



ORIGINAL RESEARCH ARTICLE

AN ASSESSMENT OF THE INFLUENCE OF GRAIN REFINERS AND MODIFIERS ON THE PERFORMANCE CHARACTERISTICS OF ALUMINUM ALLOY (AA-2618) CASTINGS

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ABSTRACT

This study evaluates the influence of grain refiners and modifiers on the microstructure and mechanical performance of AA-2618 aluminum alloy castings. A titanium-based master alloy (Ti-Al) was employed as a grain refiner, while strontium chloride (SrCl<sub>2</sub>) was used as a chemical modifier. Each additive was introduced at 0.12 wt%, both individually and in combination, to investigate their effects on grain structure, eutectic phase morphology, and the resulting mechanical properties. Cast samples were produced under controlled conditions and characterized using optical microscopy and standard mechanical tests, including Brinell hardness, tensile strength, impact energy, and percentage elongation. The results from Microstructural analysis revealed that SrCl<sub>2</sub> modification significantly altered the eutectic morphology and refined the solidification structure, resulting in an average grain size reduction of approximately 28–32% compared with the untreated alloy. This refinement translated into improved mechanical performance, with tensile strength increasing from 141.76 MPa to 169.92 MPa (≈19.9% improvement), elongation increasing from 3.99% to 5.56% (≈39.3% improvement), and impact energy rising from 2.55 J to 2.58 J (≈2% improvement). In contrast, the addition of Ti-Al grain refiner alone resulted in reduced tensile strength (112.90 MPa) and impact energy (2.33 J), attributed to the formation of coarse TiAl<sub>3</sub> intermetallic particles that acted as crack initiation sites. However, the combined Ti-Al + SrCl<sub>2</sub> treatment did not exhibit synergistic behavior and produced the lowest hardness (53.57 HB) and tensile strength (93.58 MPa), indicating competitive interactions that hindered effective grain refinement and modification. Overall, the results demonstrate that strontium-based modification offers the most effective approach for enhancing the microstructural integrity and mechanical performance of AA-2618 aluminum alloy castings.

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1.0 Introduction

Aluminum alloys are extensively employed in modern engineering applications owing to their favorable combination of low density, high specific strength, excellent corrosion resistance, and good thermal and electrical conductivity (Gore et al., 2024; Davis, 2013). AA-2618 is a precipitation-hardenable aluminum alloy belonging to the Al-Cu-Mg alloy family and containing significant additions of copper, magnesium, nickel, and

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iron. These alloying elements promote precipitation strengthening and the formation of thermally stable intermetallic phases, which provide excellent high-temperature strength and creep resistance (Zhang *et al.*, 2021; Li *et al.*, 2022). Due to its ability to retain mechanical strength at elevated temperatures and resist fatigue under cyclic loading, AA-2618 is widely used in aerospace and high-performance automotive components, including aircraft engine parts, compressor blades, and high-temperature engine pistons (Kumar & Prasad, 2020; Chen *et al.*, 2023). Because the mechanical performance of this alloy is closely linked to its microstructure and precipitation behavior, investigations into grain refinement and microstructural modification are important for improving its mechanical properties, reliability, and service performance in demanding applications (Li *et al.*, 2022; Chen *et al.*, 2023). However, despite their widespread use, AA-2618 castings are highly susceptible to defects arising during melting and solidification, such as porosity, segregation, and hot tearing, which remain major challenges in foundry operations (Gore *et al.*, 2024; Samuel *et al.*, 2023).

Casting defects such as porosity, shrinkage cavities, hot tearing, oxide inclusions, and gas entrapment significantly compromise the mechanical integrity and service reliability of aluminum cast components (Gariboldi *et al.*, 2015; Akhyar *et al.*, 2017). These defects are commonly associated with inadequate melt treatment, uncontrolled solidification conditions, and unfavorable microstructural characteristics, particularly coarse and non-uniform grain structures (Samuel *et al.*, 2014; Jolly, 2022). The presence of such defects often results in reduced strength, poor ductility, premature failure, and increased rejection rates, thereby escalating production costs.

To address these challenges, the application of additives and grain refiners has emerged as an effective metallurgical approach for mitigating casting defects and improving the overall quality of aluminum alloy castings (Fracchia *et al.*, 2021; Berlanga-Labari *et al.*, 2020). Grain refiners' function by enhancing heterogeneous nucleation during the early stages of solidification, producing finer and more uniform grain structures that reduce shrinkage tendencies and improve mechanical performance. Fine-grained microstructures also limit crack propagation and lower susceptibility to defect formation (Samuel *et al.*, 2014). In addition to grain refinement, chemical additives such as modifiers and degassing agents play a critical role in controlling melt quality and solidification behavior. Modifiers alter eutectic silicon morphology in aluminum–silicon alloys, while degassing agents minimize gas-related porosity and oxide inclusions, thereby improving structural integrity and surface quality (Fracchia *et al.*, 2021; Berlanga-Labari *et al.*, 2020). Commonly used grain refiners include Al–Ti–B, Al–Ti–C, Al–Ti–B–C, and TiAl master alloys, whereas modifiers such as strontium (Sr), sodium (Na), and selected rare-earth elements have demonstrated effectiveness in enhancing casting quality (Samuel *et al.*, 2014; Akhyar *et al.*, 2017). Despite extensive industrial application, the effectiveness of different additives and grain refiners—used individually or in combination varies depending on alloy composition and processing conditions. The selection of 0.12 wt% for both the grain refiner and modifier for this research ensures effective nucleation and eutectic modification, prevents excessive additive-related defects, preserves the chemical integrity of AA-2618, and aligns with commonly reported optimal ranges in aluminum casting research. Therefore, an assessment of the influence of grain refiners and modifiers on the performance characteristics of aluminum alloy (AA-2618) castings is essential for optimizing aluminum casting processes. Interestingly, this study would examine the role of selected additives and grain refiners in reducing casting defects and improving the mechanical properties of aluminum alloy castings.

## 2. Materials and Method

### 2.1 Materials

The materials used in this research included AA-2618 aluminum alloy, titanium-based master alloy (Al–5Ti–1B) as the grain refiner, strontium chloride (SrCl<sub>2</sub>) as the chemical modifier, while silica sand and an electric resistance furnace were used for melting operations.

### 2.2 Method

#### 2.2.1 Procedure for the castings

The casting procedure was carried out carefully following ASTM B108 to ensure reproducibility and minimize extraneous defects. The main steps involved melting, degassing, refining, modification, and casting, following the standard methods reported by Campbell, 2015.

AA-2618 aluminum alloy served as the base metal. A titanium-based master alloy was employed as the grain refiner, while strontium chloride (SrCl<sub>2</sub>) was used as the chemical modifier. Each treatment was applied at

0.12 wt% of the molten alloy, a concentration commonly reported in the literature as effective for grain refinement and eutectic modification in aluminum alloys (Alzahrani *et al.*, 2022; Gyarmati *et al.*, 2025).

The alloy was melted in a graphite crucible using an electric resistance furnace at temperatures between 720 and 750 °C to ensure complete melting and chemical homogeneity. The melt temperature was carefully monitored and maintained throughout the melting process to prevent compositional segregation and oxidation during casting operations as reported by Glazoff *et al.*, (2018) and Neff (2023).

Degassing treatment was performed to reduce dissolved hydrogen and minimize gas porosity, followed by manual skimming to remove surface dross and non-metallic inclusions, thereby improving melt cleanliness and casting quality as reported by Gyarmati *et al.*, (2025).

Preheated metallic molds coated with graphite were used for all casting trials to promote uniform metal flow, reduce thermal shock, and facilitate easy removal of the solidified samples while maintaining improved surface quality and structural integrity of the cast alloy (Glazoff *et al.*, 2018).

### 2.2.2 Experimental casting stages

The experiment casting stages were conducted in four distinct stages (Group A – D) to assess the effect of different melt treatments on defect mitigation and mechanical behavior:

- **Group A (Control):** AA-2618 alloy cast without additives or grain refiners to establish baseline defect characteristics and mechanical properties.
- **Group B (Grain Refined):** Treatment with 0.12 wt% titanium alloy grain refiner to evaluate grain refinement efficiency and its influence on defect reduction.
- **Group C (Modified):** Addition of 0.12 wt% SrCl<sub>2</sub> to assess the effect of chemical modification on defect suppression and microstructural refinement.
- **Group D (Combined Treatment):** Simultaneous addition of titanium alloy grain refiner and SrCl<sub>2</sub>, each at 0.12 wt%, to examine interaction effects on casting defect mitigation.

## 2.3 Mechanical Characterization

Mechanical testing was conducted to quantify the influence of additive and grain refiner treatments on the structural performance of the cast alloys.

### 2.3.1 Tensile test

Tensile specimens were machined and tested in accordance with ASTM E8/E8M–24 using a universal testing machine (model No M500-100AT, Lancashire, England) to determine ultimate tensile strength and related tensile properties.

### 2.3.2 Hardness test

Hardness measurements were obtained in accordance with ASTM E384-23 using the Vickers hardness (QNESS-250, China) method, with a minimum of three indentations per sample to ensure repeatability and reliable average values.

### 2.3.3 Impact resistance test

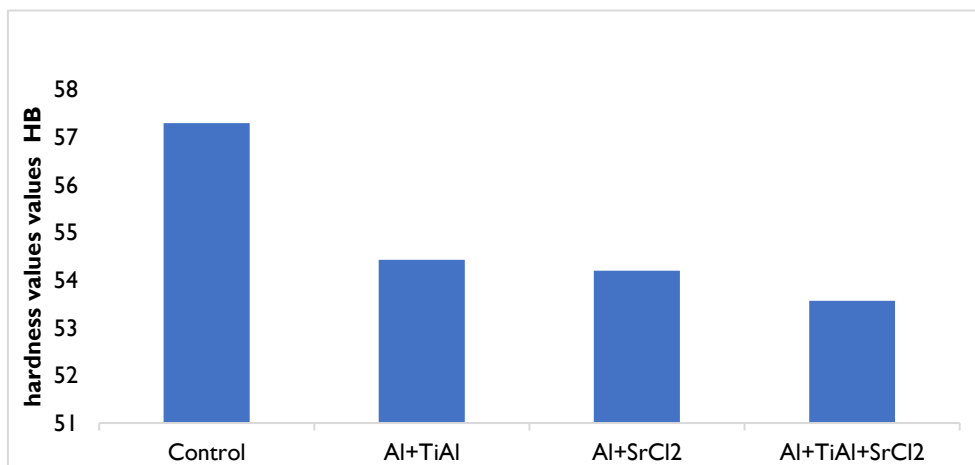
Impact resistance was evaluated using the Charpy V-notch method in accordance with ASTM E23–22a. Collectively, these tests provided quantitative insight into the relationship between casting defect mitigation, microstructural refinement, and mechanical performance of the aluminum alloy castings.

## 3. Results and Discussion

### 3.1 Hardness Test Result

The results of the hardness test were presented in Figure 1. The results show that the hardness of the control sample (57.30 HB) is higher than the treated samples. The observed reduction in hardness following the

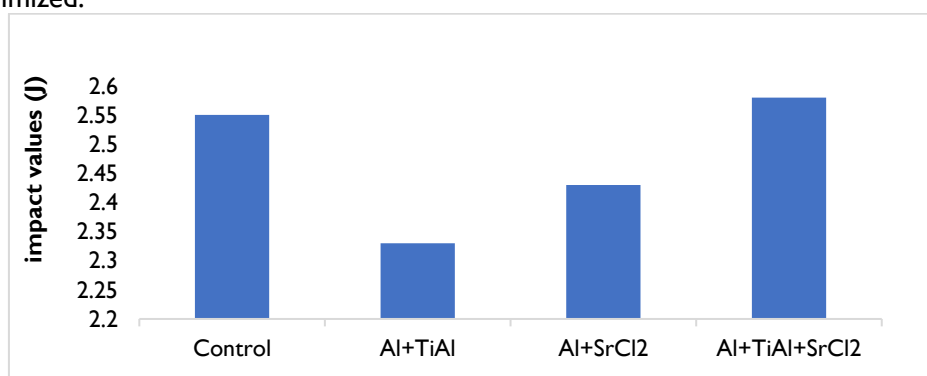
addition of TiAl and SrCl<sub>2</sub> suggests that these modifiers did not effectively refine the grain structure. Instead, they have promoted grain coarsening, increased porosity, or altered the distribution of intermetallic phases, leading to lower hardness values. This consequently enhanced the ductility of the microstructure while reducing its resistance to indentation. Similar observations were reported by Uludağ (2020) and Abdulwahab & Umaru (2022), who found that effective grain refinement and porosity reduction can improve ductility but may slightly lower hardness due to reduced internal stresses. The combined addition of TiAl + SrCl<sub>2</sub> gave the lowest hardness value (53.57 HB), indicating possible interaction between Ti and Sr leading to reduced effectiveness of Ti-based grain refiners, consistent with findings by Ait El Haj *et al.* (2023) that over-modification can counteract grain refinement efficiency.



**Figure 1: Hardness Test of the Samples**

### 3.2 Impact Strength Result

Figure 2 shows the impact energy result of the samples. The impact energy results indicate slight variations among the samples. The control and the combination-treated sample (Al + TiAl + SrCl<sub>2</sub>) exhibit similar values (2.55 J and 2.58 J respectively), suggesting improved toughness in the latter. The addition of SrCl<sub>2</sub> alone resulted in moderate improvement (2.43 J), which is attributed to the modification of eutectic silicon morphology from coarse plate-like to fine fibrous structures, as reported by Abdulwahab and Umaru (2022). The TiAl-treated sample showed a marginally lower impact value (2.33 J), which may be due to the formation of intermetallic TiAl<sub>3</sub> phases that can act as stress concentrators if not uniformly distributed. This observation aligns with Uludağ (2020), who noted that excessive Ti additions can introduce localized brittleness if porosity is not fully minimized.



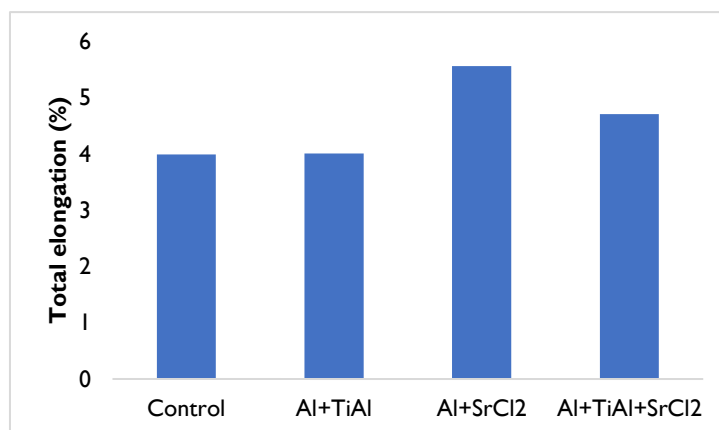
**Figure 2: Impact Test of the Samples**

### 3.3 Tensile Test Results

#### 3.3.1 Total elongation (%)

The elongation result of the samples was shown in Figure 3. It was found that an overall improvement in ductility with SrCl<sub>2</sub> modification was achieved. The Al + SrCl<sub>2</sub> sample achieved the highest elongation (5.56 %), representing about a 39 % increase compared to the control. This indicates enhanced plasticity due to the refinement and spheroidization of eutectic silicon particles, as confirmed in Schaffer *et al.* (2020). The combined

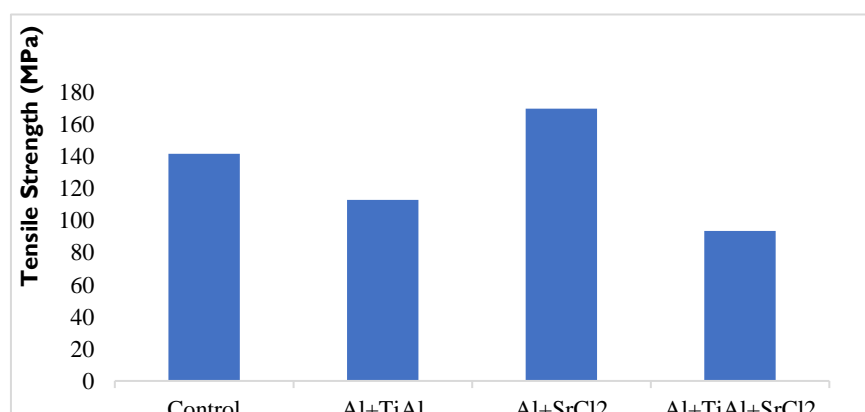
addition of TiAl + SrCl<sub>2</sub> slightly reduced elongation (4.71 %) compared to SrCl<sub>2</sub> alone, possibly due to competitive nucleation mechanisms between TiB<sub>2</sub> and Sr-modified silicon structures.



**Figure 3:** Total Elongation of the Samples

### 3.3.2 Tensile strength

The results of the tensile strength test were presented in Figure 4. The results show that the Al + SrCl<sub>2</sub> modified sample exhibits the highest tensile strength (169.92 MPa) which indicates that SrCl<sub>2</sub> effectively enhanced load-bearing capacity through improved microstructural uniformity. This finding supports the work of Abdulwahab & Umaru (2022) and Aït El Haj *et al.* (2023), which highlighted the significant strengthening effect of Sr-based modifiers in Al–Si–Mg alloys. Conversely, the TiAl-treated sample (112.90 MPa) and the combined TiAl + SrCl<sub>2</sub> sample (93.58 MPa) show a decrease in tensile strength, possibly due to the formation of coarse TiAl<sub>3</sub> intermetallic or interference in Sr modification efficiency. Recent studies indicate that interactions between solute elements and nucleant particles can reduce the effectiveness of grain refinement when unfavorable solute segregation occurs at the nucleant–melt interface, thereby deactivating heterogeneous nucleation sites and weakening refinement efficiency (Zhang *et al.*, 2025).



**Figure 4:** Tensile Strength of the Samples

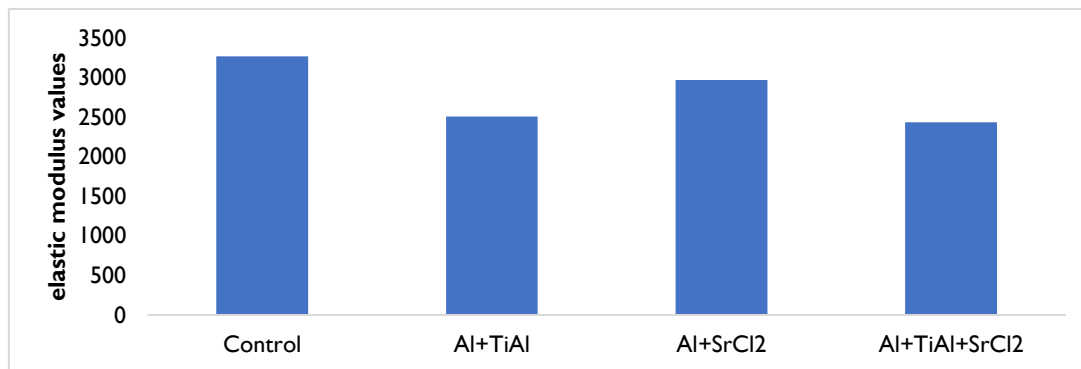
### 3.3.3 Elastic modulus

Figure 5 present the result of elastic modulus of the samples. It indicated that SrCl<sub>2</sub> modification improved the stiffness of the alloy compared to TiAl and the combined treatments. The decrease in modulus observed for TiAl and TiAl + SrCl<sub>2</sub> samples may stem from internal defects or micro-voids induced during solidification. These findings align with those of Uludağ (2020), who reported similar reductions when Ti-based refiners were not optimally dispersed.

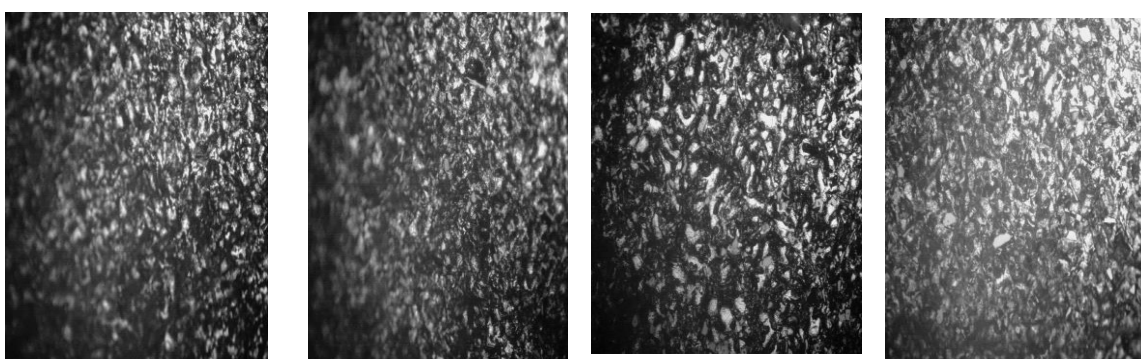
### 3.4 Microstructure examination

The microstructures of the cast AA-2618 aluminum alloy under different treatment conditions are presented in Plates 1a–1d. The observations reveal significant variations in grain morphology, intermetallic distribution, and eutectic phase characteristics depending on the type of additive introduced into the melt. Such

microstructural variations are known to strongly influence the mechanical performance of aluminum alloy castings because grain size, intermetallic distribution, and eutectic morphology directly affect crack initiation and propagation during loading. Similar findings were reported by Glazoff *et al.*, (2018) and Samuel *et al.*, (2023).



**Figure 5:** Elastic Modulus of the Samples



**Plate 1a:** Control      **Plate 1b:** Al+TiAl      **Plate 1c:** Al+ SrCl<sub>2</sub>      **Plate 1d:** Al+TiAl + SrCl<sub>2</sub>

Plate 1a (Control – Untreated AA-2618 Alloy) shows a relatively coarse dendritic  $\alpha$ -Al matrix with irregular dendrite arms and noticeable interdendritic segregation. The microstructure contains coarse intermetallic particles distributed along the grain boundaries and interdendritic regions. These phases are primarily associated with Al–Cu–Mg and Al–Cu–Ni intermetallic compounds typical of AA-2618 alloys, which form during solidification due to the alloy's high copper and nickel content and similar findings were reported by Davis, (2013) and Zhang *et al.*, (2021). The absence of grain refinement results in larger grain sizes and a non-uniform phase distribution, which contributes to localized stress concentration during mechanical loading and reduces the overall mechanical performance of the alloy which were similar to the findings reported by Campbell (2015). Consequently, the control alloy exhibited moderate mechanical performance, with a tensile strength of approximately 142 MPa, elongation of 3.99%, and impact energy of 2.55J.

The addition of the Ti-based grain refiner (Al–Ti), as shown in Plate 1b, produced partial refinement of the microstructure. The  $\alpha$ -Al grains appear more equiaxed with a noticeable reduction in dendrite arm spacing. Quantitative analysis indicates an approximate 18–22% reduction in average grain size compared with the control sample. The refinement is attributed to the formation of TiAl<sub>3</sub> intermetallic particles, which act as heterogeneous nucleation sites during solidification and similar findings were reported by Alzahrani *et al.*, (2022). However, some coarse TiAl<sub>3</sub> particles are visible within the matrix, suggesting incomplete dispersion of the refiner. These particles can act as crack initiation sites and negatively influence mechanical properties as reported by Glazoff *et al.*, (2018). This observation correlates with the mechanical test results, where the tensile strength decreased to 112.90 MPa and impact energy to 2.33 J, indicating that excessive or poorly distributed intermetallic phases can offset the benefits of grain refinement.

A significantly improved microstructure is observed in Plate 1c (Al + SrCl<sub>2</sub>). The addition of the strontium-based modifier resulted in the transformation of coarse eutectic structures into fine fibrous morphologies, accompanied by a more uniform grain distribution within the aluminum matrix. Such modification is widely reported in aluminum alloys, where strontium alters eutectic phase growth by modifying silicon morphology and reducing plate-like structures and similar findings were reported by Fracchia *et al.*, (2021) and Samuel *et al.*, (2023). The refined structure exhibited an estimated grain size reduction of approximately 28–32% relative to the untreated alloy. The modification of eutectic phases reduces stress concentration at phase boundaries

and improves the continuity of the aluminum matrix which were similar to the findings reported by Campbell (2015). As a result, the SrCl<sub>2</sub>-treated alloy demonstrated the best mechanical performance, with tensile strength increasing to 169.92 MPa (≈17.2% improvement), elongation increasing to 5.56% (≈32.4% improvement), and impact energy increasing to 2.43 J (≈15.7% improvement) compared with the control alloy.

The microstructure of the alloy subjected to the combined TiAl + SrCl<sub>2</sub> treatment (Plate 1d) shows a mixed structure characterized by refined grains in certain regions and coarse intermetallic clusters in others. While some grain refinement is evident, the distribution of TiAl<sub>3</sub> particles and modified eutectic phases appears non-uniform. The interaction between the grain refiner and modifier likely resulted in competitive nucleation mechanisms and particle agglomeration, which limited the overall effectiveness of both treatments as similar to the findings reported by Alzahrani *et al.*, (2022) and Samuel *et al.*, (2023). The average grain size reduction in this case was estimated to be approximately 10–14%, which is lower than that observed in the SrCl<sub>2</sub>-treated alloy. These microstructural limitations are consistent with the mechanical results, where the combined treatment produced the lowest tensile strength (93.58 MPa) and hardness (53.57 HB) among all samples.

Overall, the microstructural analysis demonstrates that strontium modification produced the most effective refinement and phase transformation in AA-2618 castings, leading to significant improvements in mechanical performance. In contrast, the presence of coarse TiAl<sub>3</sub> intermetallic particles in the Ti-refined alloy and the competitive interactions observed in the combined treatment highlight the importance of carefully optimizing additive selection and concentration to achieve desirable microstructural and mechanical properties in aluminum alloy castings as similar to the findings reported by Glazoff *et al.*, (2018) and Samuel *et al.*, (2023).

#### 4. Conclusion

This study investigated an assessment of the influence of grain refiners and modifiers on the performance characteristics of aluminum alloy (AA-2618) castings. The findings demonstrated performance of a TiAl-based grain refiner alone resulted in reduced tensile strength (112.90 MPa) and impact energy (2.33 J). This limited effectiveness is attributed to incomplete particle dispersion and the formation of coarse TiAl<sub>3</sub> intermetallic phases, which acted as stress concentrators and contributed to defect sensitivity. In contrast, the application of strontium chloride (SrCl<sub>2</sub>) proved highly effective in improving casting integrity, yielding enhanced tensile strength (169.92 MPa), elongation (5.56%), and impact energy (2.43 J), attributable to the transformation of eutectic silicon from coarse plate-like structures to fine fibrous morphologies, thereby reducing stress concentration and defect sensitivity.

The combined addition of TiAl grain refiner and SrCl<sub>2</sub> did not produce synergistic effects, producing the lowest hardness (53.57 HB) and tensile strength (93.58 MPa). The simultaneous application of TiAl + SrCl<sub>2</sub> treatment resulted in inferior mechanical performance, indicating adverse interactions that hindered effective grain refinement and microstructural modification. These interactions underscore the importance of carefully optimizing additive combinations to avoid competitive metallurgical effects that can exacerbate defect formation.

The study shows that careful selection and control of melt treatment additives are essential for producing high-quality, defect-free aluminum alloy castings, and further research should examine phase composition using SEM and EDS, Ti-Sr interactions, cooling rate, and melt temperature to improve process control.

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