strengths greater than those obtained only through cold working[55]. Figure 2.4 illustrates the effect of cold working on the mechanical properties of the alloy .

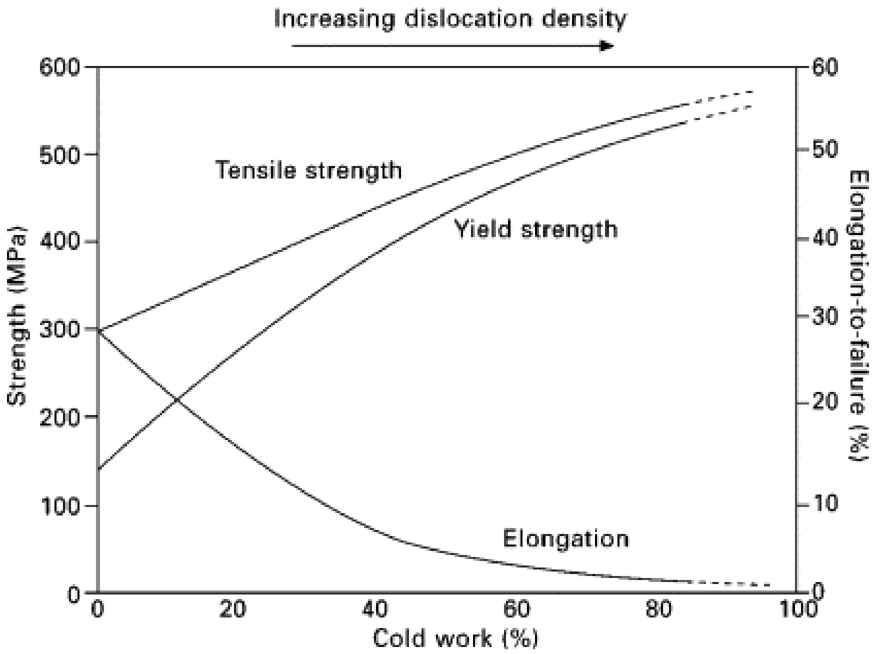


Figure 2.4. Effect of cold working on the mechanical properties of the alloys [56].

According to Budak [57], aluminum alloys can conveniently be divided into two groups: heat-treatable alloys, providing them with greater strength, and non-heat-treatable alloys, whose strength can only be increased through cold work and subsequently, undergo heat treatment to increase mechanical strength, non-heat-treatable alloys may be subjected to heat treatments such as stabilization and full or partial annealing.

2.4.2. Homogenization

This heat treatment is carried out at temperatures around 500 ºC depending on the alloy, and its objective is to reduce segregations and create more stable structures and control some characteristics of the metallurgical industry, such as its mechanical properties, formability, grain size, and even providing increased ductility and improved dimensional stability[58]. The time and temperature applied to depend on the diffusion rate and the original structure of the piece; when using higher temperatures in the process, faster homogenization is achieved; however, the material will be more exposed to harmful effects such as corrosion. Figure 2.5 shows the difference in alloy structure before and after homogenization.

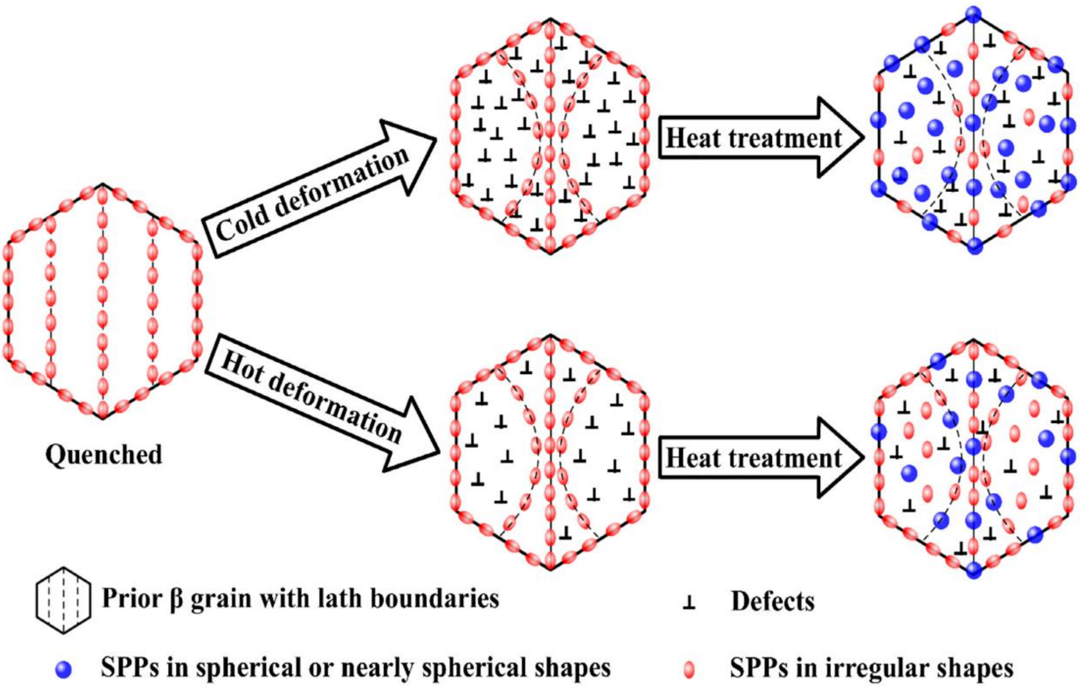


Figure 2.5. Alloy structure before and after homogenization [59].

2.4.3. Annealing

This process is generally applied to cold-worked alloys and aims to recover the hardened structure resulting from forming work at temperatures lower than those of recrystallization of the alloy [60].

the treatment can be understood between full annealing and partial annealing, and it is in full annealing, where the maximum plasticity conditions are obtained (tempera 0), equivalent to total recrystallization of the material. The process consists of heating the metal that has been cold deformed, usually around 350 ºC, which is enough to make it possible to arrange it in a new crystalline configuration that has not been deformed. This recrystallization removes the effects of cold working and leaves the metal ductile. Care must be taken not to allow overheating, which generates coalescence and excessive grain growth. Partial annealing is carried out at lower temperatures, between 200°C and 280°C, varying according to the percentage of reduction given in cold rolling. Its main function is to provide a partial recrystallization of the material, thus promoting the achievement of tempers with greater elongations. This procedure favors stamping, offering the final product greater mechanical resistance .Annealing decreases mechanical properties, which depend on the microstructure's initial state and the alloy's composition. Thus, the same alloy, with different degrees of deformation, may present radically different properties for the same treatment.

2.4.4. Stress Relieving

Stress Relieving is performed to remove internal stresses from pure aluminum, casting, or parts that have been welded, however, without fully recrystallizing the alloy. The temperature must be a maximum of 340ºC, and the time is determined from the thickness or diameter of the piece, being 1 min/mm at least. Due to the heat transfer characteristics of the solidification process, strong thermal gradients occur within the billet or cast slab. These gradients result in intense residual stresses, which in alloys with a more charged chemical composition, such as those of the 7xxx series, can even cause the cast product to break during its cooling [61]. recommends that, in this case, homogenization be performed as soon as possible after pouring the part so that heating promotes a redistribution of residual stresses and the dissolution of fragile constituents precipitated in the grain boundaries.

2.4.5. Solubilization

The solubilization treatment is based on heating the alloy to a high enough temperature to dissolve hardener precipitates [62]. In practice, a maximum temperature must also be established so that heating does not cause localized melting of low melting point constituents present in the alloy, which would compromise the finish or even the structural integrity of the treated part, depending on the quantity and the distribution of these constituents, observed in Figure 2.6.

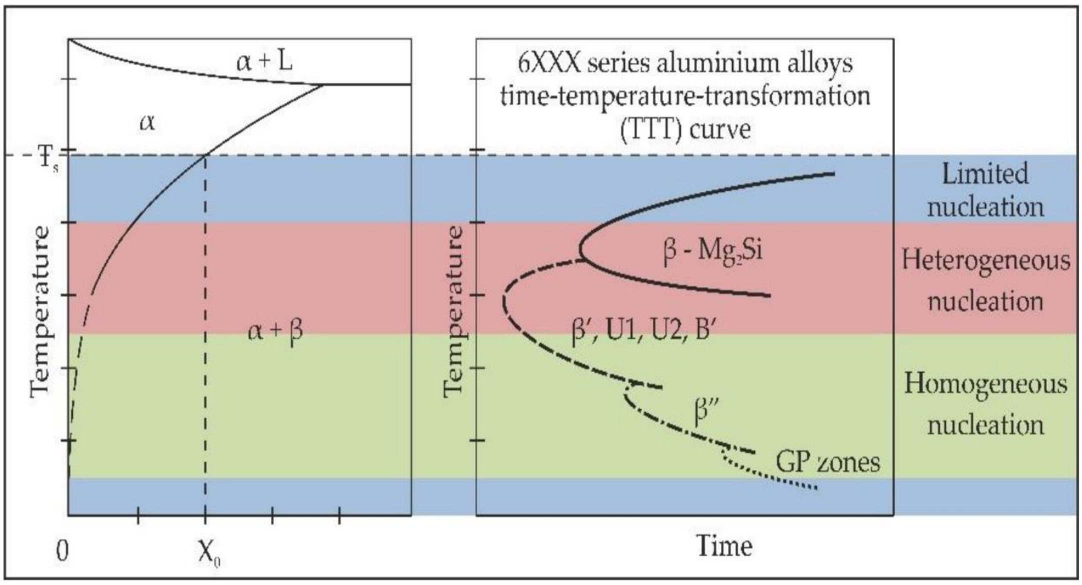


Figure 2.6. Temperature - time - transformation diagram [63].

Furthermore, the higher the temperature and the longer the treatment time, the greater the tendency for the growth of recrystallized grains, which results in loss of mechanical properties and damage to the surface finish of the final product. Solubilization practices are established based on these two limit temperatures, also considering the kinetics of precipitate dissolution reactions, heat transfer laws, and the characteristics of the ovens for determining treatment times .

In solubilization treatment, aluminum is solubilized at temperatures around 500°C; during the process, some alloying elements are re-dissolved to produce a solid solution rich in solute. This process aims to maximize the concentration of hardening elements in the solid solution, including copper, zinc, magnesium, and/or silicon [64]. The literature shows that temperature increases these elements' concentration and dissolution rate. Therefore, solubilization temperatures are generally close to the liquidus temperature of the alloy.

from the moment the alloying elements occupy the positions of the aluminum lattice in the supersaturated solid solution, there will be a period in which this situation will be maintained before the alloying elements begin to be rejected. , based on the motion kinetics of atoms at low temperatures. This incubation period generally lasts from a few hours to a few days, depending on the amount and type of dissolved alloying element.

the incubation period can be prolonged by keeping the parts at a low temperature after solubilization (-20ºC to -15ºC); this expedient is widely used in the aeronautical industry in the conformation of parts manufactured in alloys of high resistance after solubilization, as this allows a large batch of material to be treated at once and then shaped as needed, without interfering with the productivity of the operation[65].

The applied temperature is different for each type of alloy being worked on, so rapid cooling in water is done to prevent the precipitation of the alloying elements temporarily. Also necessary is the transfer time from heating to cooling medium; if it is delayed, an incomplete solubilization may occur, reflecting an unsatisfactory result [66]. The purpose of cooling is to avoid the formation of the equilibrium phase during cooling and to obtain the most significant possible amount of these elements in a solid solution at a low temperature [67]. Achieving high strength is dependent on high heat extraction rates. However, the cooling rate should not be too high. In order to avoid distortions and residual stresses in the treated components.

2.4.6. Aging

This treatment aims to provide the precipitation of constituents dissolved in the solid solution matrix during the solubilization treatment in the form of very small particles, which increases the material's hardness [68]. The main requirements for hardening are:

- the formed precipitate must be coherent with the matrix; the alloy must not crack during the solution cooling operation;
- decreasing solid solubility of a phase with falling temperature;
- Have a ductile matrix. after the solubilization process, the alloy is out of equilibrium; that is, the solid solution obtained is supersaturated with the solute and presents a driving force to generate the precipitation of other phases during the aging process.

The first precipitate to be nucleated in the aging process is the Guinier and Preston zone (GP), which is coherent with the matrix and has low interface energy. This precipitate minimizes the strain energy, acquiring a disk shape. According to Rossi (2004), when the GP zones are formed, the hardness increases due to the tensions necessary to move the dislocations through the coherent zones that generate deformation and tension in the crystalline lattice. The hardness increases with the formation of θ” precipitates because the dislocations move through a matrix highly deformed by the coherent precipitates. With the formation of θ', the spacing between the precipitates becomes more significant so that dislocations can pass, and the hardness decreases. The maximum hardness is obtained by combining precipitates θ” and θ’. With more time in aging, the distance between the precipitates increases, making them contour easier, and the hardness decreases. Figure 2.7 shows this mechanism.

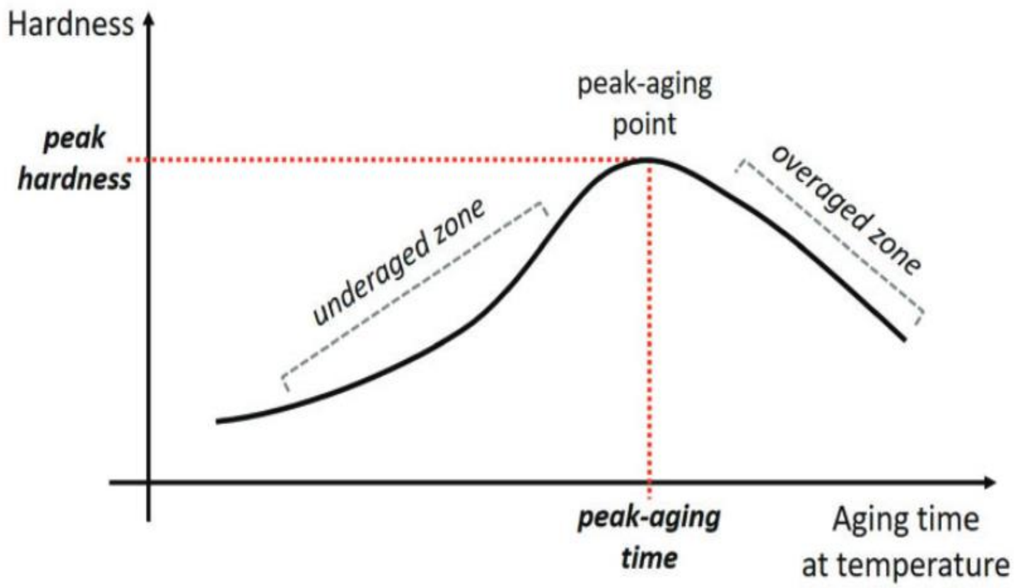


Figure 2.7. Influence of aging time on hardness [69].

aging hardening occurs because there is an interaction between the stress fields associated with dislocations and precipitates (just like a magnetic attraction between a magnet and a piece of steel). In one way or another, there is a “neutralization” of the effects of the stress fields between dislocation and precipitate, which decreases the system's internal energy. the beginning of aging, there is a progressive migration of alloying elements in solid solution to GP zones and precipitates. The volumetric fraction of precipitates increases with treatment time; the more “charged” the alloy, the greater the amount of precipitates formed. Since almost all of the alloying element is out of solid solution, the volumetric fraction of precipitates remains constant, after which the smaller precipitates will dissolve, “feeding” the larger ones. This decreases the amount of precipitates per unit volume and increases the distance between them. from the association of these two processes during the material treatment, we arrive at the simplified configuration of the aging curve known in Figure 2.8.

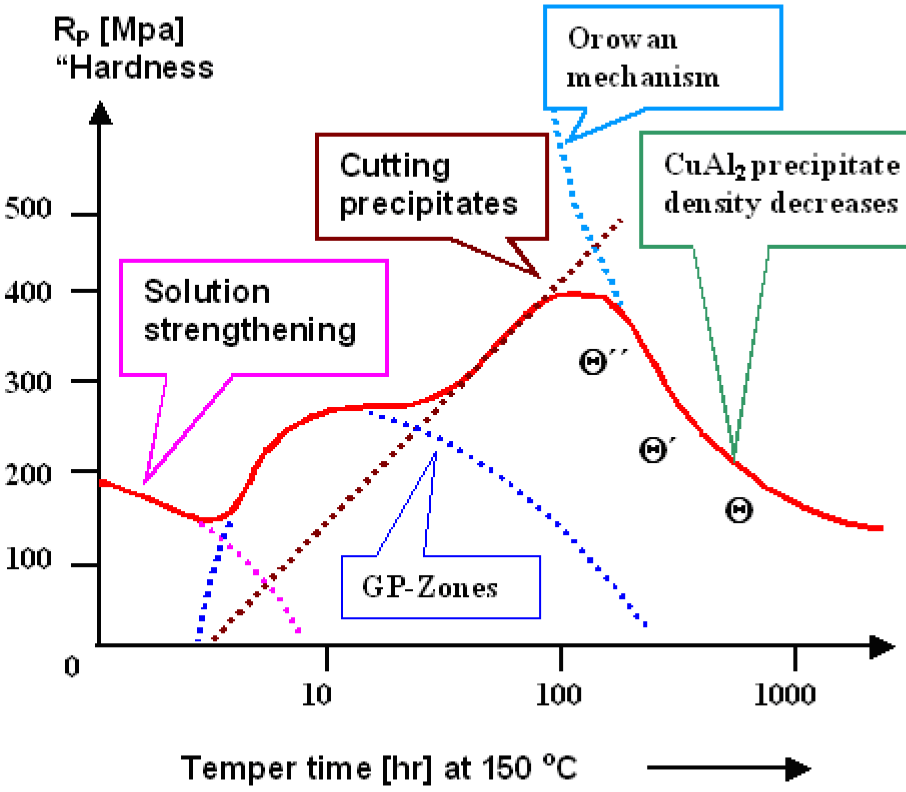


Figure 2.8. Evolution of the shape of the precipitates x time (aging curve) for Al-Cu alloy [70].

from the beginning of the treatment to the hardness peak, the predominant mechanism is "precipitate cutting". As the number of precipitates per unit volume increases and they are very close together, the stress to "bend" dislocations is higher than to "cut" them; with increasing fractions of precipitates, progressive hardening will occur until most of the alloying elements are combined in the form of precipitates.

from the peak of hardness onwards, non-coherent precipitates form due to the dissolution of the coherent ones. At this point, the mechanism in which the dislocations begin to "bend" between two precipitates and pass through them, with the formation of a dislocation ring around the precipitates, begins to predominate. This mechanism becomes predominant, and at this stage of treatment, the distance between precipitates increases progressively, and softening of the material occurs, caused by averaging.

2.5 MECHANICAL PROPERTIES OF AL-MG ALLOYS

Aluminum-based alloys have been increasingly used as potential substitutes for some applications where steels are still used, mainly to reduce weight and improve corrosion resistance. Concerning the growing applications of these alloys in the automotive and aeronautical industries, the weight factor is directly related to energy efficiency, and, in this particular case, Al is about three times less dense than steel, and Mg is about 30% less dense. Dense than Al. As for components of the naval industry, corrosion resistance is also an extremely relevant component [71] . Al-Mg diagram shows the occurrence of a eutectic at a temperature of 450.5°C, consisting of a mixture of the phase rich in Al (solid solution of Mg in Al with a maximum solubility of 15.4%) and the compound Mg28Al45. In worked alloys (series 5000), the most applicable range of compositions, according to the literature, is between 2% and 6%Mg [72]. Although the diagram does not show the occurrence of eutectic for this range of compositions, for industrial casting and casting conditions, the cooling rates associated with these processes lead to non-equilibrium solidification conditions. In these cases, eutectic formation may occur. The literature presents many examples of Al-Mg-X ternary alloys, their heat treatments, and their final properties, but systematic studies of solidification from Al-Mg binary compositions are scarce.

Al-Mg alloys do not harden by heat treatment; they do not undergo aging and have low thermal stability [73]. In principle, they could be submitted to tempering heat treatment and aging, but the resistance increase obtained by the precipitation of the intermetallic phases is minimal due to the small amount of precipitates. However, Mg increases the corrosion resistance of aluminum, slightly decreasing its malleability, which results in complex properties that make wrought alloys of the 5xxx series the most widespread aluminum alloys.

Ravi et al. [74] evaluated the influence of solute content on the fluidity of Al-Si, Al-Cu, and Al-Mg alloys. These authors verified that the fluidity of Al-Mg alloys undergoes a drastic reduction for contents up to 5% Mg and increases again with the increase of the eutectic phase fraction. There are few explanations in the literature for this occurrence, as shown in Figure 2.9. Cast alloys with a high Mg content (>12%) can exhibit some degree of age hardening when subjected to adequate thermal conditions, providing a good combination of castability and mechanical strength [73].

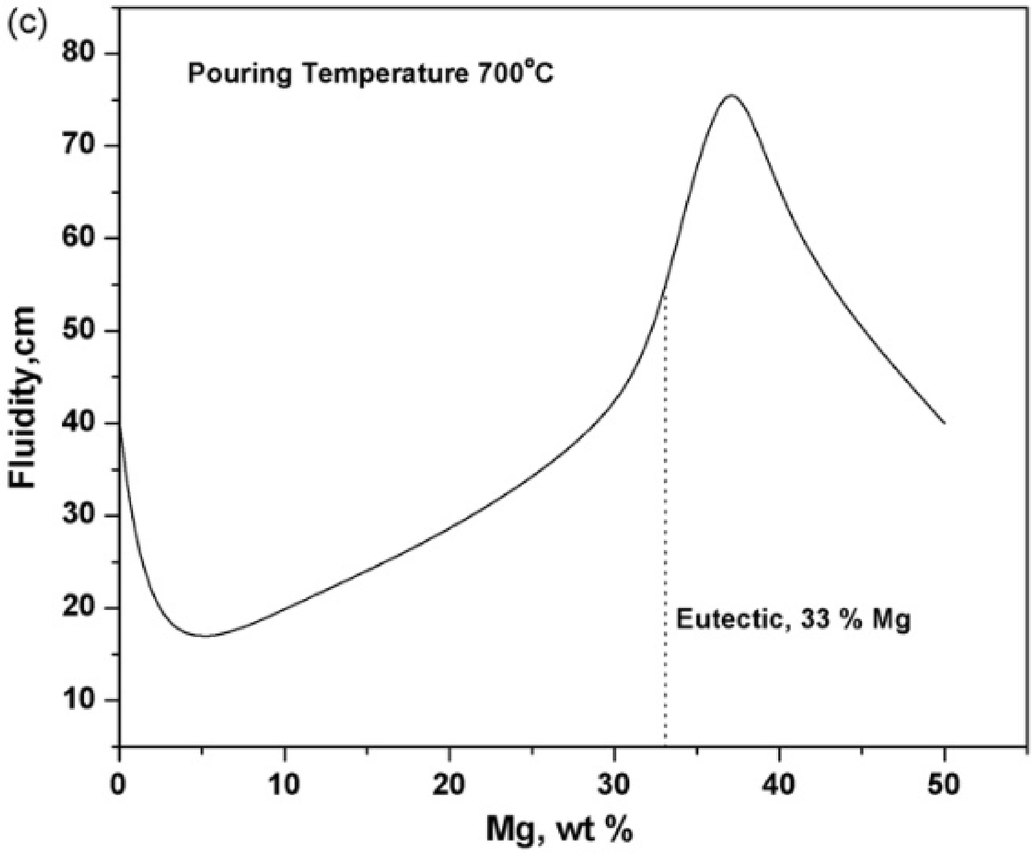


Figure 2.9. Spiral flow curve of Al-Mg binary alloys [73].

Liu and Kang [75]investigated the influence of composition and cooling rate on the solidification and segregation of Al-Mg alloys for alloys with composition within the range of 2.46 to 11.07% Mg (in Weight). These authors found that alloys with low Mg content had a microstructure restricted to α-Al dendrites and that the eutectic phase would only occur with increased Mg content and in the final moments of solidification. They also observed that the formation and growth of the eutectic phase (α-Al + Al5Mg8) depend on the cooling rate and that, however, for higher cooling rates (> 190Kmin-1), the concentration of Mg in the eutectic gradually decreases. Figure 2.10 shows the influence of the Mg content on the Al5Mg8 phase fraction and the cooling rate on the formation or non-formation of the eutectic phase for different Mg contents. Low Mg concentrations allow the formation of a single-phase α-Al structure even at high cooling rates. With increased Mg content, the eutectic reaction can be enabled. The eutectic volume continuously decreased as a function of the increase in the cooling rate within the investigated range (1K/s to 167K/s) [76]. Although the dimensions of the eutectic phase have been examined, a more detailed discussion regarding the dendritic growth of the Al-Mg alloys examined is still lacking.

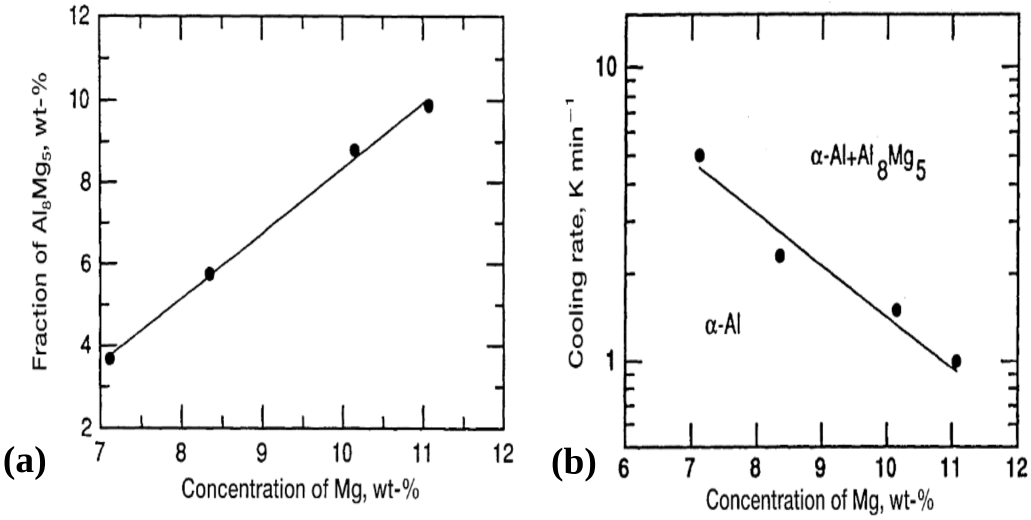


Figure 2.10. a) Fraction of the Al5Mg8 phase as a function of the %Mg of the alloy; b) influence of the cooling rate and Mg content on the formation of the α-Al + Al5Mg8 eutectic [76].

The literature is also scarce regarding the influence of convection induced by concentration and/or temperature gradients on the macrosegregation and microstructural evolution of Al-Mg alloys. Among the few works, we can mention two works addressing this objective. The first evaluated the effects of convection during vertical solidification of diluted Al-Mg alloys (%Mg < 0.1%) using the Bridgman stationary solidification technique [75]; these authors verified that the variation in the solidification speed with GL = 30°C/cm, caused a slight temperature variation caused by the thermosolutal effect resulting in the variation of the morphology of the S/L interface from planar to cellular, indicating the probable presence of macrosegregation.

In the second study, Vreeman and Incropera [77], applied a model for macrosegregation proposed by Vreeman et al. [77]during solidification in a mold of a round billet of Al-6%Mg alloy; these authors verified the occurrence of negative radial macrosegregation of Mg towards the central line of the billet. However, the authors did not consider the effects of the gravity vector, which, associated with the rejection of solute (Mg) to the liquid in front of the S/L interface, makes this liquid less dense, causing it to flow upwards in the opposite direction to gravity. , providing the formation of thermosolutal convection, which may have influenced the formation of this macrosegregation.

Al-Mg alloys are sensitive to Fe impurities, mainly for higher Mg contents (between 4% and 6.5%Mg). For more severe limitations of using these alloys for casting, Fe and Si contents are very restricted; for example, in the Russian alloy AMg61ch, no more than 0.05% of these elements are admissible. Due not only to the influence of Fe on the mechanical properties but also because it influences the corrosion resistance, mainly due to the cathodic character of the Fe-rich brittle phases. In turn, Mn, added to many Al-Mg alloys, partially reduces iron's negative influence on corrosion resistance [73].

The mechanical strength of Al-Mg alloys increases with increasing Mg content, as shown in Figure 2.11 for post-heat treatment conditions. However, specific elongation is little affected by Mg content, with a reduction of up to 1%Mg. Forged alloys of industrial interest based on Al-Mg rarely contain more than 5%Mg; this occurs because, above this level, the stability of these alloys decreases, particularly under the influence of high temperatures. The most common alloys of the 5xxx series are 5005, 5049, 5251, 5154A, 5454, 5754, 50 56, and 5083 [48] . Alloys 5454, 5754, and 5154A combine an Mg content between 2.5 and 4%, with a low amount of Mn and Cr, and are widely used in the construction, transport, and mechanical industries.

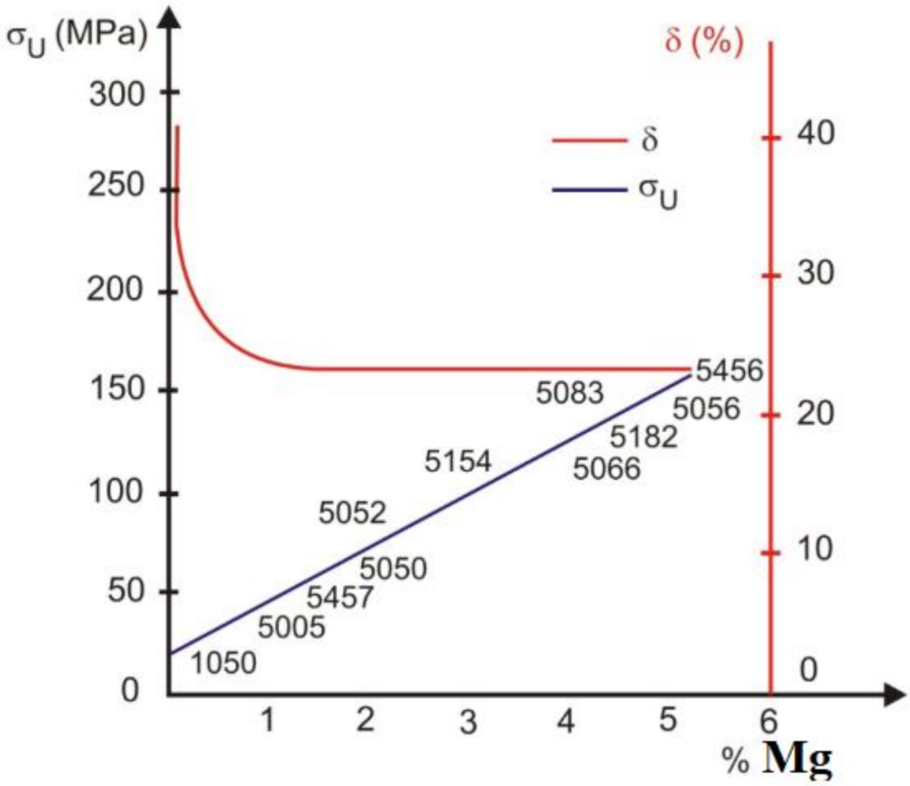


Figure 2.11. Effect of magnesium content on the mechanical property of 5xxx series alloys in heat-treated alloys by annealing [48].

Kumar et al. [78] analyzed the behavior of alloy AA5754 (~3%Mg) during solidification in a mold with high impurity contents (Fe, Si, Mn, and Cu) in order to characterize its potential for recycling. The authors found that adding low levels of these elements was enough to change this alloy's solidification path drastically. The predicted phases in the solidification path calculated using the Thermo-Calc software were confirmed after microstructural characterization of the alloy through SEM/EDS analysis. Al_2CuMg, Mg_2Si, intermetallic phases rich in Fe, and complex intermetallics such as $Al_3(Fe, Mn, Cu)_3Si$ were found.

2.6 TRIBOCORROSION OF METALLIC

Tribocorrosion or wear-corrosion is the union of mechanical and electrochemical effects on the surface, which contribute to material loss on sliding surfaces. In metals, the oxide layer formed on the surface will determine the degrees of wear and corrosion the system will suffer. Depending on its occurrence, chemical composition, thickness and the very nature of the metal, this layer may form a passivation layer. Furthermore, the electrochemical potential and ions of the medium are likely to modify its protective nature.

Degradation of a metallic or non-metallic surface occurs due to mechanical contact (sliding, friction, impact, etc.) combined with the corrosive action of the environment. Examples of Engineering systems and components subject to the phenomenon of tribocorrosion can be cited: biomedical and dental implants; processing equipment in the food industry; equipment for the mining, chemical, and petrochemical industries; turbine components, electrical connectors, and components subjected to relative motion in the automotive industry, etc. [79-81] .

The interactions between mechanical and chemical factors that govern tribocorrosion are still little known and require a deeper understanding of the relevant mechanisms to identify influential factors, whether mechanical, chemical, or related to the materials involved and the interaction between them. The interaction in the tribocorrosive process is the main focus of attention since it can result in new concepts related to the operation of materials in lubrication-free sliding conditions. The surface reactions induced by friction can change the corrosion sensitivity of the materials in contact, and once the corrosive process starts, it changes the friction conditions [82]. Few studies in the literature address the microstructure's effect on the trichobocorrosion resistance of metallic alloys. Ti alloys, for example, are widely used in the chemical, aeronautical, marine water desalination, and biomedical industries, as they have good resistance to different corrosive media. Martin et al. [83] analyzed the influence of microstructure and texture on the resistance to corrosion and tribocorrosion of the Ti6Al4V alloy, laminated bars were used, and the microstructural variation was obtained through thermal treatments. The authors observed better corrosion resistance for a bimodal microstructure (consisting of equiaxed α-phase grains in a refined β-phase matrix); the texture had influence only on the lamellar type microstructure (α + β) since a prismatic texture had better resistance to corrosion than the base texture.

As a result of a wide range of operating conditions and various forms of growth that can exist during the solidification process of metallic alloys, different and varied microstructural morphologies can be formed. Cell, dendritic or interphase spacing, morphology, size and distribution of intermetallic phases, porosity, etc. are examples of microstructural parameters that can significantly affect the mechanical properties of castings and corrosion and wear resistance. The scale of the microstructure, characterized by cellular, dendritic, or interphase spacing, can directly affect the application properties of the material. It is a known fact that the scale of structural morphology (grain size and cell, dendritic or interphase spacing), porosity distribution, segregated products, and other phases determine the mechanical properties of a metallic component. The relationship between structure and mechanical properties has been studied since the 1950s when the relationship proposed by Hall and Petch appeared [84].Hall-Petch relationships were also developed to relate experimental results of dendritic and cellular spacing with tensile strength limit, yield limit, and specific elongation for binary [85]and ternary [86].

Although there has been some effort to determine the real influence that the microstructural arrangement has concomitantly on the corrosion resistance and the mechanical resistance, little is explained which are the mechanisms that initiate the corrosion process, causing mechanical components to lose their characteristics of the project, leading to failures in service.

2.6.1 Wear Mechanisms

Understanding wear mechanisms are essential to designing materials suitable for reducing wear [87]. Wear mechanisms generally can be grouped into six generic types:

i. Adhesive wear

The surface interaction and welding of the junctions at the sliding contact cause adhesive wear. This wear mechanism is affected by the binding type (metallic, ionic, covalent, and van der Waals) in the contact junction.

The weaker part of the contact materials is removed and transferred to the counter surface if the junction bonds are stronger than the bond in bulk. Surface removal results in a rough appearance and a large volume of worn material; after that, severe Wear [87].

ii. Delamination Wear

The debris is plated, and the length to the thickness is ten times caused by forming and fracture, such as a cylinder in internal combustion machining may occur in abrasive wear. It is seen that ductility increases the strength of the material against delamination [88].

iii. Fatigue Wear

The debris of wear is generated by cyclic loading of the contact. Fatigue wear can be characterized by the crack formation and flaking of surface material [87].

iv. Erosion Wear

Caused by the impact of solid or liquid or gaseous particles forms losses in weight or removal of particles in which the fluid carries the particles. It depends on the kinetic energy of particles and the emission of the energy on the surface [87].

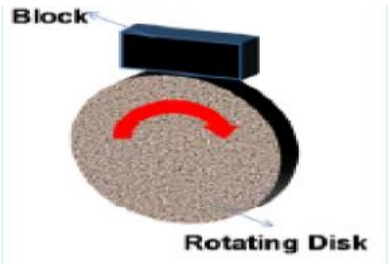
v. Tribochemical wear

Tribochemical wear results from removing reaction products/layers formed in a situation from the contacting surface [87].

2.6.2. Wear Testing Methods

Given the limitations mentioned above, especially regarding tribological properties, it is essential to characterize advanced biomaterials' wear and friction using a suitable test methodology. The most commonly used methods in studying metallic biomaterials' wear behavior are pin-on-disc, block-on-disc, and ball-on-dis, as shown in Table 2.7[89].

Table2.7. Summarizes various wear test configurations [90].

Test	Advantages	Disadvantages	Test format
Pin-on-Disk	After the run-in, surface pressure remains constant. Easy to determine wear volume and wear rate.	Difficult to stratify the pin. Suppose the pin does not stand perfectly vertical on the plate, the edge contact results. A very long run-in time is therefore necessary. The front edge of the pin can skim off lubricant. This makes a defined lubrication state impossible.	
Ball-on-Disk	High surface pressures are possible. The ball skims off lubricant less than a pin does. The model is similar to a linear friction bearing and a radial friction bearing.	Minimal contact ratio: The contact surface of the ball is small compared to the sliding track on the disk. The contact area is enlarged by wear. Difficult to determine the wear volume of the ball.	
Block-on-disc	The model is capable of simulating a variety of harsh field conditions, e.g., high temperature,high speed, and high loading pressure.		

2.7. APPLICATION OF AL-MG ALLOY

5005 aluminum alloy has many applications across different industries due to its unique properties. Here are some more specific applications [91-94]:

i. Automotive industry: 5005 aluminum alloy is used in producing car body panels, such as hoods, doors, and fenders, because of its high strength and corrosion resistance.

ii. Marine industry: The alloy is used to manufacture boats, ship decks, and other marine equipment due to its excellent resistance to saltwater corrosion.

iii. Packaging industry: The alloy is used to manufacture food and beverage cans and other packaging materials because of its excellent resistance to corrosion and hygienic properties.

iv. Electrical industry: Due to its high conductivity and low weight, the alloy is used to make electrical conductors, such as wire and cable.

v. Aerospace: The alloy is used in the aerospace industry to produce aircraft parts, such as fuel tanks and structural components, due to its high strength-to-weight ratio and corrosion resistance.

vi. Medical industry: 5005 aluminum alloy is used in the manufacturing of medical equipment, such as surgical instruments and imaging systems, because of its biocompatibility, corrosion resistance, and ease of sterilization.

vii. - Heat exchangers: 5005 aluminum alloy is used in the production of heat exchangers because of its good thermal conductivity and corrosion resistance.

Overall, 5005 aluminum alloy is versatile in many industries due to its unique properties, including high strength, corrosion resistance, lightweight, and ease of fabrication.

PART 3

METHODOLOGY AND EXPERIMENT

3.1 MATERIALS

Al-5005 alloy, which is widely used in many industrial areas from maritime applications to aviation applications, was chosen as the experimental material. Besides being easy to process, this material also has low density and high corrosion resistance, strength, electrical and thermal conductivity.

For the analysis of the behavior of aluminum alloys as a function of heat treatments, Al-5005 aluminum alloy alloy was obtained from Kayseri industrial zone with dimensions of 10mmx70mmx400mm. The chemical composition of this material is in Table 3.1, and the mechanical, electrical and thermal properties of the material are as in Table 3.2. this sheet were cut from these sheet metal samples for metallographic examination. Figure 3.1 summarizes the overall program used in the present work.

Table 3.1. Chemical composition of Al-5005 alloy

Al-5005	Mg	Si	Fe	Cu	Mn	Cr	Zn	Other products	Al
%	0.5-1.1	0.3	0.3	0.2	0.2	0.1	0.25	0.15	Balance

Table 3.2 Technical characteristics of Al-5005 alloy.

Property	Density (kg/m³)	Modulus of Elasticity (GPa)	Thermal expansion (20 º C)	Tensile Strength (Annealed) (MPa)	Yield Strength (Annealed) (MPa)	Elongation (Annealed)	Hardness (Annealed)	Annealing Temperature (ºC)
Value	$2.70x10^3$	69	$23.8x10^{-6}$	124	41	25%	28	343

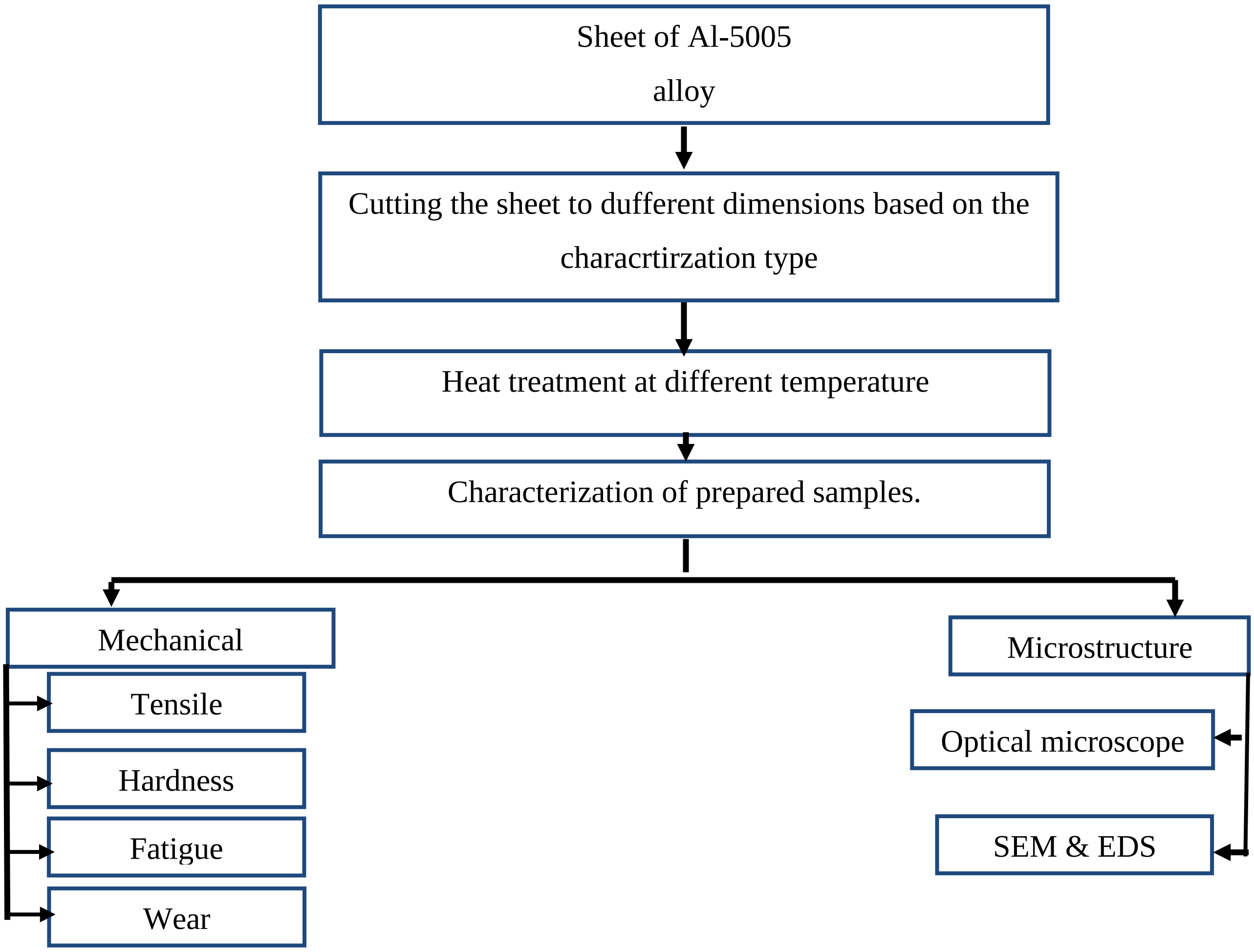


Figure 3.1. Experimental program of the present study.

3.2 HEAT TREATMENT

The heat treatment was carried out in the heat treatment furnace shown in Figure 3.2 at a variable temperature and variable time as shown in Table 3.3. After removing the samples from the oven, they were left outside under room temperature to cool with air, so that the samples are ready for use.

Table 3.3.Heat treatment temperature with time

	1	2	3	4	5
Time	60 minute	45 minute	30 minute	25 minute	15 minute
temperature	200	250	300	350	400

Figure 3.2 PROTHERM brand heat treatment furnace

3.3 COLD BAKELITE

Bakelite was used for microstructure tests Cold Bakelite was used so resin + color + hardener was used. The samples were poured into the mold and left for 12 hours, as shown in Fig. 3.3. The samples were taken out of the mold after they dried.

Figure 3.3 Bakelite casting mould

3.4 MICROSTRUCTURE CHARACTERIZATION

3.4.1 Optical Microstructure

A light microscope of type ZEISS (Figure 3.4) located in the laboratory of the Department of Metallurgical Engineering at Karabük University was used - in order to show the microstructure, a reagent solution consisting of (25 ml methanol -25 ml hydrochloric acid - 25 ml nitric acid – 1 drop hydrofluoric acid) was used.

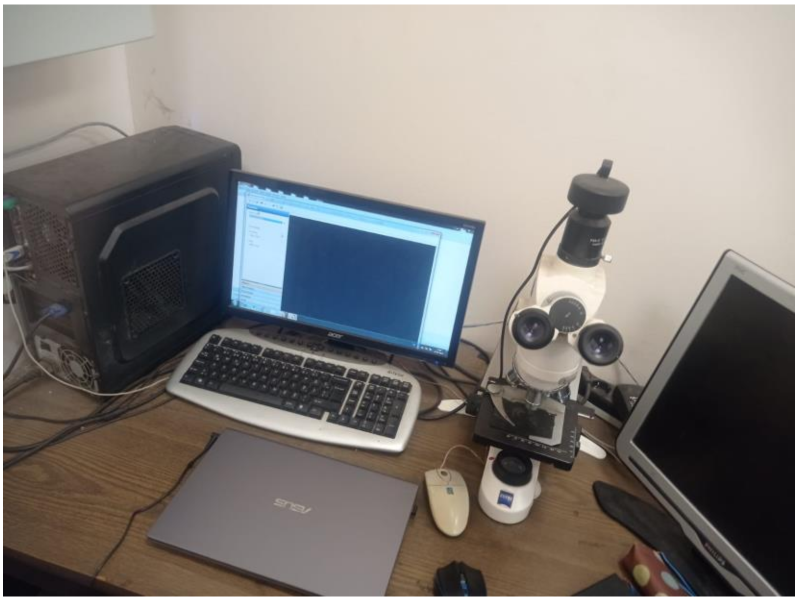


Fig. 3.4 light microscope device

3.4.2 SEM-EDX

After the sintering process, the Microstructure and energy dispersive spectrum (EDS) was used for chemical and elemental analysis of the materials. The prepared porous titanium alloys were examined using the Carl Zeiss ultra plus gemini FESEM model scanning electron microscope in the Karabuk University Scientific Technology Application and Research Center (MARGEM) laboratory (Figure 3.5).

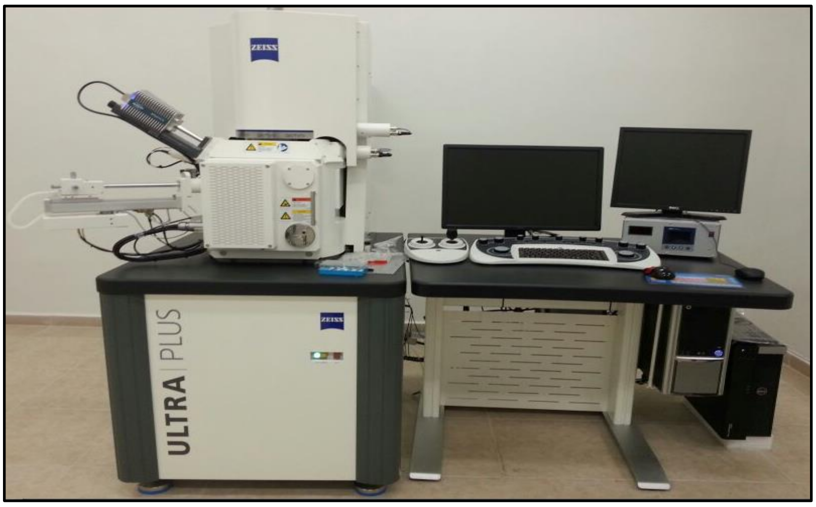


Figure 3.5. The device used for SEM analysis .

3.5. MECHANICAL PROPERTIES

3.5.1. Tensile strength

The samples which were heat treated at different times and temperatures, were subjected to tensile test at room temperature were carried out in the static laboratory of the KBU Institute for Iron and Steel according to ASTM A370-12a at a speed of 127 mm/min with a 100 kN MTS brand hydraulic servo. They were created with the Dynamic Tester.

Yield Strength (σa)

It is the stress value corresponding to the part of the tensile diagram where the plastic deformation increases significantly and the tensile diagram shows unevenness, although the applied tensile force remains approximately constant (Equation 3.1).

$$\sigma_a = \frac{P_a}{A_o}$$

Tensile Strength (σa)

It is defined as the highest tensile stress that a material can withstand until it breaks or breaks. This stress is the highest stress value in the tensile diagram (Equation 3.2).

$$\sigma_c = \frac{P_{max}}{A_o}$$

Percent Elongation at Break (KU)

It is defined as the highest percentage plastic elongation rate that occurs in the length of the tensile specimen. The final length is measured by bringing together the broken parts of the sample subjected to the tensile test and the elongation in the length is found by the equation 3.3.

$$\Delta l = L_k - L_o$$

Here L_o indicates the initial gauge length of the sample, and L_k indicates the length of the sample at the time of fracture. The elongation at break is determined with the help of Equation 3.4.

$$KU(\%) = \frac{\Delta L}{L_o} \times 100$$

Percent Cross Section Narrowing (KD)

The largest percentage shrinkage or shrinkage rate that occurs in the cross-sectional area of the tensile specimen is calculated by Equation 3.5.

$$KD(\%) = \frac{A_o - A_k}{A_o} \times 100$$

Here, A0 indicates the initial cross-sectional area of the test specimen, and Ak indicates the cross-sectional area at the time of fracture or the area of the fracture surface. Figure 3.7 shows the apparatus used for the tensile test.

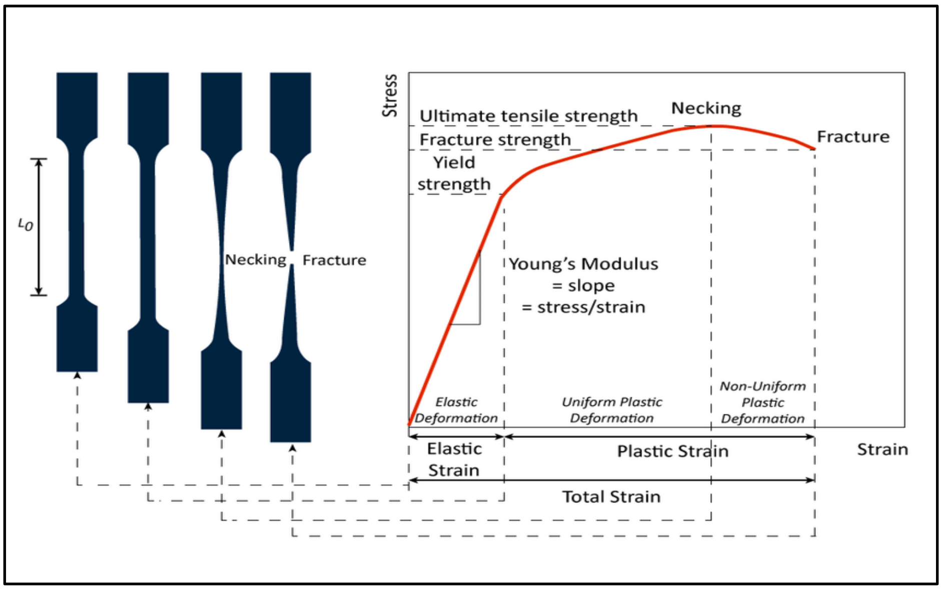


Figure 3.6 .A schematic tensile diagram of a ductile material[95].

Figure 3.7. The device used for tensile testing.

3.5.2. Hardness Test

Brinell microhardness (HB) measurements were carried out to determine the hardness distribution in aluminum alloy sheets. Hardness measurements were made on the sample surface taken perpendicular to the Al-5005 alloy, the hardness test was performed by Brinell Universal Hardness Tester, 10 seconds
It was used with steel balls with a spherical diameter of 2.5 mm and a load of 30kg. Figure 3.8. shows the Brinell Universal Hardness device.

Figure 3.8 The device used for hardness testing.

3.5.3. Fatigue Test

Most commercial stress-controlled servo-hydraulic testing machines have high maintenance, operating and service costs as well as complexity and purchase costs compared to strain-controlled testing machines . For this reason, in this study, a deflection-controlled fixed type planar bending fatigue test device, whose schematic picture is given in Figure-1, was designed and manufactured .

An engine with output speed of 2850 rpm and power of 1 HP was used in the fatigue tester. The second shaft was moved by the timing belt-pulley from the engine and the test frequency was 20 Hz. One end of the second shaft is bedded to the deflection-changer crank mechanism and the other end to the cycle counter sensor side. The data received from the cycle counter sensor is transmitted to the digital counter. When the specimen breaks, the connecting rod falls down under its own weight. At this time, the connecting rod is detected by the engine stop sensor and the engine stops. The constant deflections in the test were measured with the adjusting screws on the crank and a 0.01 precision comparator placed on the sample side. Before starting the fatigue tests, the force-deflection tests were performed to determine the maximum force that should be applied against each determined deflection (amplitude) value.

In this study, Fatigue test was carried out in an IRON AND STEEL INSTITUTE laboratory (ZWICK/ROELL Amsler500 HFP5100 MAGNETIC RESONANCE FATIGUE TESTING MACHINE)as shown in figure 3.9 , the test frequency was 20 Hz and at room temperature.

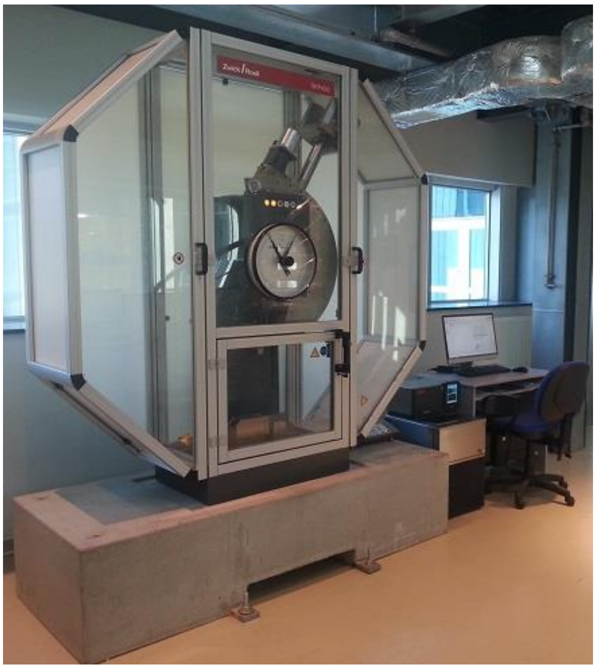


Figure 3.9. The device used for fatigue testing.

3.5.4 Wear Test

Linear wear tests were carried out in the apparatus shown in Figure 3.10. It is performed Within the scope of this thesis, it was possible to eliminate the effect of the opposite surface on the abrasion, and to observe and evaluate the wear mechanisms at the micro-nano'1 scale . the wear device includes counter surface conditioner module, wear loss measurement module, friction force measurement module, roughness measurement module, temperature measurement module, software and control modules. The most important features that distinguish the wear device from its counterparts are that the counter-surface change can be adjusted, controlled and conditioned, and instantaneous wear loss, instantaneous surface and friction force changes can be observed and analyzed.

During wear, the opposing surface will also be in contact with a polishing set and the initial conditions will be maintained at all times. Thus, the effect of counter-surface degradation on the development and speed of wear events can be reduced to negligible values. After all; Wear events and mechanisms will progress relatively slowly.

Linear wear (reciprocating wear) of the layers formed on the sample surfaces by the micro arc oxidation process was made and these experiments were carried out with a ball-on-disk test setup in a dry environment. Ambient temperature was determined as 25 °C and humidity 60% ± 2%. 6mm diameter alumina ball was used as abrasive ball. In the experiment, 10 N loads were determined as variable in the parameters, and the wear rate was kept constant at 0.10m/s. The total sliding distance was applied as 50 m. The scar volume formed as a result of the wear test and to determine the wear rate was measured.

Figure 3.10. The device used for wear testing

PART 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

In this part, the characterization of Al-5005 alloy was be viewed by optical microscope, SEM/EDS analysis,. Mechanical properties such as (tensile, wear, fatigue and hardness) of experimental specimens were also measured to show the suitability of these alloys for different applications.

4.2. MICROSTRUCTURE CHARACTERIZATION

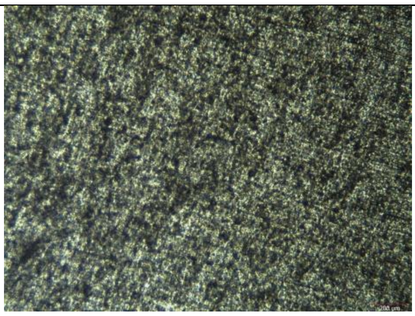
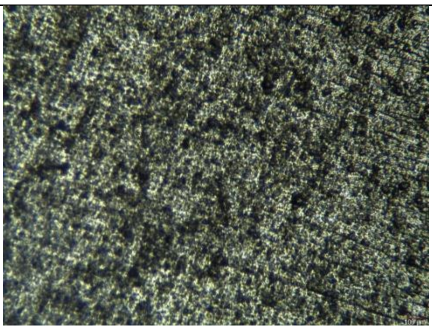
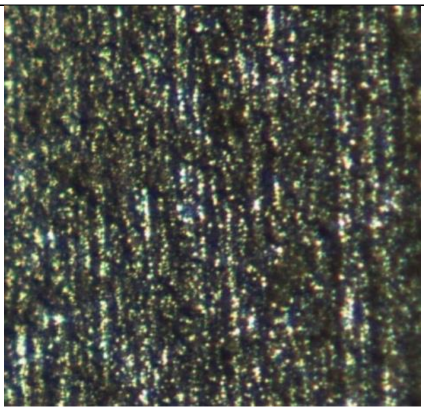
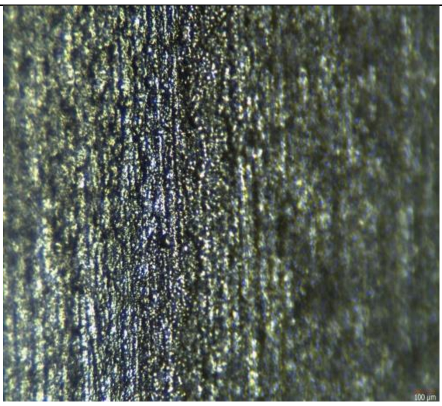
4.2.1. Optical Microscope

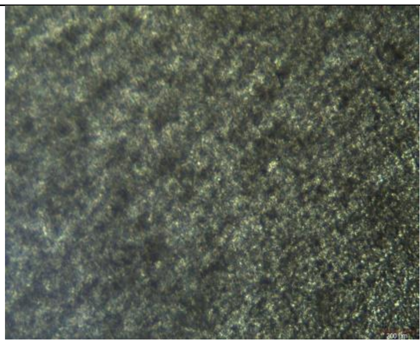
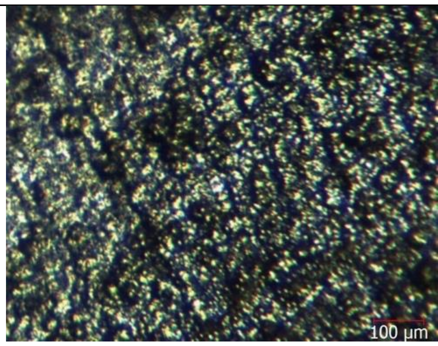
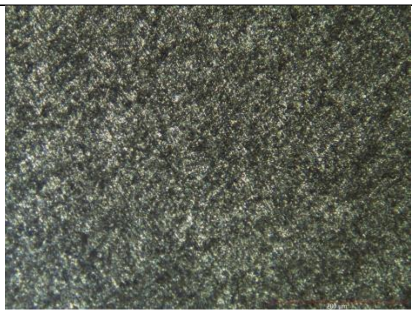
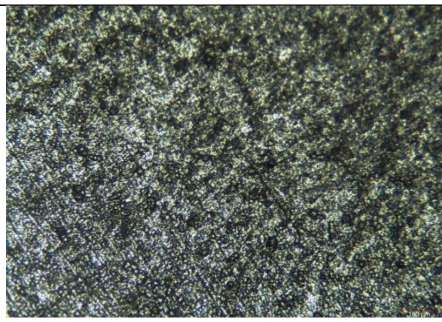
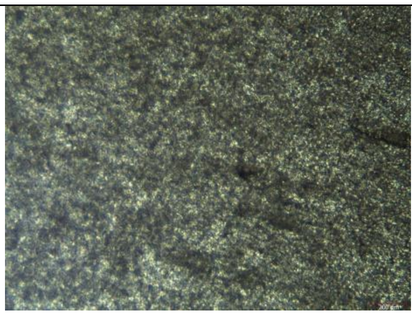
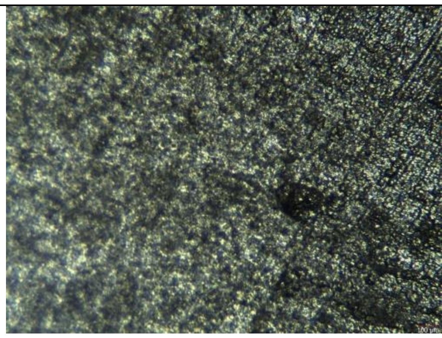
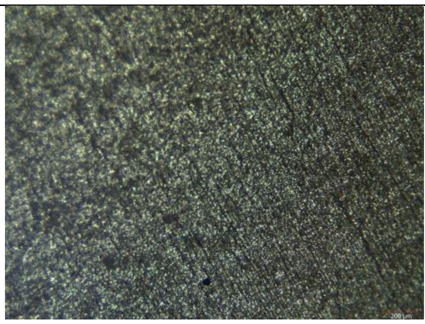
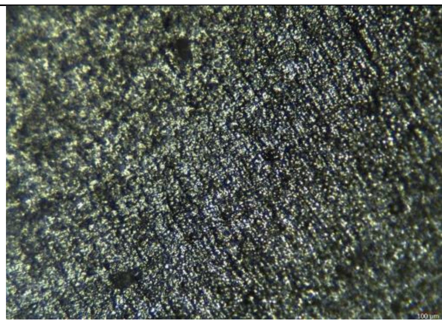
In this study, the microstructure of AL 5005 samples was studied by optical microscopy. Two optical microscope readings were taken at 200 μm and 100 μm .
The microstructure of the heat-treated samples at different times are shown in Figure table 4.1. The microstructure of annealed sample shows that the grain size becomes coarser compared to as received. On the other hand, normalized and quenched specimens show finer grain. This is consistent with finding by Rezaei et al. [96],and Kelley et al [97]. In general, fast and medium cooling rate results in finer grain whereas slow cooling results to coarse grain. This finding is similar as being found by Ridhwan et al.[98]. As aging temperature increased from 200^{o}C to 400^{o}C, it was observed that the grain and precipitate size become larger. Larger precipitates contribute to the stronger material due to dislocation motion obstruction. However, when the precipitates become too large, it will cause over age as mention previously. In this this study, over-aging was occurred at 400^{0}C after 15 min of aging which shows larger precipitates size as compare to shorter aging time. Meanwhile, no over aging condition observed at 200^{o}C. Tan and Muhammad [99] states that finely dispersed of tiny

precipitates may contribute to higher hardness and strength, thus, larger precipitates on over-aged samples had lower the strength of material.

Silicon has almost no solubility in Al, so it is present in the alloy as pure Si. In addition, there are covalent bonds between metallic Al and non-metallic Si, and the Si phase grows anisotropically as crystals with sharp corners. There may be an interaction of the Si particles, which become larger after aging, with the Al matrix phase. The impurities contained in the Al matrix phase can affect the Si microstructure. If impurities are present in Al, they act as nucleators and Si particles can be formed in finer morphology. However, this is not the case in the alloy studied, and Si particles are formed and grown without the nucleating effect [100].

Table 4.1 Microstructure images of 5005AL samples captured by optic microscopy.

	200 μm	100 μm
original		
200.60		

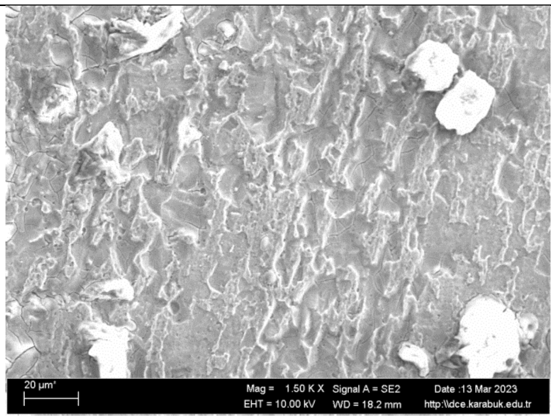
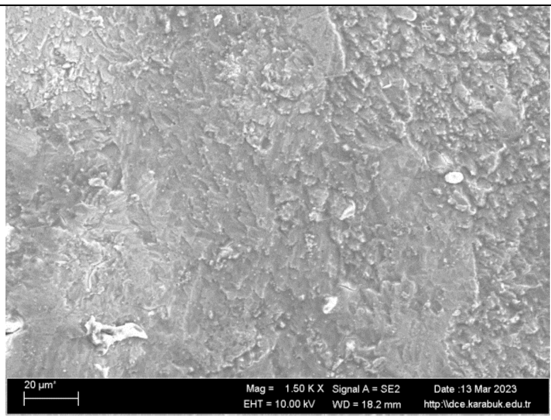
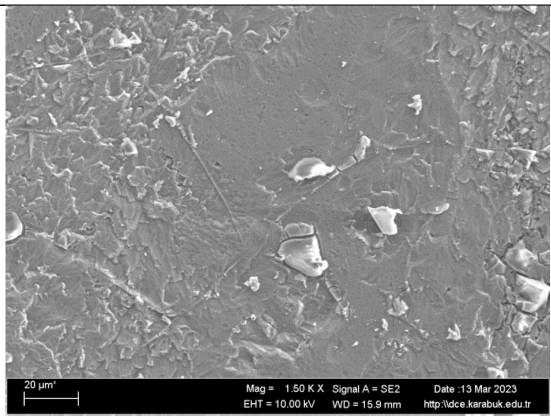
250.45		
300 .30		
350 .25		
400 .15		

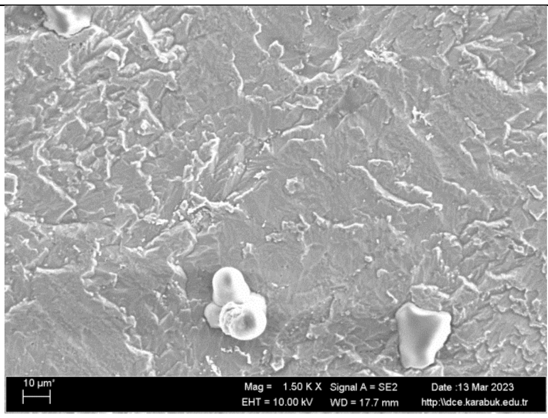
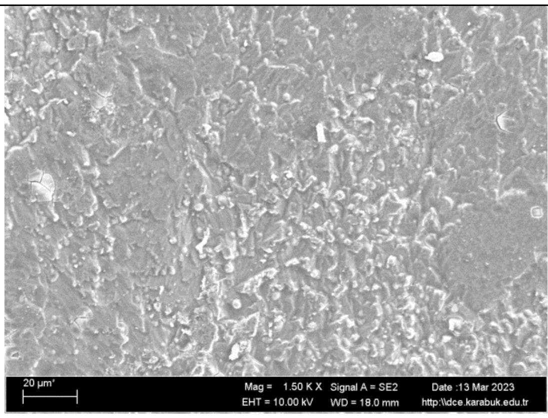
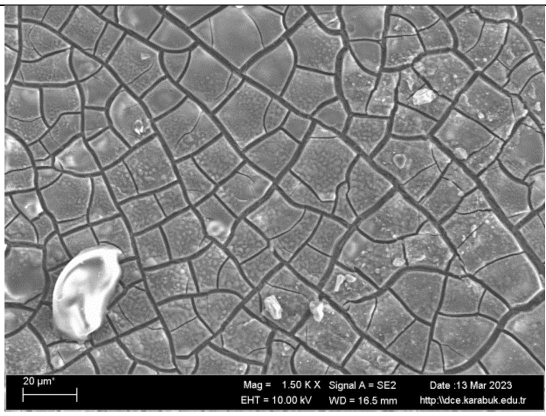
To better explain the microstructure observed after heat treatment at 400 °C for 15 min, it seems that the microstructure is mainly composed of parallel lamellar boundaries (LBs) containing structures elongated cells with a width of about 0.4 µm. The cell boundaries are essentially low-angle and oriented along traces of 111 planes [101].

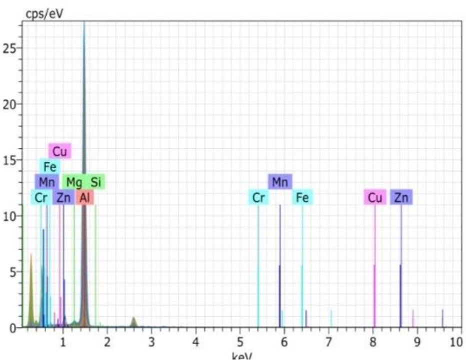
4.2.2 SEM and EDX Result

Table 4.2. shows the images captured by SEM of 1500 micron. Figure 4.1. show the elemental ratios for EDX-analysed Alloy 5005

Table 4.2 Microstructure images of 5005AL samples captured by Scanning_electron microscope

	1.5 k µm
original	
200.60	
250.45	

<table>
<tr><td>300 30</td><td>
</td></tr>
<tr><td>350 25</td><td>
</td></tr>
<tr><td>400 15</td><td>
</td></tr>
</table>



Mass percent (%)

Spectrum	Mg	Al	Si	Cr	Mn	Fe	Cu	Zn
1	1.21	96.55	0.16	0.74	0.00	0.00	0.77	0.56
2	1.01	94.71	0.34	0.54	0.00	1.44	0.32	1.65
3	1.50	95.04	0.52	0.16	0.66	0.00	0.66	1.47
4	1.36	95.94	0.79	0.00	0.00	0.07	1.09	0.75
5	1.35	95.65	0.24	1.13	0.10	0.37	0.55	0.61
6	1.32	96.24	0.12	0.02	0.00	0.91	0.80	0.59
Mean value:	1.29	95.69	0.36	0.43	0.13	0.46	0.70	0.94
Sigma:	0.17	0.71	0.25	0.45	0.26	0.59	0.26	0.49
Sigma mean:	0.07	0.29	0.10	0.18	0.11	0.24	0.11	0.20

Figure 4.1. EDX analysis of 5005AL samples

From Table 4.2. it follows that: The microstructure of the host material consists of Al 5005 grains containing iron-rich particles that appear as white photomicrographs (SEM) showing heat treated areas. The results of the SEM-EDX analysis showed that these particles contain iron and silicon in the study area. It was difficult to determine the stoichiometry of the analysis phase of EDX However, the iron and silicon concentrations indicate that it is probably the Al15Fe3;The subduction zone showed a fine-grained microstructure with discontinuous deposits rich in iron and magnesium-silicon along the intermediate zones, possibly a-Al and Al15Fe3Si, and fine iron-rich particles in the grains (Figure 4.1), in Table 4.2, at a temperature of 400, it is noted that there are dislocations on the surface of the alloy caused by exposure of the material to a greater temperature than the rest of the samples (applied error during the experiment) during the process of using a etchant liquid that needs heat [102].

4.3 MECHINCAL PROPERTIES

4.3.1. Tensile Strength

The “strain elongation” of al5005 alloy is examined in Figure 4.2. The stress-to-tensile graphs consist of elastic and plastic regions. All together, the plastic deformation line has some ups and downs. It can be attributed to the structure of the plastic series. From Figure 4.2, it will be observed that the alloy samples exhibit tensile strength values of 53-138 MPa, giving a difference of about 2 – 70 MPa between the base alloy TR1 (UTS 136.82 MPa) and the remaining alloys, namely TR2 (138.15MPa), TR3 (134.41 MPa), TR4 (126.02 MPa), and TR5 (53.17 MPa). The yield strength follows the same trend, exhibiting somewhat lower values compared to UTS. The increase in the tensile strength was due to the low-temperature aging resulting in the formation of nano Si precipitates in the central part of the cellular structures. The reason is that by the formation of nano Si precipitates, dislocations tend to accumulate in the center of the cellular structure, and dislocations are hindered to accumulate in the boundary of the cellular structures which was shown in Park et al. Research [103]. The TR5 heat treatment doesn't have a destructive effect nor a significant positive effect on cellular structure enhancement. The TR5 sample experienced the lowest tensile strenth due to its dissolved structure.

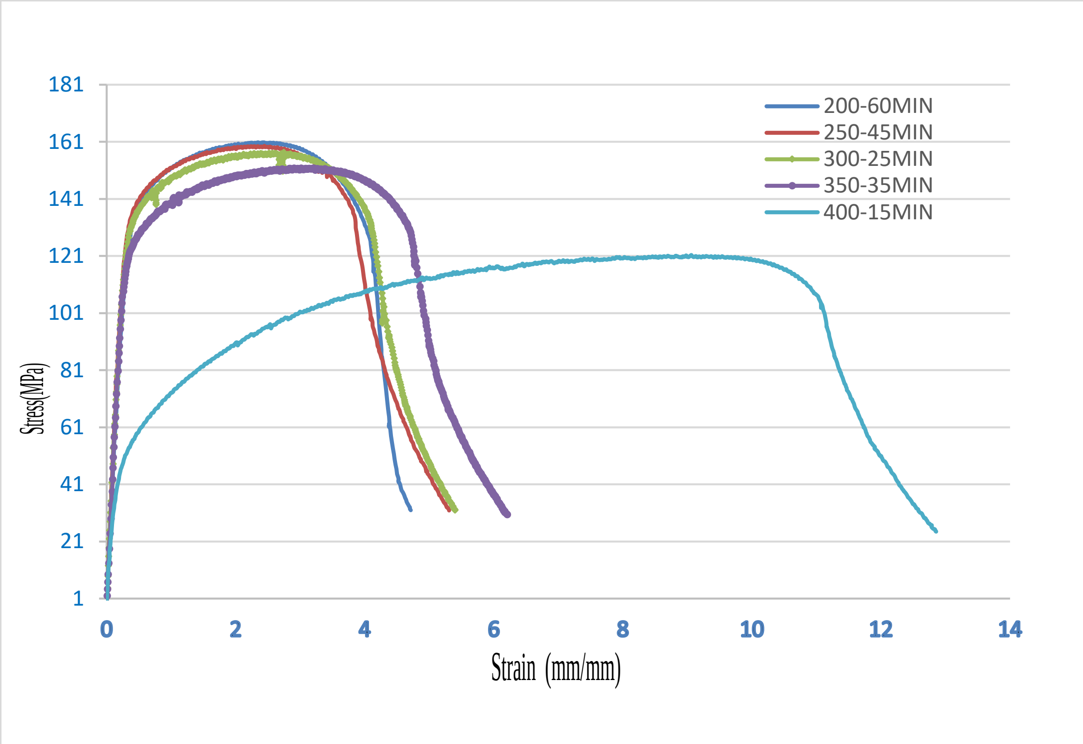


Figure 4.2 The tensile strength of 5005al samples diagram.

Yield strength, tensile strength, obtained by utilizing stress-strain graphs strength, elongation and elastic modulus values are given in Table 4.3.

Table 4.3 Tensile test results for 5005al samples.

TR	SAMPLE	Peak Load (kN)	Peak Stress (MPa)	Strain at Break (mm/mm)	Stress at Offset Yield (MPa)
TR1	200-60	3.017	160.8	2.442	136.729
TR2	250-45	2.842	159.5	2.447	138.156
TR3	300-35	2.892	157.3	2.744	134.418
TR4	350-25	2.834	151.8	3.197	126.028
TR5	400-15	2.231	121.3	9.061	53.173

An increase in the heat treatment temperature from 200° to 400° indicates a decrease in tensile strength.The highest average tensile value (160.8 MPa) is in the alloy with 200 deg/60 min and the lowest tensile value (121.3MPa) is 5005 al 400 deg/15 min.has been in the material [104].

4.3.2 Hardness

A hardness test was carried out for aluminum 5005 samples, and six readings were taken for different areas for each sample. Table 4.4 shows the results of the hardness test . From hardness measurement, it is seen that the hardness increased slowly up to 1 hour and the peak hardness is reached eventually at different ageing temperatures. The final hardness of the alloy decreases with increasing ageing temperature and this is referred to over-aged condition. Table 2 shows time to reach peak hardness and peak hardness value for Al-5005 alloys that artificially aged at different ageing temperatures. In increasing in hardness values during ageing treatment has been related to the formation of hardening precipitates in the alloy. These precipitates interference the dislocation motion, thus the hardness of alloy is increased [105]. It can be seen that the peak hardness are reached most rapidly (1 hour) at the higher ageing temperature but the hardness values decrease as the ageing temperature is increased. This can be explained that the higher the ageing temperature (up to 400 ^{o}C), the faster the rate of formation resulted the larger the precipitates formed at shorter ageing time [106]. This situation leads to give lower peak hardness value (27.98 HB) for the higher ageing temperature.

Table 4.4 Hardness test results for 5005al samples

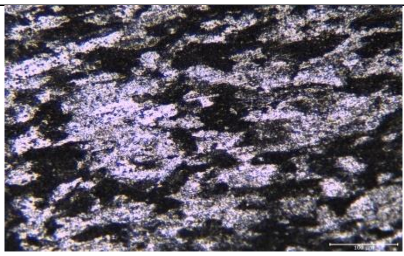
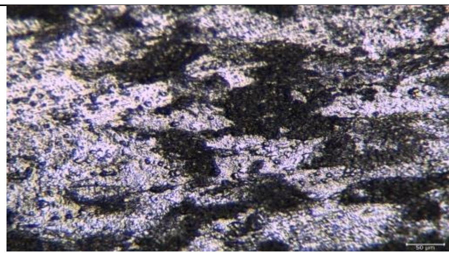
Temp.	1	2	3	4	5	average
0 ˚C	27.77	28.44	29.59	30.32	30.56	29.336
200 ˚C	35.17	31.83	26.71	26.71	27.77	29.638
250 ˚C	29.83	27.34	27. 13	26.09	26.29	27.336
300 ˚C	26.09	26.92	26.71	21.91	23.09	24.944
350 ˚C	26.92	25.89	26.71	20.34	22.75	24.522
400 ˚C	26.71	26.50	29.83	28.21	28.66	27.982

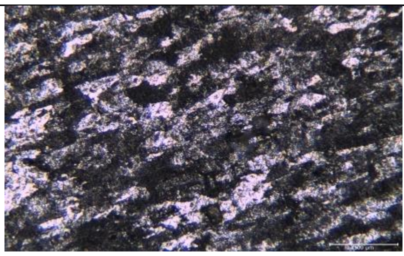
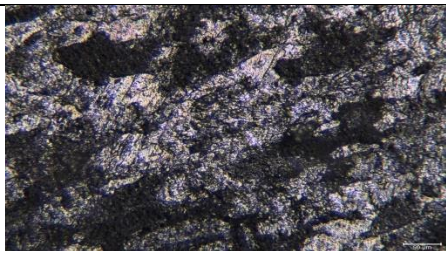
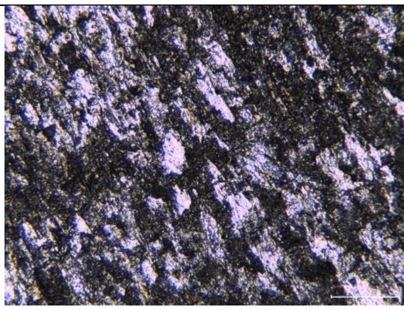
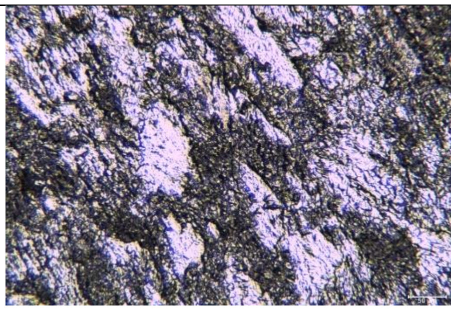
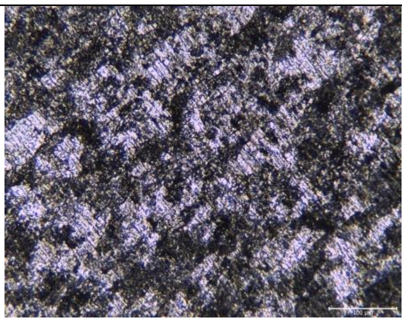
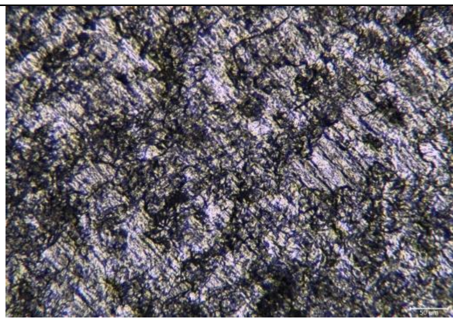
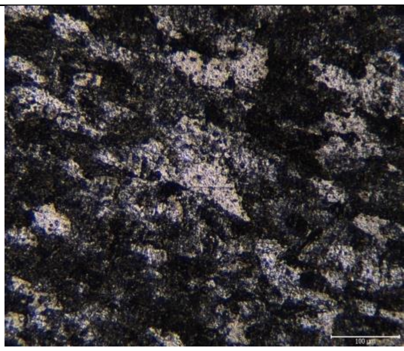
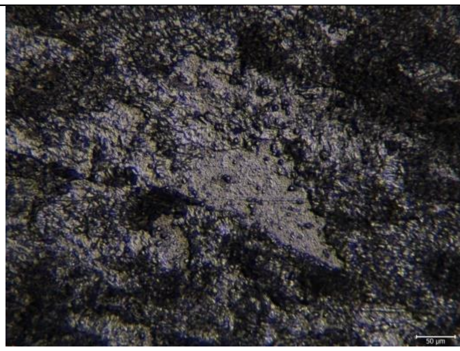
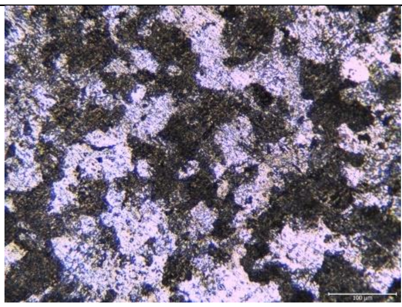
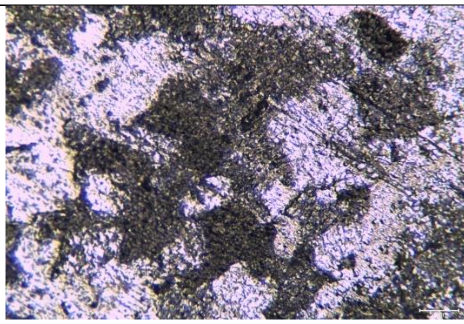
From Table 4.4 it concluded that the hardness increases slightly when curing at 200˚/ 60 minutes, then it begins to decrease from the heat treatment temperature of 250 ˚ to 350 ˚ degrees, then it rises again at 400 degrees, and this is caused by the effect of heat treatment on the alloy, as it was slowly cooled by air [107].

4.3.3 Fatigue Result

When the fatigue experiment was done for all samples applied to heat treatment and the original sample, an increase in fatigue resistance was discovered. The samples that were subjected to heat treatment lasted much longer than the original sample. Therefore, the microstructure of the samples that were not broken was studied to discuss the reasons for their resistance to fatigue(Table 4.5).

Table 4.5 Microstructure images of 5005AL samples captured by optical microscopy aftar fatigue test.

	100 µm	50 µm
original		

200˚/60 min		
250˚/45 min		
300˚/30 min		
350˚/25 min		
400˚/15 min		

It is noted from Table 5.2 that alloy 5005AL was affected by heat treatment and its grains became homogeneous and its elements were better distributed, which gave it durability to resist fatigue test more [108].

4.3.4 Wear Result

The friction coefficient, a dimensionless value representing the resistance to motion between two contacting surfaces, can be influenced by the intricate interplay of microstructural changes caused by heat treatment. A judicious selection of heat treatment parameters, such as temperature, duration, and cooling rate, can lead to the formation of specific microstructures, such as precipitates, recrystallized grains, or grain boundaries with different orientations. These microstructural variations can affect the adhesive and abrasive interactions occurring at the sliding interface, subsequently impacting the frictional behavior of the material. For instance, a heat treatment process that promotes grain refinement and precipitate formation may lead to reduced friction due to enhanced deformation mechanisms and reduced surface contact area. Conversely, certain heat treatments could result in the formation of hard phases or surface oxides that increase friction by introducing abrasive components to the interface. The interplay of these mechanisms underscores the complexity of the relationship between heat treatment and friction behavior in the Al-5005 alloy.

Figure 3.5 below shows the corrosion graph. As the load on the samples was 10 Newtons and the time was 30 minutes.

It can be observed that COF showed decreasing trend with increase in heat treatment temperature up to 200 °C followed by an increase to 400 °C. The decrease in COF for TR2-TR3 to heat treatment temperature of (250 and 300 °C)was 30 %. At 400 °C, the observed values of COF were even greater as compared to 200 ^{o}C at 10 N. COF decreased with increase in heat treatment temperature up to 300 °C followed by an increase to 400 °C. The decrease in COF for to heat treatment temperature of 300 °C was around 20%, whereas at a temperature of 400 °C COF values were 40% greater as compared to that at 300 °C.

It is noted from Figure 3.5 that the wear coefficient for 5005 samples (heat treatment from 200˚ to 350˚) ranges from 50 to 200, , a significant increase is observed for the friction coefficient to reach 400 [109].

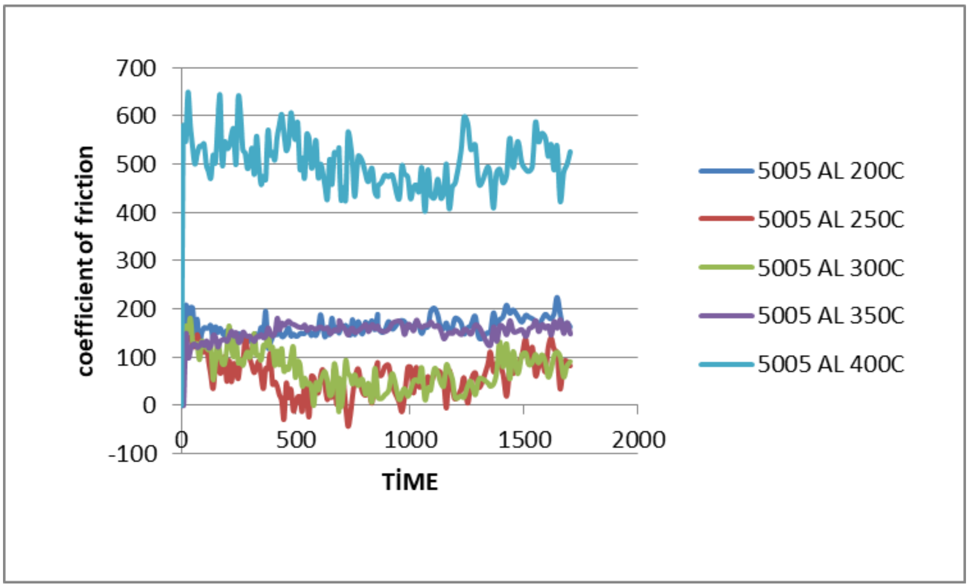


Figure 4.3. Graph of wear as the change in coefficient of friction over time.

PART 5

CONCLUSIONS AND RECOMMENDATION

5.1 CONCLUSIONS

In this study, heat treatments were applied to alloy 5005AL. The microstructure was studied by optical microscope and electron spectroscopy. Mechanical tests were applied such as tensile test, fatigue test and hardness test. wear test was performed.The results obtained as a result of the investigations are as follows:

i. The microstructure of the host material consisting of Al 5005 particles containing iron-rich particles is shown as white matter microscopy (SEM) images showing the heat-treated regions. The results of SEM-EDX analysis show that these particles contain iron and silicon in the study area.

ii. Heat treatment temperature increased from 200° to 400° decrease in tensile strength. The highest mean tensile value (160.8 MPa) was found in the alloy with 200 degrees/60 min and the lowest tensile value (121.3 MPa) was 5005 to 400 deg/15 min.

iii. The hardness increased slightly at the treatment degree of 200˚ /60 minutes, and decreased significantly for the rest of the degrees of heat treatment, to rise again at 400 degrees, but it is less than the hardness of the original sample. The highest hardness value was 29.638 at a treatment point of 200˚

iv. wear test, the friction coefficient was the highest value at 400 degrees, when its value was 600, and the rest of the heat treatment degrees recorded much lower values.

5.2 RECOMMENDATIONS

i. It is suggested that heat treatments be done with higher temperatures and a longer time,(for example, at 400 degrees, the heat treatment time is 15 hours) to obtain better mechanical properties.

ii. When using the fatigue test, it is recommended to use the fatigue test at a high temperature and not to use the room temperature to speed up the test and obtain more satisfactory results (taking into account the conditions in which the alloy is used).

iii. To obtain greater hardness, cooling must be done instantaneously.

iv. It is necessary to use a etchant solution before sem analysis. Care must be taken when using the temperature so that it does not exceed 37 degrees and a time not exceeding 35 seconds for each sample (taking into account the used etchant solution and its method of use).

v. For the wear test, it is suggested to use several readings (at different times), taking into account the distance traveled for each experiment.

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RESUME

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