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PhD Thesis
Abstract

Contribuții privind impactul finisării granulației aliajelor de aluminiu sudabile asupra structurii și proprietăților mecanice ale acestora

Contributions regarding the impact of grain refining of aluminum alloys used for welding on their structure and mechanical properties

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List of notations and abbreviations

Notation	Detail
Al	Aluminum
B	Boron
Ti	Titanium
Mo	Molybdenum
V	Vanadium
Cr	Chromium
Cu	Copper
Mg	Magnesium
EMs	Enhancer materials
Wt%	Weight Percent
HAZ	Heat Affected Zone
Abbreviation	**Detail**
SEM	Scanning Electron Microscopes
XRD	X-ray diffraction
EDS	Energy-dispersive X-ray spectroscopy
EOC	Open Circuit Potential
EMS	Enhancer materials
GTAW	Gas tungsten arc welding
TIG	Tungsten Insert Gas
HAZ	Heat Affected Zone
RSW	Resistance spot welding
Ecorr	Corrosion potential
Icorr	Corrosion current
RP	Polarization resistance
SCE	Saturated calomel electrode
UTS	Ultimate tensile strength
FCC	Face centered cubic
Bc	The slop of the cathodic curve
Ba	Slope of the anodic curve
CR	Corrosion rate
Ew	Equivalent length

Abstract

Aluminum alloys are indispensable in numerous industries, especially in welding applications, where their mechanical properties are critical. This thesis focuses on the profound impact of grain refinement on the mechanical characteristics of aluminum alloys employed in welding. With the growing demand for lightweight yet robust materials, aluminum alloys, particularly Al-, have become increasingly vital in sectors such as automotive, aerospace, and construction.

Grain refinement presents an enticing avenue for enhancing the performance of these alloys, especially in welded structures. The study commences with an extensive review of common grain refinement techniques utilized in aluminum alloys, emphasizing the efficacy of various additives and processes. It then delves into the underlying mechanisms driving grain refinement, elucidating their effects on the alloy's microstructure.

Moreover, this thesis scrutinizes the direct consequences of grain refinement on the post-welding attributes of Al and its alloys. Leveraging advanced microscopy and characterization methods, the research scrutinizes grain size distribution, grain boundary morphology, and defect formation in both as-welded and post-heat-treated conditions, offering valuable insights into microstructural evolution during welding.

In addition to structural alterations, the study explores the mechanical implications of grain refinement in aluminum alloys. Through tensile, fatigue, and impact tests, it evaluates the alloy's performance by comparing grain-refined specimens with conventional ones. The results unveil the profound influence of grain size on strength, ductility, and fracture behavior, enriching our comprehension of the alloy's mechanical response.

The findings of this thesis hold extensive ramifications for industries reliant on aluminum alloys for welding purposes. The insights gleaned from this research can inform the optimization of grain refinement processes, paving the way for the development of lightweight, high-strength materials with enhanced weldability. These advancements have the potential to revolutionize various sectors by bolstering the structural integrity and mechanical properties of aluminum alloy-welded components, thereby contributing to safer, more efficient, and sustainable engineering solutions.

Aluminum alloys have garnered widespread acclaim for their lightweight properties, impressive strength-to-weight ratio, and exceptional corrosion resistance. However, there remains room for improvement, particularly through the integration of enhancer materials. The introduction of these enhancer materials into aluminum alloys holds the promise of enhancing various aspects, ranging from mechanical properties like strength and hardness to augmenting attributes such as wear resistance and thermal stability. This thesis embarks on an exploration of the utilization of enhancer materials in aluminum alloys, investigating their profound impact on the overall properties of these alloys. Among the enhancer materials under scrutiny are Titanium (Ti), Boron (B), and Molybdenum (Mo).

In recent years, the landscape of aluminum alloy production has witnessed a significant transformation, driven by the evolution of new procedures and technologies. This transformative journey, coupled with the advent of advanced materials, has paved the way for innovative methodologies in aluminum alloy manufacturing. One particularly noteworthy approach involves the precise incorporation of multiple enhancer materials in specific weight percentages into the aluminum matrix prior to solidification during the casting process. This novel method has demonstrated remarkable efficacy in enhancing the properties of aluminum alloys [1]. The introduction of enhancer materials into aluminum alloys can yield substantial effects on their properties [2]. These effects manifest in both the microstructure and macrostructure of the alloys, leading to enhancements in strength, hardness, and wear resistance [3], along with improvements in their thermal stability. Enhancer materials play a crucial role in significantly elevating the strength and hardness of aluminum alloys [4]. Among the most commonly utilized enhancer materials in aluminum alloys, copper stands out. Copper readily forms a robust solid solution with aluminum, which serves to enhance the alloy's strength and hardness [5]. Moreover, this addition improves the alloy's resistance to corrosion, rendering it an ideal material for applications in marine environments.

Additional enhancer materials incorporated into aluminum alloys encompass magnesium and silicon, both of which play a vital role in elevating strength and hardness. Furthermore, the integration of enhancer materials in aluminum alloys can lead to a notable improvement in their wear resistance [6]. Wear resistance proves crucial in applications where materials are exposed to abrasive or erosive forces [6]. Chromium, a frequently employed enhancer material in aluminum alloys, serves to enhance the wear resistance of the alloy [7]. Enhancer materials can also improve the thermal stability of aluminum alloys [8]. This is important in applications where the alloy was subjected to high temperatures. One of the most commonly used enhancer materials for improving thermal stability is titanium [8, 9]. Titanium forms a strong intermetallic compound with aluminum that improves the thermal stability of the alloy [1]. is used in aluminum alloys to improve the thermal stability of the alloy. Titanium forms a strong intermetallic compound with aluminum that enhances the thermal stability of the alloy [9]. The titanium also contributes to increased strength and hardness.

The incorporation of enhancer materials into aluminum alloys brings about significant improvements in their properties, such as increased strength, hardness, wear resistance, and thermal stability. Each of these materials imparts its unique characteristics to enhance the overall qualities of the alloy. Understanding how enhancer materials impact aluminum alloys allows engineers and scientists to tailor alloy compositions to meet specific application requirements, whether it's enhancing strength, wear resistance, or thermal stability. Over the last century, aluminum, its alloys, and micro alloys have risen to prominence as essential construction materials in engineering, despite the complexities and costs of their extraction process. They are widely used across a range of industrial and engineering applications due to their attractive attributes, including a high strength-to-weight ratio, exceptional thermal and electrical conductivity, and resistance to corrosion [10]. However, a notable drawback is their tendency to solidify with large grain sizes in columnar structures. To address this limitation, they are alloyed with elements like Cu, Mn, Mg, or microalloyed with enhancer elements such as Ti, Ti-B, Mo, V, and more. In this thesis, the research delved into the impact of adding Ti, Ti-B, and Mo to a commercially aluminum melt before solidification. The study examined weight percentages corresponding to the peritectic limit on the phase diagrams of Al-Ti, Al-Ti-B, and Al-Mo and investigated their effects on microstructure, mechanical properties, ultimate tensile strength, ductility, and Vickers microhardness in the cast state. The research discovered that the addition of any of these elements resulted in the refinement of the aluminum structure by reducing grain size [11]. This transitioned the alloy from a predominantly columnar structure with large grains to a fine-grain equiaxed structure. The study also investigated the influence of these elements on the weldability of commercially aluminum using the Gas Tungsten Arc Welding Method (GTAW). The research involved welding together twenty different combinations of sheets with both similar and dissimilar specimens, and the results were presented and discussed. The grain refinement process was observed to enhance resistance to crack initiation and propagation in the weld metal. Moreover, it prevented the formation of centerline solidification cracks, which are often found when welding aluminum and its micro alloys without grain refiners, resulting in a columnar structure with large grain size. Various techniques, including scanning electron microscopy (SEM), XRD, EDS, and optical microscopy, were employed to investigate porosity, hairy cracks, and other defects visible in photomicrographs. The photomicrographs revealed small-sized porosities and hairy cracks in a few specimens [12]. All in all, it can be concluded that the grain refinement process for aluminum and its micro alloys not only improved their mechanical properties, ductility, and surface quality but also enabled the production of sound welds that would have been difficult to achieve without grain refinement. These findings are expected to hold significant value for engineers working in the aluminum foundry and welding industry [13].

This thesis investigates the effect of adding Titanium, Titanium plus Boron, and Molybdenum to commercially aluminum melt, at weight percentages corresponding to the peritectic limit on the phase diagrams of Al-Ti, Al-Ti-B, and Al-Mo, on the microstructure, mechanical characteristics, ultimate tensile strength, ductility, and Vickers microhardness in the cast condition. The addition of any of these elements alone caused the aluminum structure to be refined, resulting in a transition from a predominantly columnar large-grain structure to an equiaxed fine-grain one. The thesis also examines the impact of these elements on the weldability of commercially aluminum using the Gas Tungsten Arc Welding Method (GTAW), by welding twenty different combinations of sheets of similar and dissimilar specimens. The grain refinement process improved the resistance to crack initiation and propagation in the weld metal and prevented the formation of center-line solidification cracking that often exists in the welding of Al and its micro alloys without grain refiners. The research presented in this study demonstrates that the addition of enhancer materials such as Ti, Ti-B, and Mo to commercially aluminum can enhance the weldability and quality of aluminum and its alloys. Through grain refinement, which is achieved by adding these enhancer materials, the microstructure of the aluminum transitions from a columnar large grain structure to an equiaxed fine grain one, resulting in improved mechanical properties, ductility, and surface quality. Additionally, the use of enhancer materials has been found to increase the resistance to crack initiation and propagation in the weld metal, prevent centerline solidification cracking, and produce sound welds that were previously unattainable without grain refinement. These findings indicate that the use of enhancer materials in aluminum welding has significant potential for enhancing the performance and quality of welded structures, making it an important area of research for the aluminum foundry and welding industry. The research discussed in this study underscores the efficacy of incorporating enhancer materials in aluminum welding processes to enhance the microstructure and properties of aluminum and its alloys. Further exploration in this field holds the promise of propelling advancements in welding and materials science.

Aluminum alloys are categorized based on their composition, primarily determined by the key alloying element and other secondary elements. This composition significantly influences the alloy's properties, including its strength, corrosion resistance, and weldability [84]. The following are some common classifications of wrought aluminum alloys:

1xxx series: These are aluminum alloys with a minimum aluminum purity of 99%, without a major alloying element. They are frequently employed in applications that prioritizecorrosion resistance and high thermal conductivity, such as electrical components and heat exchangers.

2xxx series: These aluminum alloys primarily feature copper as the key alloying element. They exhibit remarkable strength but have low corrosion resistance, rendering them suitable for aerospace and military applications.

3xxx series: Aluminum alloys in this series are characterized by manganese as the mainalloying element. They possess good formability, moderate strength, and excellent corrosion resistance, making them suitable for building and construction, as well as automotive applications.

4xxx series: These aluminum alloys contain silicon as the primary alloying element. They are commonly used in welding applications due to their low melting point and excellent fluidity.

5xxx series: These aluminum alloys have magnesium as the primary alloying element. They offer excellent corrosion resistance, high strength, and good weldability, making them ideal for marine and automotive applications.

6xxx series: These aluminum alloys feature both magnesium and silicon as primary alloying elements. They possess good formability, excellent corrosion resistance, and moderatestrength, and are widely employed in the construction, automotive, and aerospace industries.

7xxx series: These aluminum alloys consist of zinc as the principal alloying element, with minor amounts of copper and magnesium. They provide high strength and good fatigue resistance and are often used in aerospace and military applications [85].

The classification of aluminum alloys is based on the predominant alloying element and the associated properties. This classification simplifies the selection of the appropriate alloy for specific applications.

The wrought aluminum alloy designation system employs a 4-digit code to identify and classify various types of aluminum alloys. The first digit signifies the principal alloying element added to the aluminum alloy. This digit specifies the aluminum alloy series, ranging from 1000 to 8000 series. If the second digit deviates from 0, it indicates a modification to the specific alloy. The third and fourth digits are arbitrary numbers used to identify a specific alloy within the series. For instance, alloy 5183 belongs to the magnesium alloy series (5xxx), with 1 indicating the first modification to the original alloy 5083, and 83 serving as its specific identifier in the 5xxx series. The 1xxx series of aluminum alloys (pure aluminum) is the sole exception to this numbering system. In this case, the last two digits of the alloy represent the minimum aluminum percentage above 99%. For example, Alloy 13(50) has a minimum aluminum percentage of 99.50%. The wrought aluminum alloy designation system is a standardized and systematic approach for identifying and categorizing different types of aluminum alloys based on their alloying elements and modifications. This system offers an efficient and straightforward method for selecting the appropriate aluminum alloy for specific applications [86-88].

The cast alloy designation system is another standardized method employed for the identification and categorization of various aluminum alloys based on their composition [89]. Supplementary from the wrought alloys classification there is another series 8xx.x. These are alloys of Al with tin, a low friction system used mainly in bearing and bushing applications. This system utilizes a 3-digit-plus-decimal-point designation, as exemplified by 356.0. The first digit (Xxx.x) in the designation denotes the primary alloying element introduced to the aluminum alloy. For instance, 1xxx series alloys consist of pure aluminum, 2xxx series alloys feature copper as the principal alloying element, 3xxx series alloys incorporate manganese, and so forth. The second and third digits (xxX.x) furnish more precise details about the alloy's composition. These digits specify the specific alloy within the series and any modifications that have been applied to the alloy. For instance, alloy 356.0 contains silicon as the primary alloying element, and the 0 indicates that it is the original composition of the alloy. The presence of a decimal point followed by digit(s) (xxx.X) provides supplementary information regarding the alloy's modification or casting process. The digit following the decimal point may indicate the method employed for casting the alloy or offer additional insights into the alloy's composition. The cast alloy designation system serves as a valuable tool for the recognition and selection of suitable aluminum alloys for casting applications. It establishes a standardized means of conveying information about the composition and attributes of diverse aluminum alloys, enabling manufacturers to make well-informed decisions about material selection tailored to their specific casting requirements [89-92].

In addition to the previously mentioned information, the second and third digits (xXX.x) in the cast alloy designation system consist of arbitrary numbers used for the specific identification of an alloy within the series. These digits do not signify any particular alloying element or alteration. The number that follows the decimal point signifies whether the alloy is intended for casting (.0) or as an ingot (.1 or .2). Additionally, a capital letter prefix is employed to indicate a modification made to a particular alloy. For example, the alloy A356.0 features a capital A (Axxx.x) prefix, denoting a modification of the original alloy 356.0. The number 3 (A3xx.x) signifies that it belongs to the silicon plus copper and/or magnesium series. The number 56 (Ax56.0) identifies the specific alloy within the 3xx.x series, while the .0 (Axxx.0) indicates its suitability for final shape casting rather than as an ingot. The cast alloy designation system establishes a standardized means to recognize and categorize various aluminum alloys used in casting applications. It serves as an indispensable tool for conveying information about alloy composition and attributes, empowering manufacturers to choose the most suitable alloy for their specific casting requirements [89-92].

Methods & procedures of investigation in the research of aluminum alloys

Aluminum alloy research utilizes a range of investigative techniques to examine their characteristics and performance. These approaches commonly encompass the analysis of the alloy's microstructure through methods like optical and electron microscopy, and crystallographic evaluation through X-ray diffraction. Mechanical assessments, including tensile and hardness tests, yield valuable insights into the alloy's strength and durability. Additionally, corrosion and surface analysis methods are employed to assess an alloy's resistance to environmental deterioration. Cumulatively, these investigative methodologies contribute to a comprehensive comprehension of aluminum alloys, facilitating their advancement and enhancement for diverse industrial applications.

To achieve all of these points of investigation a group of processes were done as preparing the master, binary, ternary and quarterly alloys by adding a specific amount of Mo, Ti alone or together and then preparing the specimens by the casting method with electrical furnace and graphite crucible.

By these prepared specimens the tests were done as a tensile test which gives the possibility to establish stress-strain curves, ductility, UTS and all other mechanical characteristics for the Al, Al-0.15%Ti, Al-3%Mo, Al-0.05%Ti-0.01%B and Al-0.05%Ti-0.01%B-0.1%Mo. By these results, the investigation can define the improvement in the mechanical properties of the Al and its alloys.

An optical microscopy was used to identify the grains of the aluminum and the deformation that happened in its size and shape after using the enhancers. EDS and XRD were used to identify the specimens' mapping and included elements.

SEM microscopy and Spectro analysis were used to tracking the welding lines in the HAZ area and to compare the improvement on the welding process for multi combinations specimens with reference Al vs Al specimen.

Corrosion test were tested also for the Aluminum and its alloys and were tested according to the same hard situations explained in detail in the other chapters, where the corrosion rate were detailed for every specimen from the prepared (Al, Al-0.15%Ti , Al-3%Mo , Al-0.05%Ti-0.01%B, and Al-0.05%Ti-0.01%B-0.1%Mo.

Grain size affection results and discussion

Grain size analysis procedure

The grain size analysis was investigated as per ASTM E112 using the software *Image J -Image processing and analysis in JAFA.*

ASTM E112 line intercept method describes as an actual count of the number of the grains intercepted by a test line or the number of grain boundary intersections with a test line, per unit length of the test line used to calculate the mean lineal intercept length, L. L is used to determine the ASTM grain size number, G. The precision of the method is a function of the number of intercepts or intersection counted. A precision of better than plus/minus 0.25 % grain size units can be attained with a reasonable effort. Results are free of bias; repeatability and reproducibility are less than plus/minus 0.5% grain size units. Because an accurate count can be made without need of making off intercepts or intersections, figure 4.5.

In this study, 7 lines were made for every image and the number of the grains were counted then the average value was taken and according to this procedure the following results were noticed:

Based on the observed results outlined, it can be concluded that the effect of adding enhancer materials, such as titanium (Ti), boron (B) and molybdenum (Mo) alone or together have an affection on the grain sizes and shapes. While the addition of titaniumtends to decrease the grain size where the average grain sizes for the Al is around 17,73 Micron,and the average grain sizes after adding 0.15% of Titanium resulted in decreases the average grain sizes to 16,21 Micron. Even though the percentage of decreasing is still low but adding this enhancer resulted in decreasing the grains size with a percentage of 6,99%. From another side we can noticed that adding Ti to aluminum also affect the shape of the grains and also thegrains boundaries where it can be noticed that the grains shape are more rounded shapes and the boundaries can be recognized with clear limits which gives indications that the mechanicalproperties such as the hardness, surface tension and other mechanical properties can beenhanced.

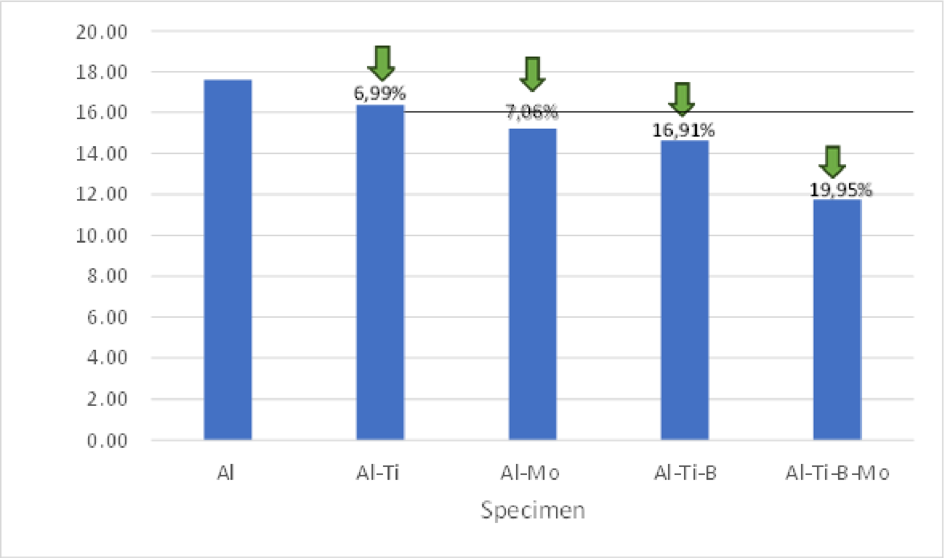


Figure 1. Al and it alloys average grain size analysis

Adding 3% Mo and based on the observed results, it can be concluded that the effect of adding Mo as enhancer material has an affection on the grain sizes and shapes more that the adding Ti. While the addition of Mo tends to decrease the grain size where the average grain sizes for the Al is around 16,73 Micron, and the average grain sizes after adding 3% of Mo resulted in decreases the average grain sizes to 14,67 Micron. The percentage of the enhancement is much better than adding Ti, which adding this enhancer Mo resulted in decreasing the grains size with a percentage of 7% which will reflect almost on the mechanical properties such as the hardness, ductility, UTS and yield stress. From another side we can notice that adding Mo to Aluminum also affect the shape of the grains and grains boundaries. It can be noticed that the corners appearing in the Al grain shapes are disappeared the tree shape grain size also disappear totally and the grain size became more roundly and more recognized than in the case of Al ,and the boundaries became close to be more ovoid shapes with smaller boundaries lengths also in some areas the boundaries can't be recognized with clear limits which gives indications that the enhancement in the mechanical properties can be noticed clearly upon the investigations. The addition of 0.05%titanium, and 0.1% boron together has a much better affection onthe grain-refining effect than Al alone or even than adding Ti or Mo alone, resulting in smallergrain sizes. Referring to figure 1, it can be noticed that adding Ti and B decrease the grain size that the average grain size became 14.92 Micron, which means the percentage of enhancement is 16.91 %. From another side, it was noticed that adding 3 enhancer elements 0.05%Ti,0.01%B, and 0.1%Mo reflects the better improvement on the grain size and also on the shapes of the grains. Adding Ti, B, and Mo decrease the average grain size with a percentage of 19,95 % thatthe new grain size after the additional became 11,27 Micron.

According to some studies, researches pointed that some materials used as an enhancer may not act as an effective grain refiner in aluminum casting. Instead, it can contribute to the growth of larger grains within the microstructure. On the other hand, the grain-refining effect of molybdenum, titanium and boron indicate its potential as a beneficial addition to aluminum casting. Molybdenum or titanium helps in promoting the formation of smaller and more uniform grains during solidification, resulting in a finer microstructure. When multiple enhancer materials are added together, including titanium, boron, and molybdenum, there may be a synergistic effect on grain refinement. However, it is important to note that the specific combination of enhancer materials, their concentrations, and the casting process conditions can influence the grain size outcome. Additionally, the poison effect, which refers to the potential variation in grain size, should be considered and accounted for in the analysis and interpretation of the results. It is possible that some enhancer materials, either alone or in combination, may lead to an increase in grain size rather than a refinement.

Corrosion test analysis for aluminum and its alloys

Table 1. The main electrochemical parameters of the corrosion process

Nr.crt.	Proba	E_{oc} (mV)	E_{corr} (mV)	i_{corr} (µA/cm^2)	β_c (mV)	β_a (mV)	R_p (kΩxcm^2)	CR (µm/year)
1	Al	-675.59	-650.05	4.951	1098	29.41	2.51	53.8
2	Al-Mo	-687.40	690.43	0.937	188.92	27.95	11.3	10.6
3	Al-Ti	-662.10	645.15	2.075	368.31	38.65	7.32	22.5
4	Al-Ti-B	-716.00	722.39	2.142	245.21	45.12	7.73	23.3
5	Al-Ti-B-Mo	-659.87	645.23	1.792	387.92	23.12	5.29	19.5

It can be observed that the open circuit potential (Eoc) values provide insights into the electrochemical behavior of the samples. More electropositive (positive) Eoc values indicate a "noble" character from an electrochemical perspective. In this case, the Al-Ti-B-Mo sample exhibits the most electropositive Eoc value (-659.87 mV), followed closely by the Al-Ti sample (-662.10 mV). When considering the corrosion potential (Ecorr) values, more electropositive Ecorr values are generally associated with better corrosion behavior. The Al-Ti sample shows the most electropositive Ecorr value (645.15 mV), with the Al-Ti sample exhibiting a similar value (-645.23 mV). A low corrosion current density (icor) is indicative of better corrosion resistance. The Al-Mo sample demonstrates the lowest icor value (0.937 µA/cm^2), suggesting superior corrosion resistance compared to the other investigated samples. Additionally, all the alloys show lower icor values compared to Al, indicating better corrosion behavior in the saline solution. Polarization resistance (Rp) is a parameter that reflects the corrosion behavior of a material. Higher Rp values indicate better corrosion resistance, while lower values suggest poorer corrosion behavior. Among the samples, the Al-Mo sample exhibits the highest Rp value (11.3 kΩ·cm²), signifying good corrosion behavior. Considering the corrosion rate, a lower value signifies better corrosion behavior. The Al-Mo sample demonstrates the lowest corrosion rate, recording a value of 10.6 µm/year, indicating superior corrosion resistance compared to the other samples. Based on the electrochemical measurements, it can be inferred that the Al-Mo sample exhibits superior characteristics, such as the lowest corrosion current density (indicating better corrosion resistance), the highest polarization resistance (suggesting good corrosion behavior), and the lowest corrosion rate (highlighting superior corrosion resistance). Therefore, the Al-Mo sample demonstrates better corrosion behavior in the saline solution compared to the other investigated samples.

The mechanical characteristics of the cast samples

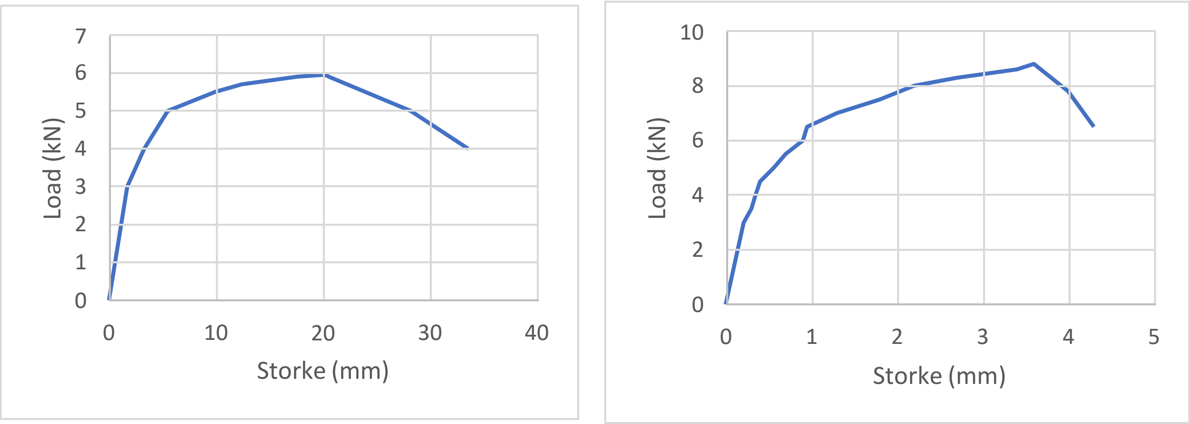
Load-stroke curves represent the connection between the applied load on a material and the resultant deformation or stroke. These curves serve to characterize the mechanical properties of materials, primarily in the realm of materials testing.

Typically, the load-stroke curve comprises a series of data points or pairs, illustrating the load imposed on the material relative to the subsequent displacement, deformation, or strain. This curve is instrumental in determining key mechanical properties of the material, such as yield strength, ultimate tensile strength, and elongation at the point of failure. The shape of the load-stroke curve may exhibit variability due to multiple factors, including the material under examination, the test type, and testing conditions. Generally, the load-stroke curve displays an initial linear segment known as the elastic region, where the material elastically deforms in response to the applied load.

As the load incrementally rises, the material eventually reaches its yield strength, after which it commences plastic deformation. This stage is termed the plastic region and is distinguished by a nonlinear increase in deformation as the load intensifies. As the load is further increased, the material eventually reaches its ultimate tensile strength, at which point it fails catastrophically. The point at which the material fails is known as the fracture point or the point of rupture. Load-stroke curves can be used to compare the mechanical properties of different materials or to evaluate the effects of different processing conditions on a given material. They are commonly used in materials testing, quality control, and product development, and are an important tool for understanding the behavior of materials under different loading conditions. The mechanical behavior of the base metal and prepared binary master alloys was determined through Uniaxial tensile standard tests conducted on a universal testing machine, by ASTM Standards. The tests were carried out at a crosshead speed of 10 mm/ min and autographic records were obtained.

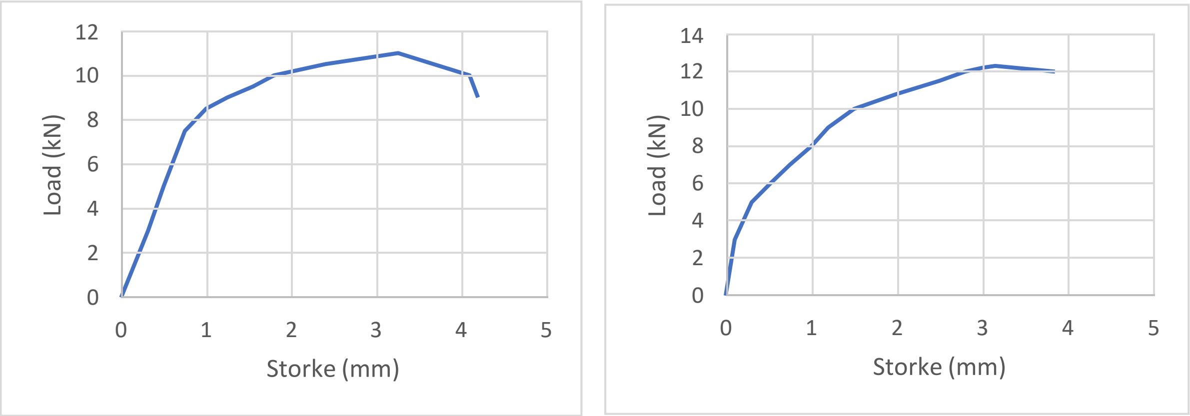
Figure 2 explain the curves that describe the load to fracture and elongation to fractureof different aluminum alloys. It can be noticed from the resulting data:

Load vs stroke curves



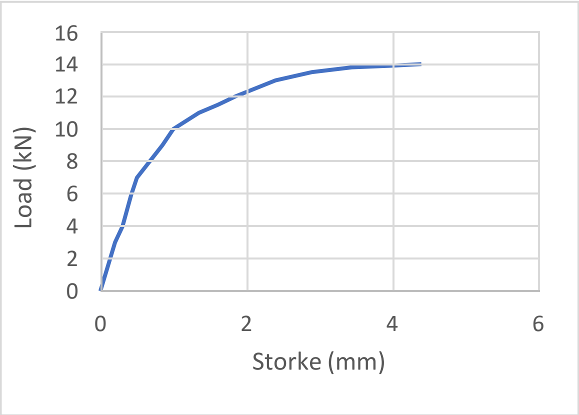
a) Al specimen Tensile Test

b) Al -Ti Specimen Tensile Test



c) Al -Mo Specimen Tensile Test

d) Al -Ti-B Specimen Tensile Test



e) Al -Ti-B-Mo Specimen Tensile Test

Figure 2. (Load, kN – Stroke, mm) for the Al and its alloys

1. **Load to fracture:**
   - aluminum requires a load of 6 kN to fracture.
   - The addition of 3% Mo to aluminum increases the load to fracture by 185%, meaning that the alloy can carry almost three times the load of aluminum before fracturing.
   - The addition of 0.05% Ti and 0.01% B to aluminum increases the load to fracture by 208%, meaning that the alloy can carry more than three times the load of aluminum before fracturing.
   - The addition of 0.05% Ti, 0.01% B, and 0.1% Mo to aluminum increases the load to fracture by 235%, meaning that the alloy can carry almost four times the load of aluminum before fracturing.

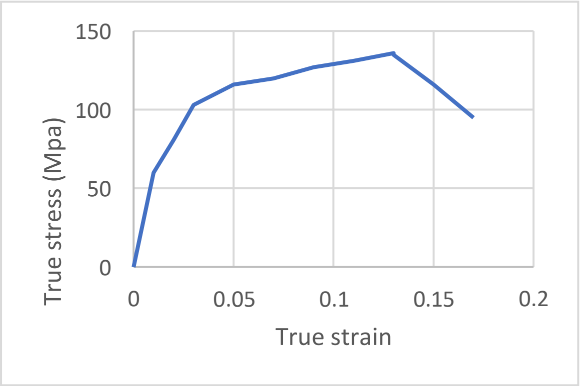
2. **Elongation to fracture:**
   - The addition of 3% Mo to aluminum increases the elongation to fracture by 145%, meaning that the alloy can elongate more before fracturing.
   - The addition of 0.05% Ti and 0.01% B to aluminum increases the elongation to fracture by 112%, meaning that the alloy can elongate more before fracturing.
   - The addition of 0.05% Ti, 0.01% B, and 0.1% Mo to aluminum increases the elongation to fracture by 120%, meaning that the alloy can elongate more before fracturing.

In general, it can be described as the addition of Mo, Ti, and B to aluminum can significantly improve its load-carrying capacity and elongation to fracture. These improvements can have important implications for the use of aluminum alloys in different applications. For example, alloys with improved mechanical properties may be better suited for high-stress or high-load applications.

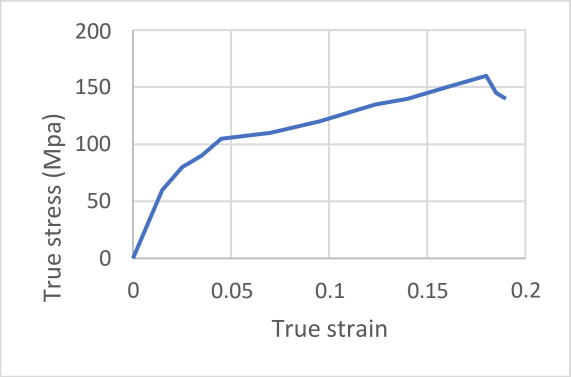
Ductility affection

Ductility, an essential mechanical property, particularly in the context of aluminum alloys, is intricately linked with the material's microstructure. The metallographic analysis offers valuable insights into the ductility mechanism of cast aluminum alloys. The addition of small quantities of Ti or Ti-B into the melt before casting can enhance the ductility of aluminum castings. When Ti is added in isolation, its presence in the melt must exceed the peritectic composition, approximately 0.15% by weight, to yield a satisfactory ductility effect. However, in the presence of boron, even in trace amounts (ppm), a substantial enhancement is observed at Ti concentrations as low as 0.005%. Optimal mechanical properties are reportedly achieved using Al-Ti-B master alloys with a Ti-to-B ratio of around 5. The commonly used ternary Al-Ti-B master alloy contains 5% Ti and 1% B by weight and comprises two crystalline intermetallic compounds: small crystallites of titanium diborideand larger crystals of $TiAl_3$. Mass for mass, the ternary Al-5%Ti-1%B master alloy is typically

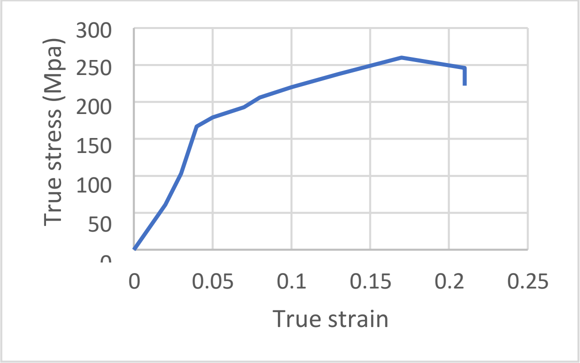
five to six times more efficient than a binary Al-Ti master alloy. Multiple mechanisms appear to contribute to ductility, contingent on the master alloy, cast alloy, and process conditions. Several hypotheses have been proposed to elucidate the mechanism, such as nucleation of Al facilitated by aluminide particles, boride particles, or TiB_2 particles enveloped by $TiAl_3$ "duplex particles."



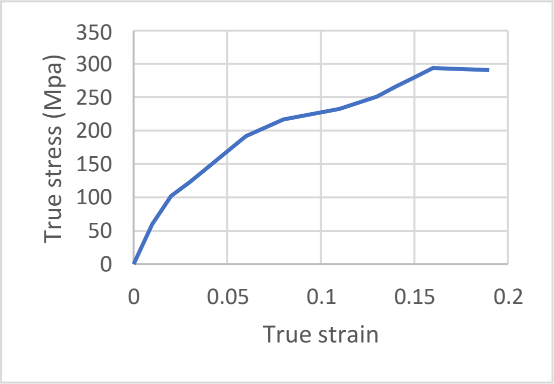
a) True Stress Vs true strain diagram for Al in tension



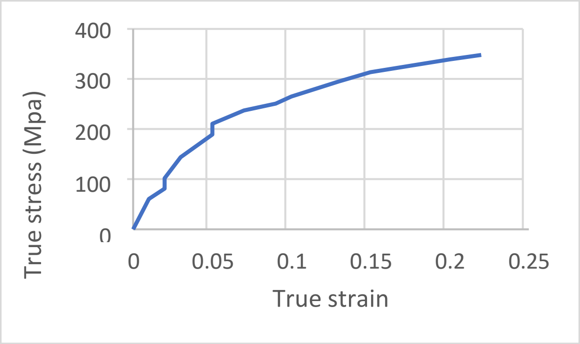
b) True Stress Vs true strain diagram for Al-Ti in tension



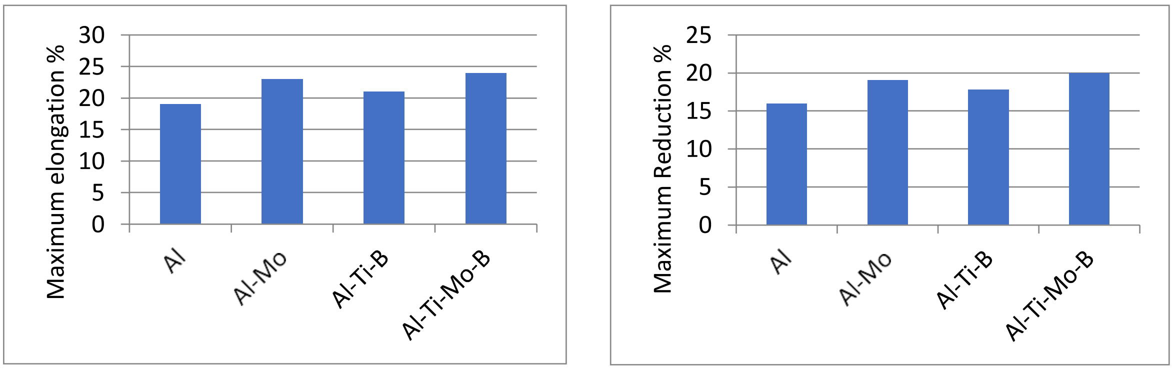
c) True Stress Vs true strain diagram for Al-Mo in tension



a) True Stress Vs True Strain diagram for Al-Ti-B in tension



Recent discussions have also underscored the notion of local Ti-enrichment associated with TiB_2 particles, corroborating high-efficiency nucleation sites for Al grain. In this investigation, we systematically compare the ductility properties of cast aluminum components when Mo is added to Al-Ti-B alloy before and after introducing enhancer materials (Ti, B, and Mo) into aluminum casting. Ductility tests are conducted on (Al, Al-Ti-B & Al-Ti-B-Mo) alloy castings, encompassing tensile biaxial loading assessments. The true stress-strain curve and fracture locus are scrutinized to assess the plasticity and ductility of the castings. Furthermore, a fractographic analysis of the specimens is undertaken to comprehend the microscopic failure mechanisms under diverse stress conditions.



a. Maximum elongation % *b. Maximum reduction %*

Figure 4. The impact of incorporating Mo into Aluminum, Ti, and Ti-B on their mechanical characteristics

UTS affection

The inclusion of enhancer materials like Ti, B, and Mo in aluminum can exert a notable impact on its mechanical characteristics, specifically its ultimate tensile strength (UTS). This notable influence is evident in Figure 5.

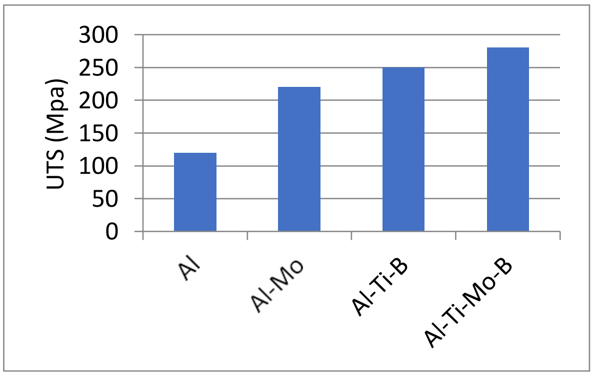


Figure 5. The ultimate tensile strength, UTS, of Al and its alloys

Microhardness analysis

Table 2. Microhardness test for the Al alloys and its alloys.

Specimen	**Hv 1**	**Hv 2**	**Hv 3**	**Hv 4**	**Hv 5**	**Averege Hv**
Al	46,50	50,10	47,90	48,30	48,80	48,32
Al-Ti	77,5	76,6	68,4	75,1	73,6	74,24
Al-Mo	89,2	86,5	87	90,6	88,7	88,40
Al-Ti-B	114,40	94,10	107,40	113,80	115,10	108,96
Al-Ti-B-Mo	124,07	124.2	120,30	121,50	120,30	121,54

It can be noticed from table 2. that added enhancer materials to aluminum can affect the hardness in high percentage, where adding 5% Ti can decrease the hardness to more than 230%, and adding 3 % Mo alone decreases the hardness to 135% and almost the same for addingTi+ B to the Aluminum, however adding 4 enhancer materials was reported enhancing in the hardness by increasing the value around 5%.

Aluminum alloy welding results and discussions

The welding of aluminum alloys is a challenging process due to the tendency for these materials to crack and develop other defects during solidification. However, the addition of certain alloying elements such as Titanium (Ti), Boron (B), and Molybdenum (Mo) can enhance the welding properties of aluminum alloys.

Ti can form stable intermetallic compounds with Aluminum, which can enhance the strength, ductility, and toughness of the weld. Ti can also act as a grain refiner, resulting in a more uniform microstructure and improved mechanical properties. Boron can improve the hardness and wear resistance of aluminum alloys, but can also have a negative effect on the grain size and casting process. Thus, the amount of Boron added to the alloy should be carefully considered to avoid adverse effects on the properties of the material. Molybdenum can improve the strength and toughness of aluminum alloys, resulting in a more ductile and crack-resistant weld. Mo can also reduce the formation of defects such as porosity and improve the microstructure of the weld. When added together, Ti, B, and Mo can have a synergistic effect on the welding properties of aluminum alloys. The precise combination of these elements can lead to a refined microstructure, improved mechanical properties, and reduced formation of defects. However, it is important to note that the addition of these alloying elements should be carefully controlled to avoid negative effects on the casting process or other properties of the material. Further research is needed to fully understand the impact of these alloying elements on the welding properties of aluminum alloys.

Overall, the addition of Ti, B, and Mo to aluminum alloys can enhance the welding process by improving the quality of the weld, reducing the formation of defects, and enhancing the mechanical properties of the material.

Final conclusions, elements of originality and futureperspectives

In this study, the effect of adding enhancer materials, namely titanium (Ti), boron (B), and molybdenum (Mo), on the properties of aluminum alloys has been thoroughly investigated. The focus was primarily on the ductility, load-carrying capacity, mechanical properties, and welding characteristics of the alloys. The results obtained from standard tensile tests conducted by ASTM Standards provided valuable insights into the impact of these enhancer materials on aluminum alloys.

The investigation revealed that the addition of Ti, B and Mo alone or together to aluminum led to significant improvements in the mechanical properties for the Aluminum. It is demonstrated that the maximum elongation percentage and maximum reduction in area percentage increased with the inclusion of Ti, B and Mo. The enhancement of the yield stress and the ultimate tensile stress also improved by a significant value, signifying the beneficial effect of Ti, B and Mo on enhancing the overall ductility of the alloy are appeared, but this improvement in the ductility values can’t be connected directly with the affection of the enhancers and more research can be focus about this result. which is how the ductility improved in the time that the grains become fines.

Moreover, the subsequent addition of Mo to the aluminum alloy refined by Ti-B exhibited even more promising results. The maximum elongation percentage increased by 26.53%, while the maximum reduction in cross-sectional area increased by 25%. This demonstrated the synergistic effect of combining multiple enhancer materials to further improve the ductility of the aluminum alloy.

Additionally, the investigation delved into the influence of these enhancer materials on the ultimate tensile strength (UTS) and hardness of the aluminum alloys. It was found that the addition of Ti had a positive effect on the UTS. However, the amount of Ti added needed to surpass the peritectic composition of approximately 0.15% by weight to achieve a satisfactory ductility effect. The inclusion of B in small amounts, particularly in combination with Ti, also resulted in a substantial increase in the UTS, enhancing it by approximately 210%.

Furthermore, the addition of Mo to the aluminum alloy was observed to increase its UTS by up to 185%. The exact effect of Mo on the UTS appeared to be influenced by various factors, including the concentrations of other alloying elements and the specific processing conditions employed.

Interestingly, the combined addition of Ti, B, and Mo in specific quantities exhibited a remarkable effect on the UTS, raising the value by approximately 240%. This demonstrated the potential for optimizing the mechanical properties of aluminum alloys by carefully controlling the composition of enhancer materials.

In terms of hardness, the investigation revealed that the addition of Ti, Mo, and Ti-B individually led to an increase in hardness. Adding Mo or Ti alone resulted in small improvement in the hardness, However, when all three enhancers' materials were added together, a notable increase (almost double) in hardness values was observed.

The findings of this study not only shed light on the mechanical properties of aluminum alloys but also explored the impact of enhancer materials on their welding characteristics. It was observed that the addition of Ti, B, and Mo had the potential to improve the welding properties of aluminum alloys, which are often susceptible to defects and cracking during the solidification process.

In terms of grain sizes, the investigation revealed that the addition of Ti, Mo, and Ti-B individually or together decrease the grainsizes and improve the grain limits and the grain shapes which led to an increase in hardness as we mentioned above and also to improve almost all the mechanical properties. Adding the three elements resulted in smaller grains than adding two elements or one element alone resulted.

The results obtained from this investigation demonstrated the significant influence of adding enhancer materials, such as Ti, B, and Mo, on the properties of aluminum alloys. The addition of these enhancer materials had a positive effect on the ductility, load-carrying capacity, UTS, hardness, and welding characteristics of the alloys. The combined addition of Ti, B, and Mo exhibited a synergistic effect, further enhancing the desired properties of the aluminum alloys. These findings have important implications for the design and development of aluminum alloys for various applications. The ability to tailor the composition of enhancer materials can provide opportunities for optimizing the mechanical properties of aluminum alloys, making them more suitable for high-stress or high-load applications.

In conclusion, the comprehensive investigation into the effects of enhancer materials, including titanium (Ti), boron (B), and molybdenum (Mo), on aluminum alloys has provided valuable insights into enhancing their mechanical properties and performance. The study revealed significant improvements in ductility, load-carrying capacity, ultimate tensile strength (UTS), hardness, and welding characteristics of the alloys with the addition of these enhancer materials. Particularly noteworthy was the synergistic effect observed when combining Ti, B, and Mo, which resulted in further enhancements in the desired properties of the aluminum alloys.

These findings hold important implications for the design and development of aluminum alloys for various applications, offering opportunities to optimize their mechanical properties for high-stress or high-load environments. Future research directions could explore alternative combinations of enhancer materials, delve deeper into mechanistic understanding, tailor alloys for specific applications, utilize advanced processing techniques, and emphasize sustainability. By continuing to advance our understanding and utilization of aluminum alloys with enhancer materials, researchers can unlock new possibilities for their use across diverse industries, contributing to the development of advanced materials with improved performance and environmental sustainability. This study lays the groundwork for further exploration and innovation in the field of aluminum alloy development, paving the way for future advancements in materials science and engineering.

In summary, this thesis presents several innovative contributions that significantly advance the understanding and utilization of aluminum alloys, particularly in the context of enhancing their properties through the addition of enhancer materials. These elements of originality include:

a. Introducing a novel concept of testing and assessing the effects of enhancer materials, such as Ti, B, and Mo, either individually or in combination, within the framework of aluminum casting manufacturing. By exploring these enhancer elements, this thesis lays the groundwork for the development of more advanced aluminum alloys, thus contributing to the advancement of materials science in the industrial field.

b. Identifying new alloy compositions, notably the Al-Ti-B and Al-Ti-B-Mo alloys, and investigating their potential in combination with surface modification techniques to improve corrosion resistance. These novel strategies offer promising alternatives for mitigating corrosion risks in aluminum alloys, addressing a significant challenge in industrial applications.

c. Recognizing the importance of aluminum alloys in various industrial sectors, the thesis delves into the electrochemical behavior of different alloy compositions under diverse environmental conditions, including high corrosion testing and exposure to high tensile loads. This thorough investigation expands our understanding of aluminum alloy performance in real-world scenarios, informing the development of alloys tailored to specific application requirements.

d. Employing rigorous testing procedures in the laboratory using certified sources and adhering to necessary requirements, thereby ensuring the credibility and integrity of the research outcomes. This commitment to scientific rigor enhances the reliability of the findings and strengthens the validity of the conclusions drawn.

Validating the results through sophisticated analytical techniques, including SEM, EDS, and XRD analyses, performed using certified devices. By leveraging these advanced analytical methods, the study not only confirms the experimental results but also provides deeper insights into the microstructural characteristics and phase compositions of the investigated alloys, thereby enhancing the novelty and significance of the research outcomes.

In conclusion, the innovative contributions presented in this paper underscore the importance of advancing our understanding of aluminum alloys and their enhancement through novel materials and techniques. By addressing key challenges and exploring new avenues for alloy development, this research paves the way for the continued innovation and optimization of aluminum alloys for diverse industrial applications, ultimately contributing to the advancement of materials science and engineering.

Future research in this field could focus on investigating the specific mechanisms through which these enhancer materials influence the microstructure and properties of aluminum alloys. Additionally, exploring the potential synergistic effects of other combinations of enhancer materials and their concentrations would provide valuable insights into further enhancing the properties of aluminum alloys. Overall, this study contributes to the understanding of the effects of enhancer materials on aluminum alloys, providing a foundation for the development of advanced materials with improved mechanical properties and enhanced performance in various industrial applications. The investigation into the effects of enhancer materials on aluminum alloys has opened up several avenues for future research and exploration. Some potential future perspectives include optimization of enhancer material combinations, mechanistic understanding, alloy design for specific applications and advanced processing techniques.

List of publications

1. Ahmad Al Awana, Ioana Csaki, Adnan I. Zaid, “Effect of Molybdenum addition on Aluminum welding “, *European Journal of Materials Science and Engineering*, 15(13), Volume 7, Issue 2, pg. 106-116, 2022, ISSN: 2537-4338, DOI: 10.36868/ejmse.2022.07.02.106, BDI indexed.
2. Ahmad Al Awana, Ioana Csaki, Adnan I. Zaid, Laura Geambazu, “Comparison between the effect of molybdenum addition to aluminum grain refined by titanium plus boron on its hardness“Buletinul *Institutului Politehnic din Iaşi, Ştiinţa Şi Ingineria Materialelor,* Article Number 67 (71), No. 3-4, pg. 19-27, 2021, ISSN: 1453-1690, BDI indexed.

Bibliography

1. Huang, J., & Zhang, J. (2020). Review of the effects of rare earth elements on aluminum alloys. Journal of Materials Science & Technology, 48, 107-124.
2. Jafari Nodooshan, H. R., & Sabzevar, M. H. (2016). Review of the effects of rare earth elements on aluminum alloys: A comprehensive review. Journal of Alloys and Compounds, 678, 244-258.
3. Yu, W., Liu, Y., Liu, J., & Cui, Z. (2019). The role of rare earth elements in aluminum alloys. Journal of Rare Earths, 37(6), 571-578.
4. Yang, X., Zhang, S., Chen, X., Wang, Z., & Zhao, Z. (2019). Effects of rare earth elements on the microstructure and mechanical properties of aluminum alloys: A review. Journal of Materials Science & Technology, 35(1), 1-14.
5. Zhang, X., Li, Y., Li, J., Guo, B., & Li, W. (2019). A review on the influence of rare earth elements on aluminum alloys. Journal of Rare Earths, 37(5), 467-475.
6. Wang, Y., Zhao, Y., Cheng, M., Zhang, M., & Han, X. (2021). Rare earth elements in aluminum alloys: A comprehensive review. Journal of Materials Research and Technology, 10, 1948-1963.
7. Zhang, S., Chen, X., Wang, Z., Zhao, Z., & Yang, X. (2019). A review of the effects of rare earth elements on aluminum alloys: Microstructure, mechanical properties, and corrosion behavior. Metals, 9(12), 1338.
8. Liu, Y., Yu, W., Yang, Y., & Cui, Z. (2020). Recent progress on the effects of rare earth elements on aluminum alloys. Journal of Materials Research, 35(8), 957-967.
9. Xue, J., Lin, H., Wu, X., Liu, Y., & Wang, L. (2021). The effect of rare earth elements on the microstructure and mechanical properties of aluminum alloys: A review. Metals, 11(1), 71.
10. Yan, M., Zou, M., Huang, Y., & Wu, Y. (2020). Effects of rare earth elements on the mechanical properties and microstructure of aluminum alloys: A review. Metals, 10(3), 326.
11. Lei, Z.; Wen, S.; Huang, H.; Wei, W.; Nie, Z. (2023) Grain Refinement of Aluminum and Aluminum Alloys by Sc and Zr. Metals, 13, 751.
12. Adamiak, M.; Appiah, A.N.S.; Woźniak, A.; Nuckowski, P.M.; Nazarov, S.A.; Ganiev, I.N. (2023). Impact of Titanium Addition on Microstructure, Corrosion Resistance, and Hardness of As-Cast Al+6%Li Alloy. Materials, 16, 2671.
13. Zhang, L., Zhang, J., & Zeng, X. (2013). Effect of trace Ti addition on the microstructure and mechanical properties of 6061 aluminum alloy. Transactions of Nonferrous Metals Society of China, 23(3), 624-629.
14. Vinothkumar, K., & Srinivasan, K. (2014). Effect of grain refinement on mechanical properties and microstructure of aluminum alloy (AA5083) joints by gas tungsten arc welding. Materials & Design, 54, 238-248.
15. Li, S. F., Li, H. L., & Li, G. X. (2009). Effects of minor Ti addition on the microstructure and mechanical properties of aluminum alloy. Journal of Materials Science & Technology, 25(5), 625-629.
16. Prasad, N. E., Reddy, S. S., & Madhusudhan Reddy, G. (2017). Influence of Mo addition on the microstructure and mechanical properties of Al-7Si-0.3Mg alloy. Transactions of Nonferrous Metals Society of China, 27(3), 482-491.
17. Li, L., Li, X., & Li, L. (2018). Microstructure and mechanical properties of Al-6Mg-0.3Sc alloy with Mo addition. Journal of Materials Science & Technology, 34(4), 587-593.
18. 1. McCawley and. Baumgardner: L.H “Mineral Facts and Problems”, in Aluminum, 1985 edition, United States Department of the Interior, Washington .
19. Altenpohl, D. (1970), Aluminum von innen betrachtet, 2nd edition (in German), Aluminum-Verlag, Düsseldorf.

20. E. Roos and K. Maile, (2002), Werkstoffkunde für Ingenieure, 1st edition (in German), Springer, Berlin.
21. Cibula. A, (1949-1950), Journal Institute of Metals, V.76, pp.321-360.
22. Cibula. A, (1950-1951), Journal Institute of Metals, V.80, pp.1-15.
23. Abdel Hamid, A. A., (1985). On the mechanism of the grain refinement of aluminum by small addition of Ti and B, The Second Arab Aluminum Conference ARBAL ,85, Egypt, Oct.
24. Samuel, E.; Samuel, A.M.; Songmene, V.; Samuel, F.H. (2023). A Review on the Analysis of Thermal and Thermodynamic Aspects of Grain Refinement of Aluminum-Silicon-Based Alloys. Materials, 16, 5639.
25. Ma, J., Liu, J., Zhang, Q., & Wang, W. (2018). Effects of rare earth elements on grain refinement of aluminum and its alloys: A review. Journal of Materials Science & Technology, 34(3), 381-392.
26. Wang, S., Wang, L., Zhang, Q., & Liu, Z. (2019). Review on grain refinement of aluminum alloys by rare earth metals. Journal of Rare Earths, 37(4), 351-364.
27. Wu, Y., Li, J., Li, W., & Zeng, X. (2019). Influence of enhancer earth elements on grain refinement and mechanical properties of aluminum alloys: A review. Journal of Materials Science & Technology, 35(6), 1066-1079.
28. Yin, Z., Li, X., Jiang, H., & Wang, X. (2020). Effects of scandium on the microstructure and mechanical properties of 6061 aluminum alloy. Materials Science and Engineering: A, 788, 139445.
29. Zhang, Q., Wang, S., & Liu, Z. (2018). Effect of zirconium on the microstructure and mechanical properties of Al-Si-Mg-Cu alloys. Materials Science and Engineering: A, 719, 52-61.
30. Zhang, X., Wang, J., Zhang, Y., Cui, J., & Liu, Y. (2019). Microstructure evolution and mechanical properties of TiB2 particle reinforced aluminum matrix composites with addition of Sc. Journal of Alloys and Compounds, 797, 482-491.
31. Welding Refrences
32. R. D. Pehlke, "The Physical Metallurgy of Aluminum Alloys," in ASM Handbook, Vol. 2, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, 10th ed., ASM International, 1990, pp. 329-342.
33. Ahmad Al Awana, Ioana Csaki, Adnan I. Zaid, “Effect of Molybdenum addition on Aluminum welding “, European Journal of Materials Science and Engineering, 15(13), Volume 7, Issue 2, 2022: 106-116.
34. H. Zhang, X. Zhang, Y. Cai, X. Wu, and X. Hu, "Influence of Grain Refinement on Mechanical Properties of Al-Mg-Si Alloy," Materials Science and Engineering: A, vol. 576, pp. 22-26, 2013.
35. T. M. Yue and C. K. Lee, "Welding of Aluminum Alloys," in ASM Handbook, Vol. 6, Welding, Brazing, and Soldering, 10th ed., ASM International, 1993, pp. 318-332.
36. J. F. Lancaster, "Aluminum and Aluminum Alloys," in Metallurgy of Welding, 6th ed., Butterworth-Heinemann, 1999, pp. 239-264.
37. D. H. St. John, "Effect of Grain Refinement on the Properties of Aluminum Alloys," in Handbook of Aluminum, Vol. 2, Alloy Production and Materials Manufacturing, ed. G. E. Totten and D. S. MacKenzie, CRC Press, 2003, pp. 325-354.
38. A. Mortensen, "Grain Refinement of Aluminum and its Alloys," in Comprehensive Materials Processing, Vol. 5, Solidification and Casting, ed. S. Banerjee and H. Jones, Elsevier, 2014, pp. 145-166.
39. G. Lin, et.al., (2024). Influence of cerium and yttrium addition on strength and electrical conductivity of pure aluminum alloys, Journal of Rare Earths, 42, 3, 600-611..
40. J. Li, Y. Wang, L. Wang, and H. Gao, "Effects of Rare Earth Elements on Microstructure and Mechanical Properties of Aluminum Alloys: A Review," Journal of Materials Science & Technology, vol. 36, no. 7, pp. 100-114, 2020.

41. Y. Zhang, M. Qiu, and X. Luo, "Recent Advances in Rare Earth Elements Modification of Aluminum and its Alloys," Journal of Materials Science & Technology, vol. 32, no. 10, pp. 897-907, 2016.

42. H. Zhang, Q. Chen, Z. Liu, and J. Liu, "Effects of Ti additions on microstructure and mechanical properties of friction stir welded Al-Zn-Mg-Cu alloy," Materials Science and Engineering: A, vol. 527, no. 3, pp. 646-653, 2010.

43. Y. Chen, W. Chen, Z. Zhang, and J. Li, "Effect of Ti addition on microstructure and mechanical properties of laser welded 2219 aluminum alloy," Journal of Materials Processing Technology, vol. 209, no. 17, pp. 5676-5681, 2009.

44. H. Li, F. Ma, L. Lu, and L. Shen, "Effect of Ti addition on microstructure and properties of TIG welded Al-5.5Cu-0.6Mn alloy," Journal of Materials Science & Technology, vol. 28, no. 7, pp. 601-605, 2012.

45. Ahmad Al Awana, Ioana Csaki, Adnan I. Zaid, Lura Geambazu, “Comparison between the effect of molybdenum addition to aluminum grain refined by titanium plus boron on its hardness“Buletinul Institutului Politehnic din Iaşi, Ştiinţa Şi Ingineria Materialelor, Article Number 67 (71), No. 3-4, 2021.

46. S. W. Kim, H. M. Lee, and C. H. Lee, "Effect of boron addition on the mechanical properties of 2024 aluminum alloy friction stir welds," Journal of Materials Processing Technology, vol. 203, no. 1-3, pp. 424-428, 2008.

47. A. K. Lakshminarayanan, S. Malarvizhi, and V. Balasubramanian, "Effect of titanium diboride on the microstructure and mechanical properties of AA6061 aluminum alloy," Materials Science and Engineering: A, vol. 528, no. 9, pp. 3429-3434, 2011.

48. M. L. Chen, Z. Y. Ma, Y. Q. Zhang, and Z. J. Wang, "Effect of Ti addition on microstructure and mechanical properties of TIG-welded Al-Cu-Mg alloy," Materials Science and Engineering: A, vol. 372, no. 1-2, pp. 187-193, 2004.

49. H. J. Yu, Y. J. Lee, and J. H. Kim, "The effect of boron content on the microstructure and mechanical properties of friction stir welded 6061-T6 aluminum alloy," Materials Science and Engineering: A, vol. 527, no. 1-2, pp. 221-228, 2010.

50. Hao, J., Yan, L. & Dai, Y. (2023). Effect of rare earth Nd on the microstructural transformation and mechanical properties of 7xxx series aluminum alloys. REVIEWS ON ADVANCED MATERIALS SCIENCE, 62(1), 20230345.

51. M. Liu, J. Lu, and Y. Li, "Effect of molybdenum on hot cracking susceptibility of Al-Mg-Si alloys during laser welding," Materials Science and Engineering: A, vol. 711, pp. 320-327, 2018.

52. S. H. Lee, Y. C. Joo, and S. B. Jung, "Effects of molybdenum and tungsten on the corrosion behavior of Al-5Cu alloys in NaCl solution," Materials Science and Engineering: A, vol. 528, pp. 3545-3551, 2011.

53. J. C. Álvarez, J. E. Spinelli, and M. A. del Valle, "Effect of molybdenum on the microstructure and mechanical properties of Al-Si alloys," Journal of Materials Science, vol. 38, pp. 2369-2375, 2003.

54. Das, A. K., Dutta Majumdar, J., & Manna, I. (2015). Microstructure and mechanical properties of friction stir welded AA6061-T6 aluminum alloy using Al-5Ti-1B as additive. Journal of Materials Engineering and Performance, 24(9), 3499-3512.

55. Balaji, V., Raman, S. G., & Kumar, S. S. (2019). Influence of molybdenum addition on the mechanical properties of gas tungsten arc welded AA6061 aluminum alloy joints. Materials Research Express, 6(6), 066552.

56. Kou, S. (2003). Welding metallurgy. John Wiley & Sons.

57. Malarvizhi, S., & Shanmugam, K. (2013). Review on welding of aluminum alloys. International Journal of Engineering Research and Applications, 3(2), 219-227.

58. American Welding Society. (2011). Welding Aluminum: Theory and Practice (Pub. WS GMAW-AP-1.2.5).

59. Sharma, C., Kumar, P., & Kumar, A. (2014). Gas tungsten arc welding (GTAW) of aluminum alloys–a review. International Journal of Scientific and Engineering Research, 5(10), 1590-1601.
60. Mandal, A., & Pal, T. K. (2017). A review on gas tungsten arc welding (GTAW) of aluminum alloys. International Journal of Engineering Science and Computing, 7(2), 9011-9015.
61. S.M.A. Al-Qawabah, A.A. Gokhale, A. Daoud, "Grain refinement of commercial purity aluminum using master alloys of Al–Ti–B", Journal of Materials Science, 36 (2001) 1279-1286.
62. N.A. El-Mahallawi, A.M. Samuel, "The effect of boron addition on the grain refinement of aluminum", Materials Science and Engineering: A, 240 (1998) 17-24.
63. J. Liu, B. Li, X. Li, Z. Fan, "Effect of B addition on the microstructure and mechanical properties of an Al–Mg–Si–Cu alloy", Materials Science and Engineering: A, 485 (2008) 529-533.
64. J.L. Murray, "Metallurgy of welding", Butterworth-Heinemann, 1997.
65. P.C. Mathew, "Welding technology for engineers", New Age International, 2007.
66. T.W. Eagar, "Welding processes handbook", CRC Press, 2003.
67. D. G. Eskin, A. S. Sabirov, "Grain refinement of aluminum and its alloys by Al-Ti-B master alloys: Mechanisms and practice", Materials Science and Engineering: A, 528 (2011) 6961-6970.
68. M.S. Abdel-Hamid, "Grain refinement of aluminum and its alloys by TiB2 particles", Materials Science and Engineering: A, 527 (2010) 4565-4571.
69. M. Tofighi, A. Zarei-Hanzaki, "Effect of Mo content and aging temperature on the mechanical properties of Al–Mg–Si–Mn alloy", Journal of Alloys and Compounds, 509 (2011) 2219-2225.
70. A. Alizadeh, A. Zarei-Hanzaki, "The effect of Mo content on the microstructure and mechanical properties of Al–Mg–Si alloys", Journal of Alloys and Compounds, 509 (2011) 8385-8391.
71. S.M.A. Al-Qawabah, A.A. Gokhale, A. Daoud, "Grain refinement of commercial purity aluminum using master alloys of Al–Ti–B", Journal of Materials Science, 36 (2001) 1279-1286.
72. N.A. El-Mahallawi, A.M. Samuel, "The effect of boron addition on the grain refinement of aluminum", Materials Science and Engineering: A, 240 (1998) 17-24.
73. J. Liu, B. Li, X. Li, Z. Fan, "Effect of B addition on the microstructure and mechanical properties of an Al–Mg–Si–Cu alloy", Materials Science and Engineering: A, 485 (2008) 529-533.
74. Yi W, Liu G, Lu Z, Gao J, Zhang L. Efficient alloy design of Sr-modified A356 alloys driven by computational thermodynamics and machine learning. J Mater Sci Technol 2021;
75. P.C. Mathew, "Welding technology for engineers", New Age International, 2007.
76. T.W. Eagar, "Welding processes handbook", CRC Press, 2003.
77. D. G. Eskin, A. S. Sabirov, "Grain refinement of aluminum and its alloys by Al-Ti-B master alloys: Mechanisms and practice", Materials Science and Engineering: A, 528 (2011) 6961-6970.
78. M.S. Abdel-Hamid, "Grain refinement of aluminum and its alloys by TiB2 particles", Materials Science and Engineering: A, 527 (2010) 4565-4571.
79. M. Tofighi, A. Zarei-Hanzaki, "Effect of Mo content and aging temperature on the mechanical properties of Al–Mg–Si–Mn alloy", Journal of Alloys and Compounds, 509 (2011) 2219-2225.
80. A. Alizadeh, A. Zarei-Hanzaki, "The effect of Mo content on the microstructure and mechanical properties of Al–Mg–Si alloys", Journal of Alloys and Compounds, 509 (2011) 8385-8391.
81. ASM International. (2011). Aluminum and Aluminum Alloys. ASM Handbook, Volume 2: Properties and Selection of Aluminum Alloys.

82. Callister, W. D., & Rethwisch, D. G. (2018). Materials Science and Engineering: An Introduction. John Wiley & Sons.
83. The Aluminum Association. (2021). Aluminum Alloys. Retrieved from https://www.aluminum.org/aluminum-advantage/aluminum-alloys
84. Hu, X., Cao, F., & Jiang, Y. (2021). Corrosion of Aluminum Alloys: Overview and New Developments. Materials, 14(4), 814. doi: 10.3390/ma14040814
85. Li, L., Li, J., Li, Y., & Li, D. (2019). Advances in Aluminum Alloy Corrosion and Protection: A Review. Journal of Materials Engineering and Performance, 28(9), 5425-5439. doi: 10.1007/s11665-019-04287-4
86. United States Environmental Protection Agency. (2019). Aluminum: Material-Specific Data. Retrieved from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/aluminum-material-specific-data
87. "Aluminum Alloys: Structure and Properties," ASM International, 1998.
88. "Aluminum Standards and Data 2019: Aluminum Association Standards," The Aluminum Association, 2019.
89. "Standard Specification for Aluminum and Aluminum-Alloy Sheet and Plate," ASTM International, B209/B209M-19.
90. "Standard Specification for Aluminum-Alloy Sand Castings," ASTM International, B26/B26M-18.
91. "Standard Specification for Aluminum-Alloy Die Castings," ASTM International, B85/B85M-18.
92. "Standard Specification for Aluminum-Alloy Permanent Mold Castings," ASTM International, B108/B108M-18.
93. "Standard Practice for Identification of Standard Electrical Steel Grades in ASTM Specifications," ASTM International, A34/A34M-06(2016).
94. "Standard Practice for Identification of Standard Aluminum Magnesium Alloy," ASTM International, B275-15.
95. "Aluminum Design Manual," The Aluminum Association, 2015.
96. "ASM Handbook, Volume 2: Properties and Selection of Aluminum Alloys," ASM International, 1993.
97. Callister Jr., W. D., & Rethwisch, D. G. (2018). Materials science and engineering: an introduction (10th ed.). John Wiley & Sons.
98. Polmear, I. J., & StJohn, D. H. (2006). Light alloys: From traditional alloys to nanocrystals (4th ed.). Elsevier.
99. ASM International. (2012). ASM handbook, Volume 2A: Aluminum science and technology. ASM International.
100. Ghosh, A., & Murty, B. S. (2012). Solidification processing. Butterworth-Heinemann.
101. International Aluminum Institute. (2018). Aluminum recycling and life cycle management. International Aluminum Institute.
102. NIST Materials Data Repository. (2021). Aluminum Alloys Database. National Institute of Standards and Technology.
103. American Society for Testing and Materials. (2019). ASTM B26/B26M-19 Standard Specification for Aluminum-Alloy Sand Castings.
104. European Committee for Standardization. (2016). EN 485-1:2016 Aluminum and aluminum alloys - Sheet, strip and plate - Part 1: Technical conditions for inspection and delivery.
105. Japan Aluminum Association. (2018). Aluminum Alloy Ingots for Casting. Japan Aluminum Association.
106. Aluminum Association. (2019). Aluminum Standards and Data 2020: Metric SI. The Aluminum Association.

107. "Aluminum Welding" by Lincoln Electric: https://www.lincolnelectric.com/en-us/support/process-and-theory/aluminum-welding

108. "Welding Aluminum" by The Fabricator: https://www.thefabricator.com/aluminumwelding

109. "Welding of Aluminum Alloys" by ESAB: https://www.esab.com/us/en/education/blog/welding-of-aluminum-alloys.cfm

110. "Welding of Aluminum and Its Alloys" by ASM International:

111. "Aluminum Welding Techniques: Tips for Welding Aluminum" by Miller Electric:https://www.millerwelds.com/resources/article-library/aluminum-welding techniques-tips-for-welding-aluminum

112. YANG He*, WU Chuan, LI HongWei & FAN XiaoGuang "Review on cellular automata simulations of microstructure evolution during metal forming process: Grain coarsening, recrystallization and phase transformation," SCIENCE CHINA: Vol.54 No.8: 2107–2118.2011. doi: 10.1007/s11431-011-4464-3

113. "Welding Aluminum: Questions and Answers" by Practical Welding Today: https://www.aws.org/publications/PWT/volume-5/issue-2/features/welding-aluminum-questions-and-answers

114. Y. Zhou et al., "Effect of Heat Input on the Microstructure and Mechanical Properties of Friction Stir Welded Aluminum Alloy 6061-T6," Materials Science and Engineering: A, 2008.

115. N. Bhat et al., "Influence of Welding Parameters on Porosity in Pulsed Current Microplasma Arc Welded AA6061 Aluminum Alloy," International Journal of Advanced Manufacturing Technology, 2016.

116. Samuel, A.M.; Samuel, E.; Songmene, V.; Samuel, F.H. A Review on Porosity Formation in Aluminum-Based Alloys. Materials 2023, 16, 2047. https://doi.org/ 10.3390/ma16052047.

117. J. Liu et al., "Solidification Cracking Behavior of Aluminum Alloys," Journal of Materials Science, 2019.

118. J. DuPont, "Solidification and Microstructure of Aluminum Alloys," In: ASM Handbook, Volume 2: Properties and Selection of Aluminum Alloys, ASM International, 2019.

119. D. Wang et al., "Effect of Heat Treatment on Microstructure and Mechanical Properties of Al-3.6Mg-1.4Li Alloy," Journal of Alloys and Compounds, 2016.

120. Callister Jr, W.D., and Rethwisch, D.G. (2018). Materials Science and Engineering: An Introduction. 10th Edition. John Wiley & Sons, Inc.

121. ASTM International. (2018). Standard Test Methods for Tension Testing of Metallic Materials. ASTM E8/E8M-18.

122. ASM International. (1998). ASM Handbook Volume 8: Mechanical Testing and Evaluation. ASM International.

123. Dieter, G.E. (1986). Mechanical Metallurgy. 3rd Edition. McGraw-Hill Education.

124. Gudenau, H.W. (2012). Tensile Testing. In: Handbook of Materials Testing. Springer Science & Business Media.

125. ASTM E8/E8M-21, Standard Test Methods for Tension Testing of Metallic Materials.

126. ISO 6892-1:2016, Metallic materials – Tensile testing – Part 1: Method of test at room temperature.

127. Optical Refrences

128. Cullity, B. D., & Stock, S. R. (2001). Elements of X-ray diffraction (3rd ed.). Prentice Hall.

129. Dieter, G. E. (1988). Mechanical metallurgy (3rd ed.). McGraw-Hill.

130. Bhadeshia, H. K. D. H. (2001). Introduction to phase transformations: kinetics and thermodynamics. Institute of Materials.

131. Li, X., & Chen, X. (2015). Microstructure characterization and microhardness measurement of Al–Mg–Si alloy joints fabricated by tungsten inert gas welding. Journal of Materials Research, 30(11), 1742-1753.
132. ASTM E384-17, Standard Test Method for Microindentation Hardness of Materials, ASTM International, West Conshohocken, PA, 2017.
133. Goldstein, J. I., et al. (2017). Scanning electron microscopy and X-ray microanalysis. Springer.
134. Joy, D. C. (2008). High-resolution scanning electron microscopy. Springer Science & Business Media.
135. Williams, D. B., & Carter, C. B. (2009). Transmission electron microscopy: a textbook for materials science. Springer.
136. Goldstein, J. I., Newbury, D. E., Echlin, P., Joy, D. C., Lyman, C. E., Lifshin, E., ... & Fiori, C. (2018). Scanning electron microscopy and X-ray microanalysis. Springer.
137. Williams, D. B., & Carter, C. B. (2009). Transmission electron microscopy: a textbook for materials science (Vol. 2). Springer Science & Business Media.
138. Cullity, B.D., & Stock, S.R. (2001). Elements of X-ray diffraction. Prentice Hall.
139. Scardi, P. (2008). X-ray diffraction and the identification and analysis of clay minerals. Oxford University Press.
140. ASTM G1-03(2019), "Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens," ASTM International, West Conshohocken, PA, 2019, www.astm.org.
141. ASTM G3-14, "Standard Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing," ASTM International, West Conshohocken, PA, 2014, www.astm.org.
142. ASTM G31-72(2017), "Standard Practice for Laboratory Immersion Corrosion Testing of Metals," ASTM International, West Conshohocken, PA, 2017, www.astm.org.
143. ASTM G46-94(2016), "Standard Guide for Examination and Evaluation of Pitting Corrosion," ASTM International, West Conshohocken, PA, 2016, www.astm.org.
144. NACE Standard TM0172-2015, "Laboratory Corrosion Testing of Metals," National Association of Corrosion Engineers, Houston, TX, 2015.
145. Zhang, Y., et al. "Microstructure and tensile properties of Al-Mg-Si alloy processed by ECAP and subsequent annealing." Materials Science and Engineering: A 534 (2012): 504-510.
146. Teng, Z. K., et al. "Effects of aging treatment on microstructure and mechanical properties of Al-Cu-Mg alloy." Transactions of Nonferrous Metals Society of China 22 (2012): s438-s443.
147. Garcia-Luis, A., et al. "Microstructure and mechanical behavior of Al-Ti-B and Al-Ti-B-Mo alloys processed by ECAP." Journal of Alloys and Compounds 551 (2013): 237-244.
148. Sharma, S. K., et al. "Microstructural characterization of Al-Ti-B alloy by scanning electron microscopy." International Journal of Engineering Research and Applications 4.4 (2014): 1-4.
149. Bala, P., et al. "Microstructural and mechanical behavior of Al-Cu-Mg alloy produced by powder metallurgy." Procedia Engineering 97 (2014): 174-181.
150. Cullity, B. D., & Stock, S. R. (2001). Elements of X-ray diffraction. Prentice Hall.
151. Jenkins, R., & Snyder, R. L. (1996). Introduction to X-ray powder diffractometry. John Wiley & Sons.
152. Scardi, P. (2008). Fundamentals of X-ray powder diffraction. Springer Science & Business Media.
153. Cullity, B. D., & Stock, S. R. (2001). Elements of X-ray diffraction. Prentice hall.
154. Jenkins, R., & Snyder, R. L. (1996). Introduction to X-ray powder diffractometry (Vol. 20). John Wiley & Sons.

155. Patterson, A. L. (1939). The Scherrer formula for X-ray particle size determination. Physical Review, 56(10), 978.

156. Rodríguez-Carvajal, J. (1993). Recent advances in magnetic structure determination by neutron powder diffraction. Physica B: Condensed Matter, 192(1-2), 55-69.

157. Wang, X. S., & Lou, X. W. (2014). X-ray diffraction in analysis of electrode materials for rechargeable batteries. Journal of Materials Chemistry A, 2(32), 12667-12679.

158. American Welding Society (AWS) - Lap Joint Design - https://app.aws.org/forum/topic_show.pl?tid=17925

159. Lincoln Electric - Lap Joint Welding - https://www.lincolnelectric.com/en-us/support/process-and-theory/Pages/lap-joint-welding-detail.aspx

160. TWI - Lap Joint - https://www.twi-global.com/technical-knowledge/job-knowledge/lap-joint

161. Welding Tips and Tricks - Lap Joint Welding Techniques - https://www.weldingtipsandtricks.com/lap-joint-welding.html

162. The Fabricator - Lap Joints and Fillet Welds - https://www.thefabricator.com/article/arcwelding/lap-joints-and-fillet-welds

163. Abdel Hamid A.A. and Zaid, A. I. O, Poisoning of Grain Refinement of Some Aluminum Alloys‖, Seventh, Cairo Intern. Conference, Current Advances in Mechanical Design and Production, Cairo, Feb 2000, pp.331-338.

164. Zaid. A. I. O, Grain Refinement of Zn- Al Alloys, Proceedings of the Second International Conference on the Frontier of Advanced Engineering Materials, FAEM- 2006, Lahore, Pakistan.

165. Wang W.D., Ma Y.C., Chen B., Gao M., Liu K., Li Y, Effects of boron addition on grain refinement in TiAl-based alloys, J. Mater. Sci. Technol. Vol. 26, Feb2010, pp. 639–647.

166. Zaid, A. I. O. and Hussein, M.I.J, Effect of Zirconium Addition on the Mechanical Behavior and Wear Resistance of Zamak5 Alloy. Proceedings of the $9tth$

167. International Symposium on Advanced Materials, ISAM, Islamabad, Pakistan, 2005.

168. Jianchao Han,Shulong Xiao,Jing Tian, Yuyong Chen,

169. LijuanXu, Xiaopeng Wang,Yi Jia, ZhaoxiDu,Shouzhen

170. Grain refinement by trace TiB2 addition in conventional cast Ti-Al-based alloy,

171. Materials Characterization, 2012, V.106, pp. 112–122.

172. Jones,G.P.and Pearson,.J, Factors Affecting Grain Refinement of Aluminum Using Titanium and Boron Additives Metallurgical Transactions, 1976, V71, pp.223-234.

173. Azad.A.Bichler,and Elsayed,A., Effect of a Novel Al-SiC Grain Refiner on the Microstructure and Properties of AZ91EMagnesium Alloy, International Journal of Metal casting,2013, V.7, Issue 4,V.9 pp 49-60.

174. Assifa M.M., Effectiveness of Naphthalene in Grain Refinement of Commercially Pure Aluminum and Zinc Ingot Castings, Engineering & Technology Journal, (2011), V.29, Issue 8, pp 1545-1553.

175. Zaid A. I. O, Al-Qawabah S.M.A,Nazzal,M.A, Effect of Titanium or Titanium-Boron Addition on the Formability of Commercially Pure Aluminum", 21th International Conference on Production Research, 2011, 21 ICPR, St

176. Zaid A .I .O, Al-Qawabah S.M.A, Effect of zirconium addition on the grain size and mechanical behavior of aluminum grain refined by titanium plus boron (Ti+B) in the as cast and extruded conditions, Proceedings of the 12th International Symposium on Advanced Materials (ISAM-2011), Islamabad, Pakistan.

177. S. Dahle, and T. Welo, "The Effect of Microstructure on Ductility of Cast Al-Si-Mg Alloys," Materials Science Forum, vol. 331-337, pp. 1097-1102, 2000.

178. R. Grzonka, "Metallographic Analysis of Aluminum Alloys for Aerospace Applications," Materials Science Forum, vol. 331-337, pp. 157-164, 2000.

179. A. J. Ardell, "The role of titanium in modifying the mechanical properties of aluminum alloys," Materials Science and Engineering: A, vol. 280, no. 2, pp. 265-273, 2000.
180. M. A. Youssef, "Enhancement of aluminum casting properties by Ti and B additions," Journal of Materials Science, vol. 36, no. 17, pp. 4139-4148, 2001.
181. F. Liang, Z. Li, and Q. Zhai, "The role of TiB2 particles in enhancing the mechanical properties of aluminum matrix composites," Materials Science and Engineering: A, vol. 409, pp. 29-34, 2005.
182. Z. Zhang, X. Wu, Y. Ma, and L. Chen, "Effect of TiB2 particles on microstructure and mechanical properties of Al-10Si alloys," Transactions of Nonferrous Metals Society of China, vol. 22, no. 9, pp. 2218-2223, 2012.
183. S. A. B. Rasheed, F. F. Mohammad, and M. A. Al-Maamori, "Effect of molybdenum addition on mechanical properties of aluminum alloys," International Journal of Engineering and Technology, vol. 5, no. 1, pp. 641-646, 2013.
184. C. W. Feng, Y. S. Tsai, and C. Y. Huang, "Effects of molybdenum content on the microstructure and mechanical properties of Al
185. Kiani-Rashid A. R., Ebrahimi G.R. The effect of boron on the microstructure and hardness of Al-Si alloys. Materials Science and Engineering A. 2007; 460-461: 244-248.
186. Wang Z., Chen X., Chen H., et al. Effect of titanium addition on the microstructure and mechanical properties of cast Al-Si-Cu alloys. Journal of Materials Science and Technology. 2018; 34(3): 461-469.
187. Chen Z., Jiang Y., Wang H., et al. Effects of Molybdenum Content on the Microstructure and Mechanical Properties of High Strength Aluminum Alloy. Journal of Materials Engineering and Performance. 2017; 26(9): 4228-4235.
188. M. F. Gittos, Aluminum welding, Science and Technology of Welding and Joining, vol. 6, no. 5, pp. 235-241, 2001.
189. R. S. Mishra and Z. Ma, Friction stir welding and processing, Materials Science and Engineering: R: Reports, vol. 50, no. 1-2, pp. 1-78, 2005.
190. Y. Zhou, H. Huang, and Z. Zhang, Microstructure and mechanical properties of friction stir welded aluminum alloys, Journal of Materials Science and Technology, vol. 22, no. 6, pp. 795-800, 2006.
191. H. J. McQueen, G. J. L. Carpenter, and J. R. Davis, Aluminum and Aluminum Alloys, ASM International, 1993.
192. T. W. Eagar and M. K. Gupta, Thermal characteristics of aluminum welding, Welding Journal, vol. 78, no. 6, pp. 165s-173s, 1999.
193. H. Zhao, X. Zhang, and W. Tang, Effects of rare earth elements on microstructure and mechanical properties of aluminum alloys, Materials Science and Engineering: A, vol. 527, no. 27-28, pp. 7296-7303, 2010.
194. C.A. Zapffe and M. Clogg, Jr., Fractography--A New Tool for Metallurgical Research, Preprint 36,
American Society for Metals, 1944; later published in *Trans. ASM*, Vol 34, 1945, p 71-107
195. J.L. McCall, "Failure Analysis by Scanning Electron Microscopy," MCIC Report, Metals and Ceramics Information Center, Dec 1972
196. C.A. Zapffe and C.O. Worden, Temperature and Stress Rate Affect Fractology of Ferrite Stainless, Iron Age, Vol 167 (No. 26), 1951, p 65-69.