Preparation and Characterisation of Zinc-Aluminium Eutectic Alloy

Priya Tharshini Ayasamy[1], Nur Azam Badarulzaman[1*]

[1] Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor

*Corresponding Author: azam@uthm.edu.my
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Abstract

This study investigates the preparation, characterization, and mechanical properties of zinc-aluminium (Zn-Al) alloys, focusing on impact toughness, hardness, and microstructural characteristics. The alloys were fabricated using sand casting and their microstructures were examined using scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). The microstructural investigation revealed unique grain shapes and phase distributions, with the eutectic alloy displaying lamellar structures and the hypereutectic alloy having dendritic patterns. The microstructural changes were associated with mechanical parameters in later tensile, hardness, and impact assessments. The tensile test showed that a hypereutectic alloy had exceptional ductility, making it suitable for flexible applications. The hypoeutectic alloy had superior yield strength and elastic modulus, making it suitable for structural applications. Pure zinc, despite having lower strength and modulus, showed enhanced ductility due to its larger grain structure. The Izod impact test showed that both Zn-Al alloys and pure zinc absorbed minimal energy, making them brittle for impact-sensitive applications. Pure aluminium showed more energy absorption, indicating enhanced durability. The research highlights the importance of alloy composition, microstructure, and casting conditions in enhancing materials for applications in sectors like automotive, aerospace, and die-casting.

1. Introduction

Zn-Al alloys have several extremely appealing qualities that make them ideal for a variety of industrial applications, including the production of automobile components, electronic/electrical systems, water taps and sanitary fittings, home articles, fashion products, and more. This is due to Zn's lower melting temperature than Al and its unique mix of mechanical qualities, such as tensile strength, elongation, and hardness [1-2].

Zinc is an abundant metal found in the Earth's crust, having several commercial and biological applications. At room temperature, Zinc is brittle and blue, white, but it may be polished to a dazzling shine. Zn alloys, particularly Zn–Al alloys, highlight numerous significant aspects of their characteristics and applications. These alloys are recognized for their appropriateness in diverse industrial applications owing to their appealing amalgamation of mechanical qualities, including tensile strength, hardness, and elongation. This renders them optimal for manufacturing components in automobile parts, electronic systems, and domestic products [3-4].

An important feature examined is the microstructural evolution of these alloys, especially under transient heat flow circumstances. The microstructure, often comprising eutectic colonies of Zn and Al phases, is essential as it affects the mechanical properties and performance of the alloy under varying temperature conditions. The

cooling rate and the composition of the alloy significantly influence microstructural morphology and hardness [5].

Zinc-aluminum (Zn-Al) eutectic alloys are increasingly recognized as versatile materials, providing a distinctive amalgamation of mechanical, chemical, and electrochemical properties suitable for numerous innovative applications. Their lamellar microstructure, defined by alternating layers of zinc and aluminum, confers a notable benefit in mechanical performance, encompassing improved tensile strength, ductility, and hardness. This shape is essential in electrochemical applications, since it facilitates effective zinc stripping and plating, substantially reducing dendrite development during battery cycling. Dendrite suppression is crucial in zinc-based aqueous rechargeable batteries, as dendrites can lead to short circuits and diminish battery longevity and reliability [6].

Studies indicate that the cooling rate during the solidification of Zn-Al alloys significantly affects their microstructure. Accelerated cooling rates yield a more refined and uniform microstructure, hence augmenting hardness, tensile strength, and corrosion resistance. The incorporation of alloying elements, including copper or rare earth metals, can enhance the microstructure, resulting in enhanced mechanical qualities and increased heat and wear resistance. These improvements expand the utility of Zn-Al eutectic alloys in challenging industrial and structural contexts [6-9].

Moreover, Zn-Al eutectic alloys demonstrate remarkable oxidation resistance, chiefly attributable to the development of a persistent aluminum oxide (Al_2O_3) layer on their surface. This protective oxide layer serves as a barrier against additional oxidation and environmental deterioration, guaranteeing longevity and sustained performance even in extreme conditions. Zn-Al alloys possess a characteristic that renders them especially appropriate for applications necessitating elevated corrosion resistance, including sacrificial coatings for steel or components subjected to severe environmental conditions [8]. In the energy sector, Zn-Al eutectic alloys are promising candidates for next-generation anode materials in high-performance batteries. Their lamellar microstructure promotes energy efficiency and maintains dependability during many charge-discharge cycles. These alloys demonstrate potential as substitutes for conventional anode materials in batteries, providing a more ecological and economical alternative [6].

The future of Zn-Al eutectic alloys depends on enhancing their properties by improvements in processing methods and alloy design. Regulated cooling rates, exact alloying element incorporations, and advanced fabrication techniques like additive manufacturing can further improve their performance. Furthermore, further investigation into their microstructural evolution, mechanical characteristics, and electrochemical behavior will facilitate their customized application in certain domains, including automotive components, electronic systems, and high-temperature soldering's-Al eutectic alloys are a potential category of materials that reconcile functionality, cost-effectiveness, and sustainability. Their capacity to function in various applications while reducing environmental effects highlights their significance as a fundamental element in future materials engineering and energy solutions [7-10].

2. Materials and Methods

2.1 Materials

The evaluation of raw materials for the production of zinc-aluminum eutectic alloys emphasizes quality and sustainability. Recycled zinc, derived from discarded dry-cell battery casings, and recycled aluminium, collected from plant-based labels, constitute the principal raw components. The zinc covers are meticulously detached from the batteries via physical disassembly, guaranteeing minimal contamination from other battery constituents, including carbon rods and manganese dioxide. The covers are subsequently cleansed with water to eliminate contaminants, ensuring the purity necessary for alloy manufacturing. The aluminium tags are selected for their flat, rectangular shape, which enhances melting and mixing efficiency during casting. They undergo a stringent sorting procedure to remove contaminants like plastics or other metals, hence improving material quality.

The characterization of these materials employs sophisticated analytical methods, such as Energy Dispersive X-Ray Spectroscopy (EDS) and X-Ray Diffraction (XRD), to verify their elemental composition and crystalline structure. This guarantees that the raw materials conform to the requisite standards for manufacturing superior alloys. The preparation method matches sustainability goals, as utilizing recycled materials diminishes environmental effect by reducing waste and decreasing dependence on virgin resources. This strategy illustrates a balance between attaining superior material qualities and fostering environmentally sustainable procedures.

2.2 Fabrication of Zinc, Aluminium, Eutectic, Hypereutectic and Hypoeutectic

The fabrication of zinc-aluminium eutectic alloys commences with the procurement of essential raw materials, chiefly recycled aluminium and zinc. The aluminium utilized is derived from plant-based aluminium tags, chosen for their lightweight, corrosion-resistant characteristics and recyclability. These attributes render aluminium appropriate for the sand-casting process, as it provides a low melting point, ease of manipulation, and little impurities that could otherwise undermine the alloy's integrity. The zinc component is derived from abandoned battery casings, an eco-friendly approach that minimizes waste by repurposing materials that would otherwise be disposed of. Prior to alloying, the zinc undergoes meticulous cleaning and is assessed for purity by Energy Dispersive X-ray Spectroscopy (EDS), guaranteeing it conforms to the requisite composition devoid of impurities.

Upon preparation of the raw components, the subsequent phase involves a meticulously regulated melting procedure. The zinc and aluminium are accurately measured to guarantee the appropriate material ratio. (Table 1). The electric melting furnace (CN, G235) employed in this method is calculated to precise temperatures to guarantee consistent melting of both metals, as the eutectic point of zinc-aluminium alloys is notably sensitive to temperature variations. Molten metal is put into preheated molds to ensure uniform temperatures and is cooled gradually to prevent internal stress that may result in flaws. In the cooling process, the metal hardens into ingots. The ingots are further scrutinized for any apparent faults or surface anomalies. All oxidation on the surface is eliminated, guaranteeing that the finished product is pristine and devoid of contaminants that may influence its characteristics.

Once the ingots are cleansed and polished, they are molded into sheets, which are subsequently ready for further examination. Microstructural analysis is crucial to the procedure, as it guarantees the alloy satisfies particular mechanical and physical specifications. Optical microscopy and scanning electron microscopy (SEM) are utilized to examine the composition, phase distribution, and crystalline structure of the alloy. These techniques offer comprehensive insights into the microstructure, aiding in the assessment of the alloy's quality and its anticipated performance in applications. The meticulous selection of components, exact fabrication methods, and comprehensive testing protocols guarantee that the generated zinc-aluminium eutectic alloys are of superior quality, conforming to all requisite criteria for subsequent processing and utilization in diverse industrial applications.

Table 1 *Aluminium and zinc wt.% composition data for 8 ingots*

Sample	Al%	Zn %	Zn(g)	Al(g)
Zn	0	100	968.68	0
Al	100	0	0	386.56
Hypoeutectic	97	3	940.59	11.06
Eutectic	95	5	921.20	18.43
Hypereutectic	93	7	901.80	25.80

The fabrication of zinc-aluminium alloy ingots necessitates precise electric melting furnace (CN,G235) procedures to attain ideal melting, blending, and casting outcomes. Zinc and aluminium are meticulously measured to achieve specified compositions, such hypoeutectic, hypereutectic and eutectic. The furnace is preheated to designated temperatures 450–500°C for zinc and 660–700°C for aluminium. Zinc is initially melted, after which aluminium is incrementally added, maintaining the temperature at 500–550°C to ensure the complete dissolution of aluminium. Homogeneity is attained via constant agitation using a heat-resistant stirrer.

After the alloy is completely blended, the molten substance is put into prepared molds to guarantee uniform filling. The molds are thereafter permitted to cool slowly at ambient temperature, reducing the likelihood of internal tensions or imperfections. Upon solidification, the ingots are meticulously extracted and examined for defects, including voids or fractures. The final process entails cleansing the ingots to eliminate any oxidation or residual flux, yielding high-quality alloy ingots prepared for further characterization and application. This meticulous method ensures dependable and uniform material characteristics, crucial for sophisticated engineering and industrial applications.

2.3 Microstructure Analysis

The alloy's microstructure was analyzed using an optical microscope (OM)(Nikon Eclipse LV150NL), while its phase composition was assessed via scanning electron microscopy (SEM)(Hitachi Su-1510) (Fig. 1(b)) combined with energy dispersive spectroscopy (EDS). X-ray diffraction (XRD) was utilized to ascertain the atomic and

molecular structure of the alloy (SEM-EDS). X-ray Energy Dispersive Spectroscopy (EDS, EDX, or XEDS) is a qualitative and quantitative microanalytical technique employed to determine the chemical composition of a material. This approach is efficacious for elements with an atomic number (Z) exceeding three, or Z more than two for particular sample and equipment combinations. The sample undergoes analysis using an electron beam emitted by the SEM, which interacts with the material's atoms. The generated X-rays are detected by the energy dispersive detector, which presents the data as a spectrum illustrating intensity versus energy. The energies of characteristic X-rays determine the elements, whereas their intensities measure the concentrations. The size of the interaction volume, influencing spatial resolution, is dictated by the accelerating voltage and the sample's mean atomic number, Z.

The XRD technique, conversely, ascertains a material's atomic and molecular structure by subjecting the sample to X-rays and evaluating the intensities and scattering angles of the dispersed X-rays. The diffraction peaks elucidate the interatomic or intercrystallite spacing within the substance. Narrow peaks imply larger crystals, whereas broad peaks signify smaller crystals, structural defects, or amorphous conditions. Diffraction patterns can be analyzed against reference databases to ascertain chemical composition and structural characteristics.

OM (Fig. 1(a)) employs visible light and lenses to enlarge and analyze tiny objects. It is adaptable and extensively utilized in disciplines like biology, materials science, and physics. Optical microscopy techniques, including bright-field, dark-field, phase-contrast, and fluorescence microscopy, yield diverse information regarding the specimen's morphology, texture, and structural characteristics. Optical microscopy has made substantial progress in recent years, facilitating high-resolution imaging and dynamic monitoring of biological phenomena in four dimensions (xyz + time), in addition to label-free quantitative phase imaging. These analytical techniques, SEM with EDS, XRD, and OM, provide complementary approaches for elucidating the microstructure, content, and molecular configuration of materials, allowing researchers to obtain extensive data regarding the samples examine


(a) **(b)**
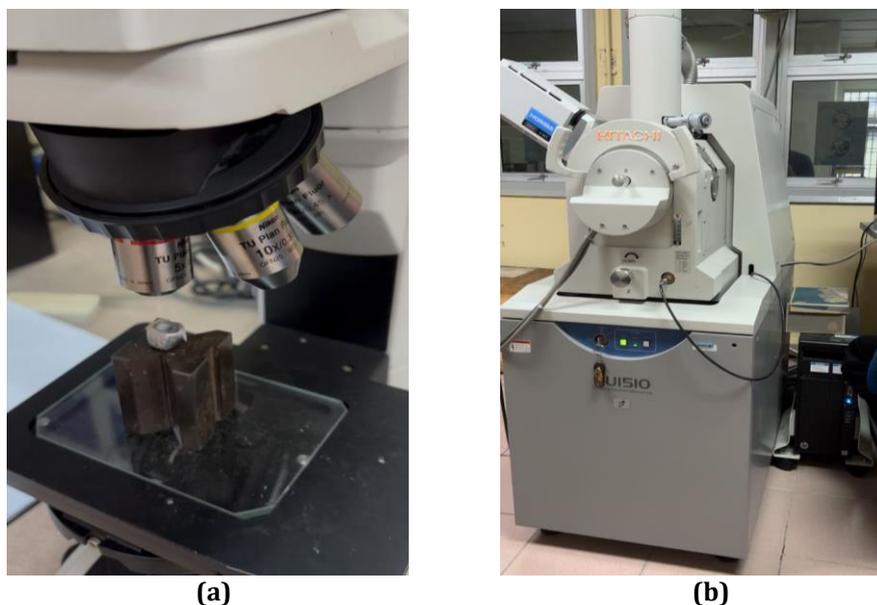
Fig. 1: *(a) Optical Microscopy (OM) ;(b) Scanning Electron Microscopy (SEM)*

2.4 Mechanical Testing

Mechanical testing is essential for evaluating the performance and appropriateness of materials like zinc-aluminum eutectic alloys, renowned for their superior mechanical strength, corrosion resistance, and thermal characteristics. This study encompassed three essential mechanical tests: tensile testing, Vickers hardness testing, and impact testing, to thoroughly assess the alloy's mechanical properties.

The Izod impact test evaluated the alloy's toughness and energy absorption capacity during sudden impacts, replicating real-world situations involving abrupt loading. Standard specimens featuring a V-notch were impacted by a pendulum at a designated energy level, and the absorbed energy was quantified. This examination disclosed the alloy's fracture characteristics and energy absorption capability, which are critical for applications necessitating impact resistance.

Tensile testing was performed to ascertain essential characteristics including ultimate tensile strength (UTS), yield strength, and elongation at break. These measures offer insight into the material's capacity to endure stresses and deform without failing, crucial for comprehending its strength and ductility. Standard dog-bone shaped specimens (Fig. 2) were evaluated utilizing a universal testing machine (UTM) (Figure 3) under uniaxial tensile stress. The resultant stress-strain curve emphasized the alloy's load-bearing capacity and deformation properties, informing its use in structural and engineering applications.
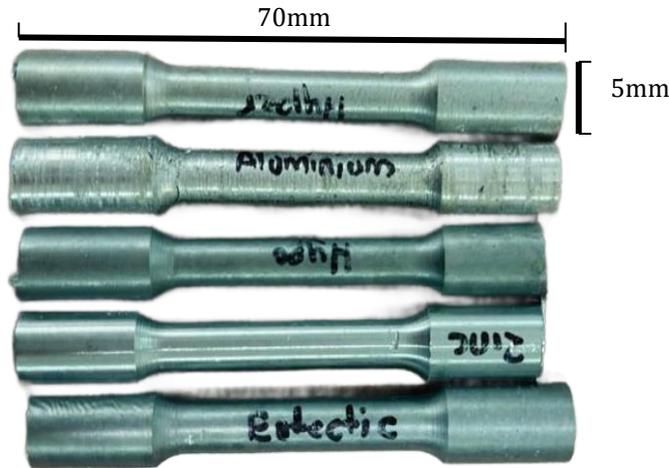

Fig. 2: *Dog-bone shape specimen*
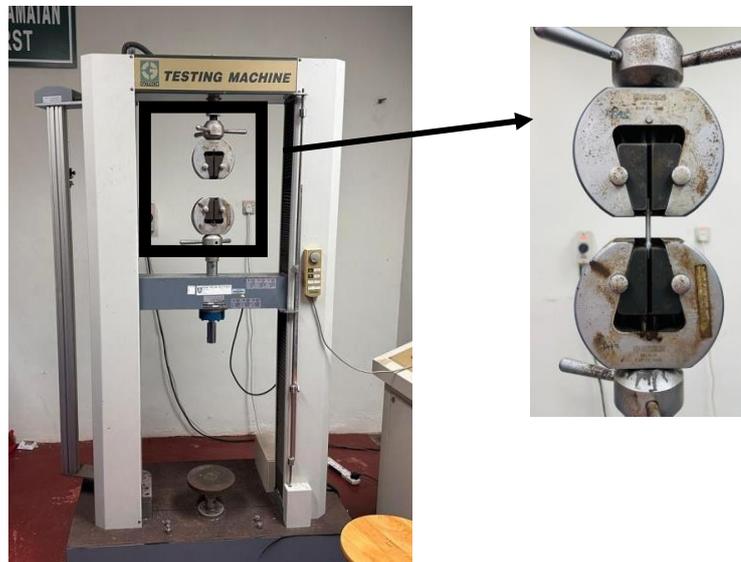
Fig. 2: *Universal Testing Machine (UTM)*

The Vickers hardness test was employed to assess the material's hardness, a crucial determinant of wear resistance and durability. Polished specimens were depressed using a diamond pyramid (Fig. 3) under a specified force, and the resultant indentation was measured to determine the Vickers hardness number (HV). This test yielded essential data regarding the alloy's resistance to surface deformation, facilitating forecasts about its performance in conditions characterized by abrasion or surface stress.

A full understanding of the properties of the zinc-aluminum eutectic alloy was attained through the integration of various mechanical experiments. The results confirmed the material's applicability for many applications and established a basis for optimizing alloy composition and processing processes to further enhance its performance. These findings are crucial for the development of high-performance materials in industrial and engineering applications.
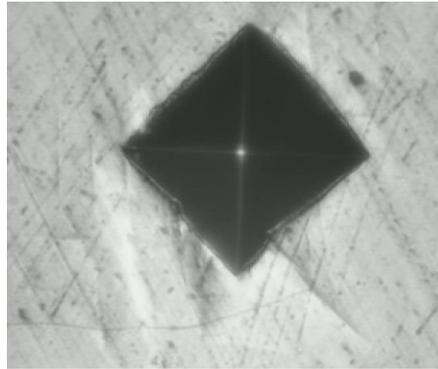
Fig. 3: *diamond pyramid indentation*

3. Results and Discussion

3.1 Microstructure analysis

The XRD stacked data (Fig. 4) elucidated the phase composition and crystalline structure of the alloys. Distinct diffraction peaks at 30°, 34°, and 39° 2θ validated the existence of the α-Zn phase with a hexagonal close-packed (hcp) structure, demonstrating high crystallinity attributed to the reduced cooling rates characteristic of sand casting. The larger peaks linked to eutectic phases signified finer grains and heightened defect density. The sand-casting technique facilitated the development of coarse primary α-Zn grains and finer eutectic structures, which influenced the mechanical characteristics. The course α-Zn phase boosted overall strength, whereas the refined eutectic intermetallic structures enhanced ductility and toughness. Nonetheless, casting-induced imperfections like porosity functioned as stress concentrators, potentially diminishing tensile strength.
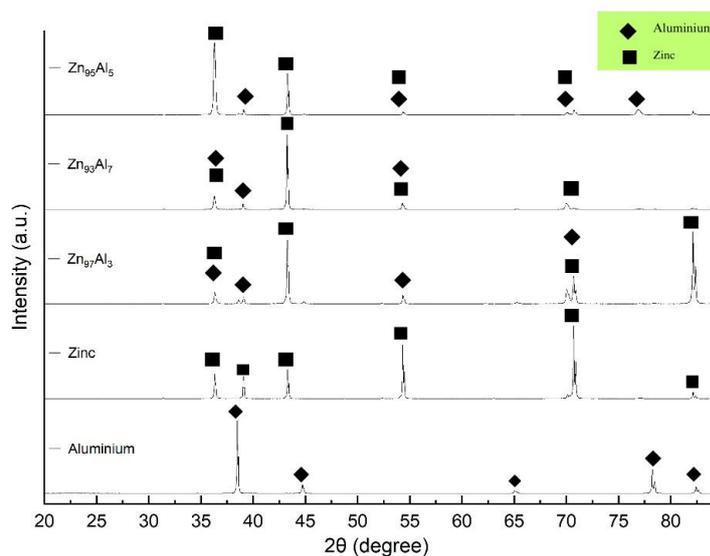

Fig. 4: *XRD stacked data*

The integrated SEM, EDS, and XRD investigations clarified the microstructural and compositional attributes of sand-cast Zn-Al alloys, illustrating the impact of reduced cooling rates and compositional variations on phase stability and mechanical properties. Refining casting parameters may improve the microstructure, diminish flaws, and augment the alloy's strength and ductility for industrial applications.

The microstructural study of sand-cast zinc-aluminum alloys was performed by applying OM on polished and etched specimens, elucidating the effects of alloy composition, cooling speeds, and sand-casting parameters. Etched aluminium (Fig. 5(a)) exhibited smooth surfaces with distinct grain boundaries post-etching, revealing non-uniform grain sizes and shapes resulting from uneven cooling. This variability suggested bigger grains that diminish strength and fracture resistance. In etched zinc (Fig. 5(b)), optical microscopy revealed polygonal

grains with twin boundaries and slip bands typical of its hexagonal close-packed (HCP) structure, indicating slower cooling rates and enhancing ductility and machinability.

(a)   **(b)**
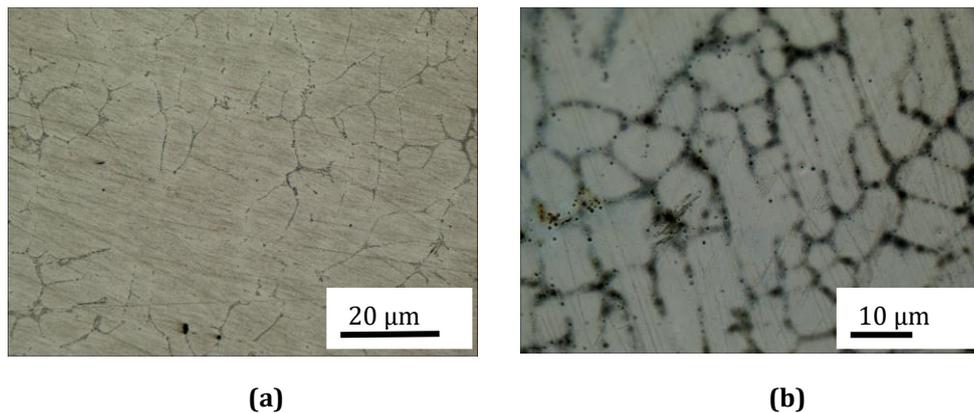
Fig. 5: *(a)aluminium after etched 500x ;(b) zinc after etched 1000x*

Eutectic alloys (Fig. 6 (c)) examined via optical microscopy displayed alternating lamellae of α (aluminum-rich) and β (zinc-rich) phases, signifying rapid cooling and a refined microstructure that optimized strength and ductility. Microporosity, characteristic of the sand-casting process, was apparent. Hypereutectic alloys (Fig. 6 (a)) exhibited prominent primary zinc-rich dendrites encircled by a finer eutectic matrix, indicating gradual cooling that enhanced ductility but diminished strength due to the coarse grain structure. Hypoeutectic alloys (Fig. 6 (b)) exhibited distinct dendritic structures and grain boundaries, indicating elevated aluminium content and regulated cooling, hence improving strength and toughness.

(a)   **(b)**   **(c)**
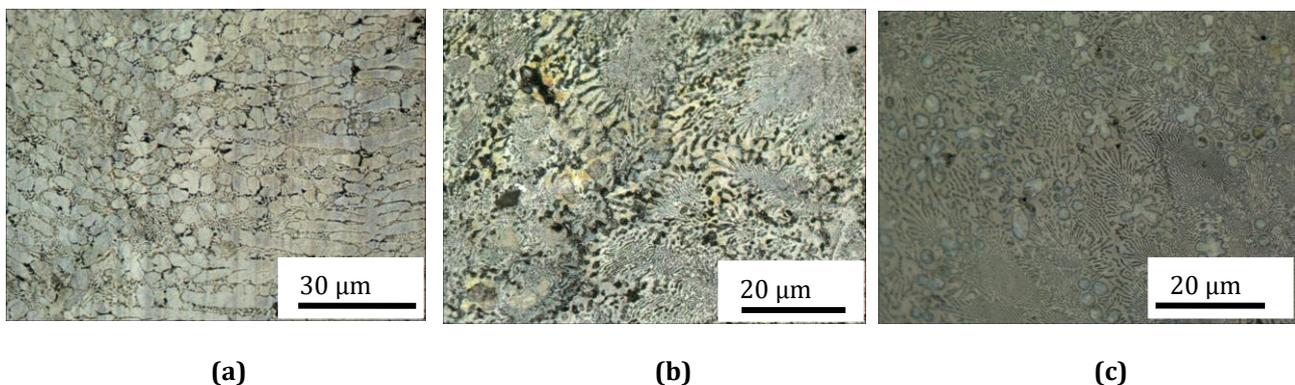
Fig. 6: *(a)Hypereutectic after etched 300x; (b)Hypoeutectic after etched in 500x ;(c) Eutectic after etched in 500x*

OM observations of all alloys revealed microstructural defects, including porosity and segregation, characteristic of the sand-casting process. The refined and consistent microstructures of eutectic and hypoeutectic alloys enhance mechanical qualities, whereas hypereutectic alloys prioritize machinability at the expense of strength. The results underscore the significance of employing OM for comprehensive microstructural analysis and the necessity of optimizing casting parameters to reduce flaws and attain the requisite mechanical qualities suited to particular applications.

The microstructure of zinc-aluminum eutectic alloys was examined by SEM and EDS to uncover essential structural and compositional characteristics affected by sand-casting parameters. The SEM micrographs (Fig. 7) of the eutectic alloy revealed a distinct lamellar structure of alternating aluminum-rich (α-phase) and zinc-rich (β-phase) layers, indicative of eutectic solidification. This configuration arises from concurrent crystallization during cooling and improves mechanical attributes, including wear resistance and isotropic strength. Hypereutectic alloys exhibited pronounced zinc-rich dendrites encircled by eutectic mixtures, whilst hypoeutectic alloys presented primary aluminium dendrites mixed with eutectic zones, both demonstrating distinct solidification patterns. EDS examination validated the alloy compositions, with zinc and aluminium as predominant elements, closely according to phase diagram forecasts. Secondary peaks of oxygen and carbon indicated surface oxidation and contamination, perhaps from sand molds or handling during casting. The SEM and EDS results emphasized the significance of casting circumstances, including cooling rates and mold interactions, in influencing grain structure, phase distribution, and porosity, indicating opportunities for optimization to improve mechanical and structural qualities.
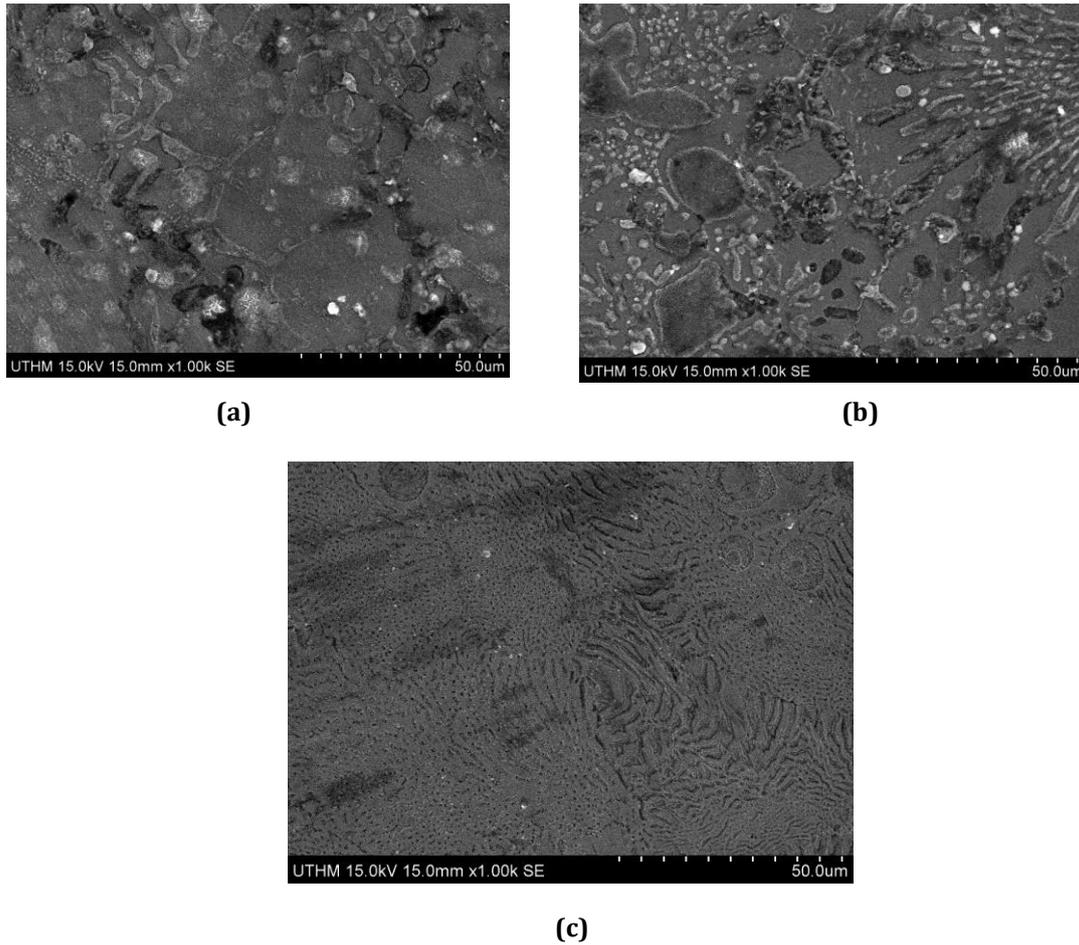
(a)

(b)

(c)

Fig. 7: *(a)Hypoeutectic ;(b) Hypereutectic ;(c) Eutectic*

3.1 Mechanical testing analysis

The tensile test study of aluminium, hypoeutectic, hypereutectic, eutectic and zinc (Table 2) demonstrates considerable differences in mechanical properties attributable to composition and alloying influences. Aluminium exhibits superior stiffness (Elastic Modulus: 15,680.80 MPa) and yield strength (54,866.10 kN/m^2), making it ideal for structural applications necessitating high rigidity. Hypereutectic has superior ductility (Elongation: 5.38 mm) and maximum stress (372.02 MPa), underscoring its capacity to withstand deformation under substantial loads, making it suitable for forming procedures. Hypoeutectic demonstrates the highest Elastic Modulus (20,128.69 MPa) and yield strength (82,083.452 kN/m^2) among the alloys, indicating a substantial enhancement in Zinc's mechanical properties with minimum Aluminium incorporation.

Eutectic, exhibiting the lowest stiffness (Elastic Modulus: 1,567.35 MPa), offers improved flexibility for applications requiring intermediate strength and ductility. Pure Zinc has moderate stiffness (Elastic Modulus: 2,093.64 MPa), yield strength (47,256.365 kN/m^2), and favourable elongation (1.16 mm), rendering it appropriate for malleable die-casting applications. These findings underscore the significance of alloy composition and cooling rates in affecting tensile characteristics, offering critical insights for the optimization of materials to satisfy industrial demands.

Table 2: *Tensile Test Data*

Sample	Elongation (mm)	Elastic Modulus (MPa)	Yield Strength (kN/m^2)	Maximum strain (%)
Aluminium	0.72	1.568×10^4	54866.10	2.407
Eutectic	4.07	1.567×10^4	-	13.577
Hypereutectic	5.38	1.50×10^4	-	17.932
Hypoeutectic	0.56	2.0128×10^4	82083.452	1.869
Zinc	1.09	2.093×10^4	47256.365	3.632

The Izod impact test findings underscore the toughness properties of different materials, demonstrating their capacity to absorb energy at sudden impact. The Zn-Al alloys in addition to pure zinc, absorbed 0 Joules of energy, demonstrating their brittle characteristics under impact loading. Conversely, aluminium absorbed 1 Joule of energy, demonstrating its better toughness compared to the other materials evaluated.

The brittleness of Zn-Al alloys, demonstrated by their failure to absorb substantial energy during testing, can be ascribed to their microstructure, characterized by a high concentration of intermetallic compounds. These compounds increase hardness and strength but diminish the material's ability for plastic deformation under abrupt stress. The consistency of energy absorption across all alloy compositions indicates that fluctuations in aluminium content (3%-7%) have little effect on their impact resistance. The intrinsic brittleness of Zn-Al alloys makes them inappropriate for applications subject to impact loads or sudden stress situations.

Pure zinc also absorbed 0 Joules, consistent with its established brittle properties. The poor ductility and hardness of zinc lead to minimal energy absorption during impact loads, indicating its vulnerability to fracture and its inadequacy for applications requiring high toughness. In contrast, aluminium exhibited the potential to absorb 1 Joule of energy, highlighting its ductility and propensity for plastic deformation, which facilitates energy dispersion and averts catastrophic collapse. The toughness of aluminium renders it a favored material for applications necessitating impact resistance and structural integrity, particularly in transportation and aerospace components.

These findings underscore the fragility of Zn-Al alloys and pure zinc in contrast to the comparative durability of aluminium. Although Zn-Al alloys and zinc have superior hardness and strength, their deficiency in toughness limits their applicability in impact-sensitive contexts. The versatility and resilience of aluminium render it ideal for situations requiring a combination of strength, toughness, and ductility.

The Vickers hardness test on sand-cast zinc specimens provides essential insights into their resistance to plastic deformation. The assessments performed using an HMV-2 hardness tester at a load of 980.7 mN for 10 seconds, yielded hardness values ranging from 63.24 HV to 64.88 HV, with an average of 63.64 HV. A standard deviation of 0.835 HV and a coefficient variation of 1.84% signify substantial consistency and uniformity in the data. These results indicate the consistent microstructure attained with the sand-casting method, albeit with its prolonged cooling rates.

The assessed hardness corresponds with the inherent characteristics of pure zinc, recognized for its ductility and malleability. A hardness of roughly 63-64 HV indicates that zinc may experience considerable plastic deformation without fracture, rendering it appropriate for applications necessitating shaping and bending. Nonetheless, the coarse microstructure produced by slower cooling rates may diminish wear resistance. Enhancing casting characteristics, such as accelerated cooling or alloying, may improve Zinc's hardness and expand its engineering applications.

Vickers' hardness testing of aluminium under identical conditions produced results between 30.03 HV and 32.64 HV, with a mean of 31.89 HV. The standard deviation of 1.07 HV and a coefficient variation of 3.36% signify consistent results. These properties align with aluminum's inherent softness and ductility, making it suitable for lightweight and malleable applications. Nonetheless, its modest hardness restricts its application in high-abrasion settings. Process optimization or alloying can improve aluminum's mechanical characteristics, increasing its applicability for more rigorous applications.

The Vickers hardness test for the eutectic illustrates its well-rounded mechanical properties. The hardness values varied from 68.29 HV to 73.35 HV, with a mean of 71.03 HV. The results indicate that the eutectic alloy possesses a finely interwoven dual-phase microstructure, which impedes dislocation migration and increases hardness. The uniformity of output underscores competent management of the sand-casting process and the lack of substantial flaws.

The increased hardness of the eutectic alloy relative to pure metals such as aluminium or zinc highlights the impact of its microstructure. The closely arranged eutectic phases improve strength while preserving mild toughness. These attributes render the alloy appropriate for applications necessitating a balance of hardness and ductility. Future endeavors to improve the microstructure by optimized casting methods or modifications in alloy composition may further augment its mechanical capabilities.

The experimental findings indicate that zinc and Zn-Al alloys possess elevated hardness but restricted toughness, whereas aluminium displays moderate hardness and enhanced toughness. The sand-casting technique efficiently generates uniform microstructures; nevertheless, reduced cooling rates constrain enhancements in hardness. It is advisable to implement process optimization and allow for improvement of the mechanical properties of these materials, hence expanding their use in engineering and industrial settings.

3.1.1 Tensile test microstructure

The aluminium tensile test indicated a peak stress of 70.49 MPa, a yield strength of 54.87 kN/m², an elastic modulus of 15,680.80 MPa, and a maximum strain of 2.407%. The stress-strain curve displayed a clear elastic phase succeeded by plastic deformation, signifying ductile behavior. Necking transpired subsequent to attaining

peak stress, a hallmark of aluminium alloys subjected to tensile loading. The elongation at maximum load was 0.72 mm, while the elongation at break was 1.52 mm, indicating substantial plastic deformation prior to failure. The results underscore the equilibrium between ductility and strength in the sand-cast aluminium specimen, making it appropriate for applications necessitating both properties. Nonetheless, poor elongation values indicate the presence of microstructural flaws or inclusions, which may impair its deformation capacity.
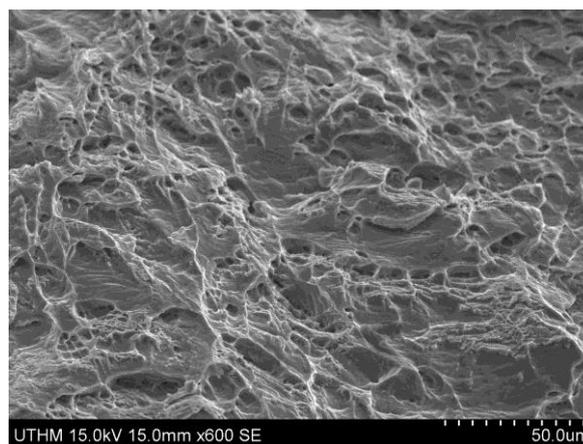
The SEM micrograph (Fig. 8) of the fracture surface exhibited a dimpled structure indicative of ductile failure, with micro voids signifying coalescence during deformation. Dimples of differing dimensions indicated substantial plastic deformation in extensive regions, whilst smaller dimples emphasized localized stress concentrations. Rugged fracture surfaces exhibited significant plastic deformation prior to failure, and directional dimples indicated stress orientation. Casting faults like porosity or inclusions, prevalent in sand-casting methods, manifested as voids or irregular cavities, acting as stress concentrators that diminished ductility and strength. The tensile test and SEM results underscored the necessity of optimizing the casting process to reduce flaws and enhance mechanical performance.
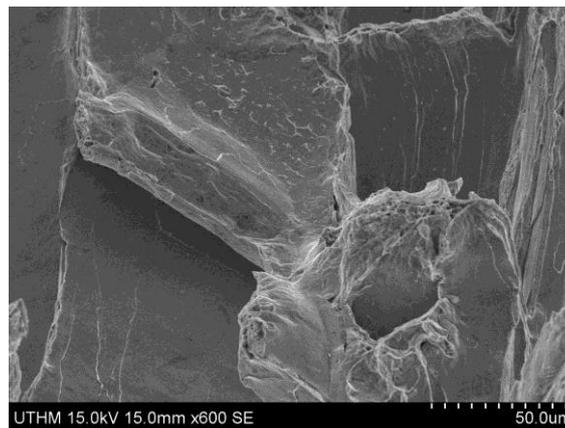
Fig. 8: *Aluminium tensile micrograph*

The zinc tensile test indicated a yield strength of 47.26 kN/m^2, a maximum stress of 71.45 MPa, an elastic modulus of 2,093.64 MPa, a failure strain of 3.632%, and a break elongation of 1.16 mm. The stress-strain curve exhibited an elastic phase succeeded by plastic deformation, signifying substantial ductility. Notwithstanding zinc's usual brittle failure, the curve indicated localized necking or microstructural deformation prior to fracture, consistent with the characteristics of sand-cast zinc affected by coarse grains and porosity.
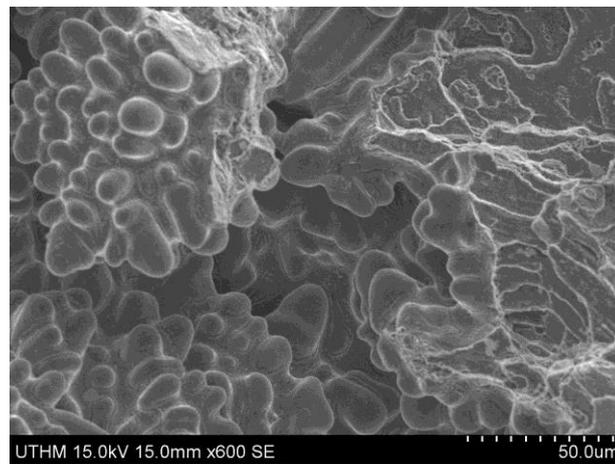
The SEM micrograph (Fig. 9) of the fracture surface revealed both intergranular and trans granular features, indicating a mixed-mode fracture. Smooth surfaces suggested brittle intergranular fracture, whereas rough, jagged edges with dimples showed ductile trans granular tearing. The cleavage planes linked to zinc's hexagonal close-packed structure highlight its inherent brittleness under tensile stress. Porosity and voids, presumably resulting from the sand-casting process, were apparent as stress concentrators that facilitated crack propagation. The mixed-mode fracture and low ductility underscored the impact of coarse grains and casting flaws, accentuating the constraints of sand-cast zinc for structural applications.

Fig. 9: *Zinc tensile micrograph*

The SEM micrograph (Fig. 10) of the eutectic specimen exhibited a dual-phase microstructure characteristic of eutectic materials, markedly affecting its mechanical properties under tensile stress. The fracture surface displayed dimples characteristic of ductile failure resulting from micro void coalescence. A fibrous structure emphasized plastic deformation inside the matrix, absorbing energy prior to fracture. Smoother regions on the fracture surface signified brittle failure in the harder phase, illustrating the interaction of brittle and ductile properties.

Phase interfaces served as stress concentration locations during tensile loading, corresponding to eutectic lamellae or colony borders. The mechanical behavior was dictated by the interplay between soft and hard phases; the softer phase absorbed energy and impeded crack propagation, whilst the harder phase originated or advanced cracks. This study highlighted the want for additional examination of composition, phase distribution, and tensile testing settings to enhance the material's performance and comprehend its failure causes.

Fig. 10: *Eutectic tensile micrograph*

The fracture surface of the hypereutectic specimen (Fig. 11) exhibited characteristics characteristic of hypereutectic alloys cast in sand. Coarse primary particles scattered inside the eutectic matrix were observed, attributable to sluggish cooling rates during sand casting. These particles enhanced strength while also acting as stress concentrators during tensile loading. Dimples and ripping ridges on the softer eutectic matrix indicated significant plastic deformation, but the brittle fracture of hard primary particles highlighted their rigidity and susceptibility to crack propagation.

The coarse microstructure, marked by broader eutectic phase intervals and larger primary particles, diminished strength while somewhat improving ductility. Casting flaws like porosity, commonly linked to sand casting, were evident as voids on the fracture surface, acting as locations for crack initiation. The dual behavior, shaped by the interactions between the rigid primary phase and the pliable eutectic matrix, underscored the constraints of sand-cast hypereutectic alloys for structural applications. Enhancing the casting process may reduce flaws and elevate the material's mechanical properties.
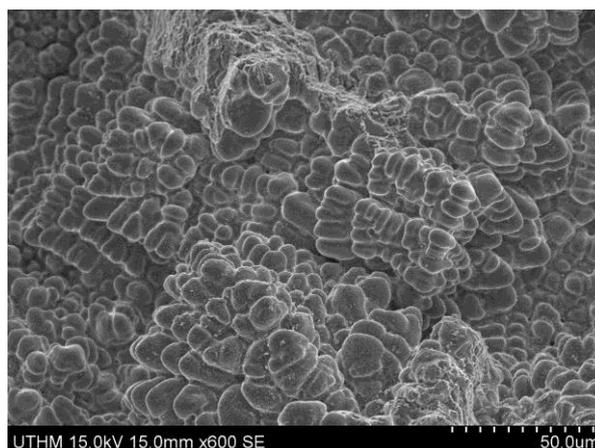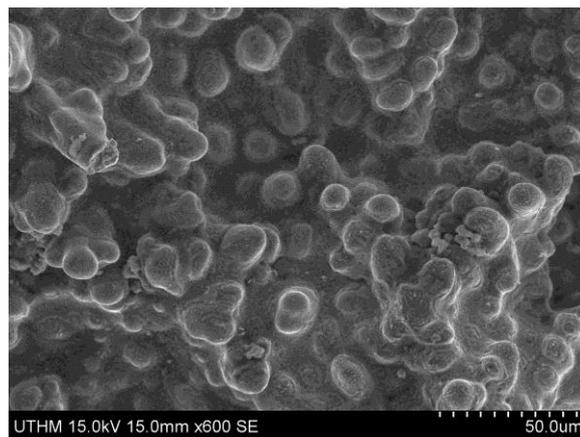

Fig. 11: *Hypereutectic tensile micrograph*

The SEM micrographs (Fig. 12) of the hypoeutectic tensile specimen exhibit a microstructure characterized by coarse proeutectoid phase particles encircled by a finer eutectic matrix. The sand-casting process substantially affects this structure, as reduced cooling rates result in the development of big, irregular proeutectoid grains and a widely dispersed eutectic phase filling interstitial gap. The dual-phase structure is clearly evident, with the proeutectoid phase exhibiting a rough and uneven texture, whereas the eutectic phase has a smoother and finer appearance.

The fracture surface reveals both ductile and brittle failure mechanisms. The eutectic matrix demonstrates plastic deformation via dimples and ripping ridges, absorbing energy under tensile stress. Conversely, the more rigid proeutectoid phase undergoes brittle fracture, with cracks originating at the phase boundaries due to disparities in mechanical properties. The fissures extend into the proeutectoid phase, leading to localized failure.

Slower cooling rates in sand casting result in a coarse microstructure that diminishes tensile strength while potentially increasing ductility. Nonetheless, the technique may also induce porosity or inclusions, so compromising the material's integrity. Refining casting parameters is crucial for enhancing the microstructure and mechanical properties of hypoeutectic alloys.

Fig. 12: *Hypoeutectic tensile micrograph*

4. Conclusion

The study evaluated the mechanical characteristics, microstructure, and sustainability of zinc-aluminum eutectic alloys produced from recycled components via sand casting. It found that by regulating essential elements like alloy composition, melting techniques, and cooling rates, alloys with enhanced mechanical properties, including elevated tensile strength, ductility, and hardness, can be achieved. These alloys are competitive with conventional metals commonly used in industrial applications, offering a sustainable alternative to traditional materials. The research aimed to enhance the production process of these alloys through sand-casting to obtain uniform and superior microstructures across various alloy compositions. The findings showed a significant association between the alloy's microstructure and its mechanical properties, providing critical insights into the design and production of high-performance alloys derived from recycled materials. The study suggests further research in multiple domains, including long-term performance assessments under various climatic conditions and cyclic loads, incorporating additional alloying elements, refining casting methods, and advancing manufacturing processes like additive manufacturing. Future studies should focus on evaluating the alloys' long-term performance, comparing manufacturing costs and ecological advantages with traditional metals, and investigating the integration of alternative alloying elements and advanced production techniques.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

References

[1]   Brady, G. S. ,George S., Clauser, H. R., & Vaccari, J. A. (2002). Materials handbook: an encyclopedia for managers, technical professionals, purchasing and production managers, technicians and supervisors. McGraw-Hill.

[2]   Wang.S.B. (2022). All about alloys. In *Nature Synthesis* (Vol. 1, Issue 2, p. 97). Nature Publishing Group. https://doi.org/10.1038/s44160-022-00036-1

[3]   Pola, A., Tocci, M., & Goodwin, F. E. (2020). Review of microstructures and properties of zinc alloys. In *Metals* (Vol. 10, Issue 2). MDPI AG. https://doi.org/10.3390/met10020253

[4]   Liu, Z., Li, R., Jiang, R., Li, X., & Zhang, M. (2016). Effects of Al addition on the structure and mechanical properties of Zn alloys. *Journal of Alloys and Compounds*, *687*, 885–892. https://doi.org/10.1016/j.jallcom.2016.06.196

[5]   Hammam, R. E., Abdel-Gawad, S. A., Moussa, M. E., Shoeib, M., & El-Hadad, S. (2023). Study of Microstructure and Corrosion Behavior of Cast Zn–Al–Mg Alloys. *International Journal of Metalcasting*, *17*(4), 2794–2807. https://doi.org/10.1007/s40962-022-00944-0

[6]   Zhai, Y., Wang, T., Liu, M., Zhou, N., & Li, X. (2024). Effect of Al Content on the Microstructure and Properties of Zn-Al Solder Alloys. *Metals*, *14*(6). https://doi.org/10.3390/met14060689

[7]   Pola, A., Tocci, M., & Goodwin, F. E. (2020). Review of microstructures and properties of zinc alloys. In *Metals* (Vol. 10, Issue 2). MDPI AG. https://doi.org/10.3390/met10020253

[8]   Kolenak, R., Kostolny, I., Drapala, J., Babincova, P., & Sahul, M. (2021). Characterizing the soldering alloy type zn–al–cu and study of ultrasonic soldering of al7075/cu combination. *Metals*, *11*(1), 1–18. https://doi.org/10.3390/met11010027

[9]   Septimio, R., Silva, C. A. P., Costa, T. A., Garcia, A., & Cheung, N. (2022). Hypereutectic Zn–Al Alloys: Microstructural Development under Unsteady-State Solidification Conditions, Eutectic Coupled Zone and Hardness. *Metals*, *12*(7). https://doi.org/10.3390/met12071076

[10]   Wang, S. B., Ran, Q., Yao, R. Q., Shi, H., Wen, Z., Zhao, M., Lang, X. Y., & Jiang, Q. (2020). Lamella-nanostructured eutectic zinc–aluminum alloys as reversible and dendrite-free anodes for aqueous rechargeable batteries. *Nature Communications*, *11*(1). https://doi.org/10.1038/s41467-020-15478-4