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Influence of mechanical vibration, mold type, and grain refiner on the microstructure and mechanical behavior of A356 aluminum alloy

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ABSTRACT

In aluminum alloys, the final product properties are directly influenced by the solidification process. The microstructure can be modified through the addition of alloying elements and by altering the solidification mechanism. A refined structure is known to result in positive improvements in fluidity, feedability, mechanical properties, fatigue resistance, and corrosion resistance of the alloy. Therefore, various methods are applied to enhance the properties of cast aluminum alloys. This study investigates the combined effects of grain refiner addition (0.2 wt.% TiB) and mechanical vibration during solidification on the microstructure and mechanical properties of A356 aluminum alloy cast in sand and plaster molds. The results show that both grain refinement and vibration led to a visibly refined microstructure and enhanced mechanical performance of the A356 alloy. The application of vibration alone increased hardness by approximately 10% compared to the untreated samples, while the addition of a grain refiner led to an improvement of up to 13%. The highest ultimate tensile strength (210 MPa) was achieved with the combined effect of grain refiner and vibration in sand mold castings, representing an increase of about 25% over the base alloy (168 MPa). Optical microscopy confirmed a finer, more uniform grain structure in the modified samples. These findings suggest that the combination of grain refiner and mechanical vibration is an effective method to improve the casting quality and mechanical performance of A356 alloy.

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1. INTRODUCTION

Lightweight alloys are increasingly utilised in diverse industries, including automotive, electronics, food, and healthcare, due to their high strength-to-weight ratio and superior functional properties. Among these alloys, aluminum stands out as a widely used non-ferrous metal, favoured for its energy efficiency, recyclability, and adaptability to advanced manufacturing technologies [1-3]. Aluminum casting alloys, in particular, offer excellent castability, good mechanical strength, and remarkable corrosion resistance, making them a preferred material for numerous engineering applications. To achieve optimal mechanical properties, including tensile strength, ductility, fatigue life, and wear resistance-porosity and casting defects must be minimised during production [4, 5]. Various processing techniques, such as liquid metal preparation, filtration, grain refinement, modification, and degassing, are employed to enhance the microstructure and mechanical performance of aluminum alloys [6]. The structural characteristics at both the macro and micro scales directly influence the alloy's performance, highlighting the importance of precise control over processing parameters. In the case of aluminum casting, each stage, from molten metal preparation to final solidification, requires careful monitoring to ensure consistent quality [7–9]. Among these alloys, A356 is notable for its wide solidification range, excellent castability, high corrosion resistance, and favourable mechanical properties, making it one of the most commonly used aluminum casting alloys [10].

Grain refinement is widely recognised as an effective method to enhance various properties of aluminum alloys, including mechanical strength, ductility, and even electrical conductivity [11, 12]. Among the commonly used refiners, Al-5Ti-1B master alloys, containing TiB_2 particles and dissolved Ti, have long been employed in the aluminum industry to achieve a finer grain structure. The addition of approximately 0.1 wt. % Al-5Ti-1B can reduce the grain size of commercial aluminum from the millimetre scale to around 200 μm by promoting heterogeneous

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nucleation through TiB_2 particles. Titanium is particularly effective in grain refinement due to its strong nucleating ability, which facilitates structural cooling and suppresses grain growth [11, 12]. For A356 alloys, mechanical properties are often further improved by introducing reinforcements such as Al_2O_3, SiC, B_4C, TiB_2, and SiO_2. Grain refinement also benefits aluminum castings by reducing porosity size, modifying intermetallic phases, and enhancing feeding ability [13].

Numerous studies have reported the positive influence of grain refiners on microstructural evolution [11–21]. For instance, the addition of TiB_2 particles to A356 alloys has been shown to refine the grain structure, leading to significant improvements in hardness and wear resistance [18]. Similarly, studies combining Ti powder additions with T6 heat treatment reported a reduction in Si particle size and enhanced hardness and tensile strength [19]. Other investigations have demonstrated that grain refiner additions improve kinetic behaviour, increase elongation, and enhance thermal expansion characteristics [10, 20]. Research on Al6061 alloys has also highlighted improvements in abrasion resistance and hardness with the incorporation of grain refiners [21]. Several studies have demonstrated that the properties of aluminum alloys can be further enhanced through external post-processing techniques. In addition to commonly used alloying elements such as Cu, Ni, Ti, and Mn, to refine microstructure and improve mechanical performance, casting parameters themselves play a crucial role. Factors such as applied pressure, cooling rate, casting temperature, vacuum conditions, and vibration can significantly influence the microstructure, fluidity, elongation, feedability, and mechanical properties of aluminum alloys [22]. Among these, mechanical vibration applied during solidification has been shown to produce effects comparable to grain refinement, leading to notable improvements in material properties. Moreover, vibration is a cost-effective and easily applicable technique compatible with various casting methods [6, 15]. Research indicates that the combined use of grain refinement and mechanical vibration can effectively reduce grain size, enhance feedability, and decrease porosity, ultimately resulting in superior mechanical performance [23–25].

Aluminum alloys contain various alloying elements added to the melt to enhance microstructural characteristics and mechanical performance. In addition to alloying, processes such as mechanical vibration and heat treatment are also effective in improving the alloy's properties. Among these, T4 and T6 heat treatment processes-commonly referred to as precipitation hardening-are widely applied to aluminum casting alloys. These treatments involve solutionizing, quenching, and ageing steps, which collectively lead to significant improvements in mechanical strength and ductility [26–28]. However, the impact of heat treatment on the morphology of Si phases within the alloy can vary. For instance, studies on A356 alloys have shown that extended heat treatment times can induce cracking and shrinkage in Si particles, which may result in a reduction in tensile strength [29]. One of the most critical factors influencing the final properties of cast parts is the mold material and design, which are closely related to the thermal conductivity of the mold [30, 31]. Sand mould casting, which utilises sand-based materials, is one of the most widely used methods in the industry, accounting for approximately 60% of all metal castings due to its cost-effectiveness and versatility [32]. In contrast, plaster mold casting is primarily employed for shaping non-ferrous metals and is known for producing exceptionally smooth surface finishes. The low thermal conductivity of plaster molds promotes slow and uniform solidification, resulting in improved surface quality and dimensional accuracy. This method is particularly suitable for casting complex geometries with significant cross-sectional variations. Plaster mold casting is commonly applied to low-melting-point metals such as copper and aluminum alloys. Furthermore, to enhance the quality and mechanical properties of the final product, additional treatments and processes can be applied to both sand and plaster molds [33].

Although many studies have examined the effects of grain refinement, mechanical vibration, and casting parameters on aluminum alloys, limited research has addressed their combined influence on A356 alloy in different mold environments. Most previous studies have focused on either chemical grain refinement or mechanical treatments separately, without systematically analysing their synergistic effects on tensile strength, hardness, and microstructural evolution. To fill this gap, the present study investigates the combined effects of 0.2 wt.% Al-5Ti-1B grain refiner addition and mechanical vibration during solidification, applied to castings made in both sand and plaster molds. A ladder-shaped model was designed to achieve varying solidification times, enabling a comprehensive comparison of casting conditions. Tests were conducted on samples produced under three conditions: without additives, with grain refiner addition, and with mechanical vibration. Additionally, heat treatments were performed to evaluate their combined impact. This study specifically examines how grain refinement and vibration influence tensile strength, hardness, and microstructural evolution, providing valuable insights into optimising casting parameters for enhanced quality and performance of A356 alloy components.

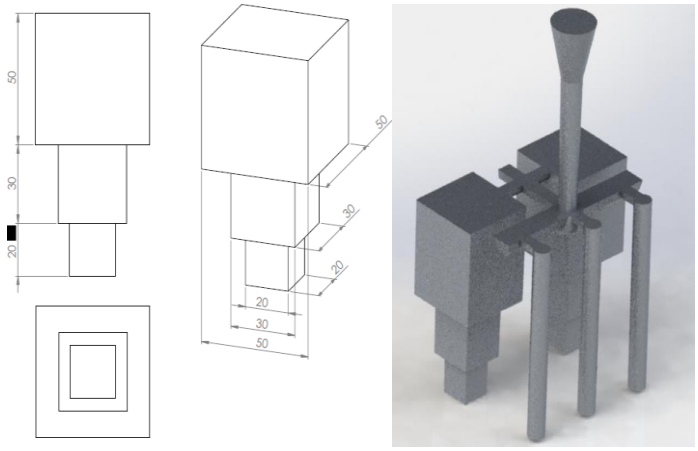
2. EXPERIMENTAL

The chemical composition of A356 primary ingots is given in Table 1. Al5Ti1B master alloy, on the other hand, was used as a grain refiner.

Table 1. Chemical composition results (% wt.)

Alloy	*Si*	*Mg*	*Fe*	*Cu*	*Zn*	*Mn*	*Ti*	*Al*
A356	6.5-7.5	0.25-0.45	0.2	0.2	0.2	0.2	0.2	Rem.

The study involved the preparation of castings using different methods, including with and without the addition of a grain refiner and under vibration. The castings were performed in six different parameters, both normal and under vibration, using a plaster mold. To affect 0.2% Ti in the castings with grain refiner addition, Al5Ti1B alloy was used, and the castings were carried out 10 minutes after alloy addition. The molds were prepared using a stepped rectangular prism model consisting of three sections: a lower section (20 × 20 mm), a middle section (30 × 30 mm), and an upper section (50 × 50 mm). The modulus values for the model geometry ranged from 0.33 cm to 0.83 cm modulus [34]. Each mold contained two models and three pull rods. Figure 1 shows the solid model image illustrating the model dimensions and the mold layout.



(a) (b)

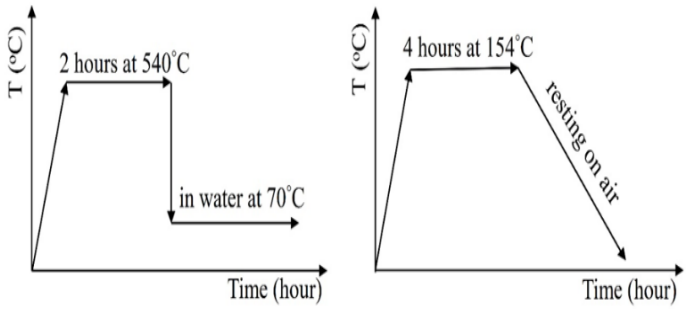
Fig. 1. (a) Dimensions of the stepped casting model, (b) 3D model of the mold.

A free model was used to prepare the molds. In the preparation of sand molding sand, dry silica sand with 90-110 AFS grain size, 3-5% bentonite, 1-2% coal dust, and 5-7% water were used. The slurry prepared with the addition of casting plaster and water at a ratio of 1:1 was used in the preparation of plaster molds. The prepared molds were kept in the oven at 150 °C for 24 hours and kept on the mold heater at 80 °C to prevent moisture from the environment before casting. Melting processes are 10 kW, 8 kg electric resistance furnace with aluminum melting capacity and a SiC crucible was used. Castings: the liquid metal prepared in accordance with the test parameters using a primary ingot was taken from the furnace after cleaning with nitrogen, slag removal, and poured into the mold. Mechanical vibration was generated by an AC electric motor (130 W) with an unbalanced weight of 50 g attached to the rotor. Vibration responses were recorded during casting, and Fast Fourier Transform (FFT) analysis was used to determine the vibration characteristics. The dominant vibration frequency was found to be 18.63 Hz, and the corresponding FFT amplitude at this frequency was 20.59 (a.u.). During the experiments, the sand mold was placed on the vibration platform, and the molten metal was poured while vibration was continuously applied for approximately 10 minutes, corresponding to the complete solidification time of the melt. The prepared molds were placed on the apparatus, starting with the filling of the liquid metal into the mold, and ending with the completion of solidification. Figure 2 shows the mechanical vibration mechanism and sample mold images after casting.

(a) (b)

Fig. 2. (a) Mechanical vibration system, (b) mold after casting.

After removing the samples from the molds, they were cut off from their runners and examined. In the microstructure investigations, samples were taken from each horizontally cut step of the ladder model. The samples were polished using alumina suspension and then etched with Keller solution, following grinding on 60-100-200-400-600-800-1000-1200 mesh SiC paper. Images of the metallographically prepared surfaces were captured using a Nikon Eclipse L150A light microscope and a Clemex digital camera. Before conducting the mechanical test, the test specimens underwent an ageing heat treatment process. This process involved three stages: solution, quenching, and ageing. Initially, the samples were heated to 540 ºC in a heat treatment furnace and maintained at this temperature for 12 hours. Afterwards, the samples were removed from the furnace and immersed in 70 ºC water before being left at room temperature for 12 hours. The samples were then aged after undergoing quenching. To do this, they were heated up to 154 ºC in the heat treatment furnace and kept at this temperature for 4 hours. Finally, the samples were removed from the furnace and allowed to cool in the air. Solution quenching and ageing processes are shown graphically in Figure 3 [26].



(a) (b)

Fig. 3. (a) Solution quenching and (b) ageing processes graphic diagram.

The solution treatment was performed after casting because this step is essential to dissolve Mg_2 Si and other solute-rich phases formed during solidification. Performing solutionizing after casting homogenises the alloy matrix, eliminates microsegregation, and enables subsequent precipitation hardening during artificial ageing. This procedure follows the standard T6 sequence recommended for A356 alloys in the literature. These heat treatment parameters were selected based on widely accepted standards for A356 alloys. Previous studies have shown that this T6 cycle effectively dissolves eutectic Si and Mg_2 Si phases, reduces microsegregation, and enhances precipitation hardening, resulting in improved tensile strength and hardness [35, 36]. These findings guided the selection of the current heat treatment parameters. After heat treatment, the cast samples were CNC-machined into tensile specimens and tested in accordance with the ASTM E8/E8M-21 standard for metallic materials. Tensile tests were carried out at room temperature with a Zwick-Roell brand tensile tester. The drawing speed is 0.05 mm/s. In order to determine the hardness values of the samples, Brinell hardness measurements were made at room temperature. The Struers Duramin-500 brand hardness measuring device was used to perform the Brinell hardness tests. At least five measurements were taken for each sample using a 2.5 mm diameter ball under a 62.5 kg load. The average of these values was considered the hardness value for each condition.

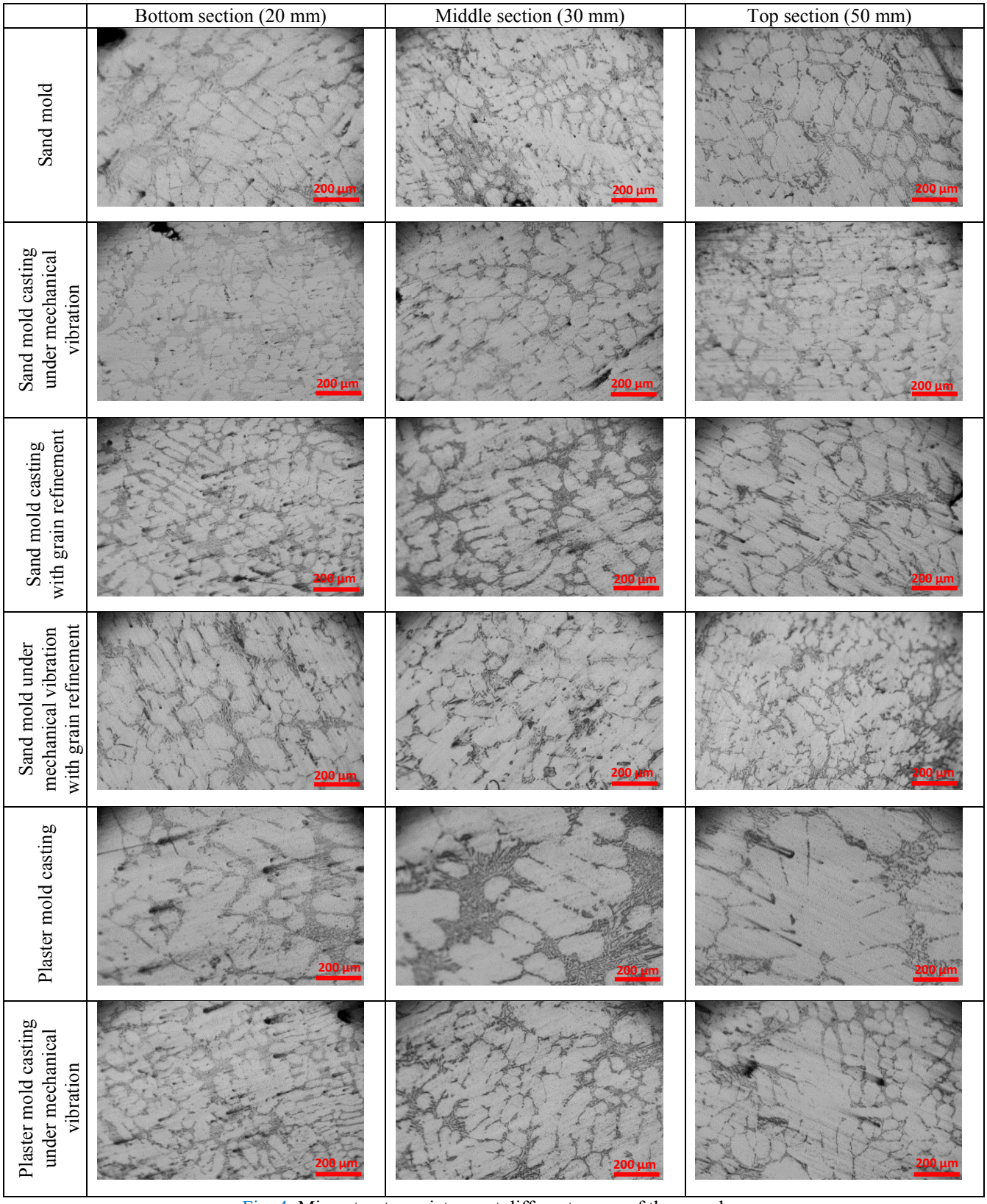


Fig. 4. Microstructure pictures at different zones of the samples.

3. EXPERIMENTAL RESULTS AND EVALUATION

In the microstructure investigations, the samples for each casting were prepared the horizontally cut ladder model. Microstructural examination procedures for samples in all casting conditions were observed under an optical microscope at 50X, 100X, and 200X magnifications. Figure 4 shows the microstructure images of the castings taken at 100X magnification under an optical microscope.

The optical micrographs presented in Figure 4 show a clear refinement of the dendritic structure when the Al-5Ti-1B grain refiner and mechanical vibration were applied. This refinement is directly associated with improved feeding ability and a decrease in shrinkage porosity. The microstructure of the A356 alloy is composed of a primary α-Al matrix with eutectic Si distributed at the interdendritic regions. Minor Mg_2 Si and Al–Fe–Si intermetallic phases may also be present as secondary constituents. As reported by Ding et al. [37], a finer grain structure leads to better tensile properties due to a more uniform stress distribution across the microstructure. These findings align with previous studies on casting with grain refiner using A356 and different aluminum alloys [9-17]. It has also been noted that the application of vibration during solidification in castings made under mechanical vibration breaks the dendrites in the structure, leading to the formation of a finer-grained structure [6]. Furthermore, it has been determined that the reduction of grain size in the structure results in an increase in feed ability and a decrease in the number of pores in the structure [38, 39].

The formation of microstructures is influenced by the rate at which liquid metal solidifies. A higher solidification rate leads to thinner microstructures. In all casting conditions, the grain size increased as the thickness of the casting section increased, resulting in coarser dendrites. This trend is related to the cooling rate. The images of microstructures in the figures show that the grain structures and Si crystals appearing in the structure are even larger when the section thickness increases. This is due to the cooling rate in the plaster mold, which results in larger grains as the thickness of the structure increases [40, 41].

In addition, the presence of TiB_2 particles acted as effective nucleation sites, promoting the formation of a refined equiaxed grain structure. The vibration-assisted samples displayed a more uniform and compact morphology compared to the samples without vibration, indicating that vibration enhanced nucleation and reduced solute segregation. Similar observations have been made by Wang and Apelian, who reported that vibration-induced convection improves thermal gradients and solidification uniformity [36]. Ayar et al. highlighted that mechanical vibration during solidification disrupts dendritic growth, resulting in reduced DAS and improved tensile strength [42]. This suggests a synergistic mechanism between TiB_2 - induced nucleation and vibration-enhanced melt convection. It should be noted that the microstructural analysis presented here is qualitative and intended to illustrate the relative refinement trends among casting conditions. Although no quantitative grain size or phase fraction measurements were conducted, the observed refinement is consistent with the improved hardness and tensile strength values.

Future work will focus on quantitative image analysis and EBSD characterisation to statistically support these findings. Although XRD analysis was not performed in the present work, the optical micrographs indicate the presence of α-Al matrix and eutectic Si phases, which are characteristic of A356 alloys. Future studies will incorporate XRD and SEM/EDS characterisation to confirm and analyse the phase constituents formed under different processing conditions.

The Struers Duramin-500 hardness measuring device was used to make Brinell hardness measurements. At least 5 pieces of each sample were tested under a load of a 2.5 mm diameter ball and a 62.5 kg load. The graphical representation of the average hardness values obtained is shown in Figure 5.

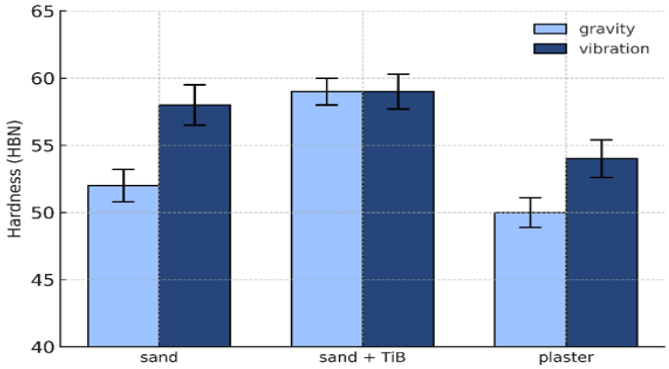


Fig. 5. Hardness measurement results for three different materials under two different conditions (light blue: with gravity effect, dark blue: with vibration effect).

Based on the data presented in Figure 5, it is evident that the hardness values of the test samples range from 50.1 HBN to 62.3 HBN. The sand mold without any alloy addition has a hardness value of 52.34 HBN. When TiB is added to the same alloy, the hardness value increases to 59.3 HBN. The additive-free alloy poured into the sand mold solidified under vibration also exhibited an increase in hardness, but not as much as the grain refiner effect. The value for this sample was determined to be 58.5 HBN. The highest increase in hardness was observed in the sample where TiB was added to the sand mold and solidified under vibration, with a value of 59.3 HBN.

The measurements indicate that both grain refinement and vibration have positive effects on hardness. It is understood that due to the low heat transmission coefficient of the mold in the plaster mold casting experiments, the solidification is slower and the resulting structure is lower, as seen in the microstructure pictures, and the lowest hardness value was obtained with 50.1 HBN in this experiment. An increase in hardness was observed in plaster mold casting experiments performed under vibration, and the average hardness value was found to reach 54.3 HBN in the measurements. The case where the increase in hardness is most obvious among the casting test samples was determined in the experiments with the addition of a grain refiner, as can be seen from the values in Figure 5. The hardness of alloys increased by up to 10% in both sand and plaster mold casting tests when a grain refiner was added. Solidification under vibration also had a positive effect on hardness, but its impact was not as significant as grain refinement when the results were analysed. Figure 6 illustrates the tensile strength graph of the test results.

After analysing the results of the tensile test as presented in Figure 6, it is evident that the test samples produced under vibration and with added grain refiner exhibit higher yield and tensile strength compared to the normal and non-addition castings. Although the complete stress–strain curves were not recorded, the reported yield strength, ultimate tensile strength, and elongation values reflect the mechanical response under each processing condition. The yield and tensile strength values for the normal cast test sample, made in a sand mold, were 137.9 MPa and 168.5 MPa, respectively, while those for the grain refiner addition were 148.9 MPa and 198.1 MPa.

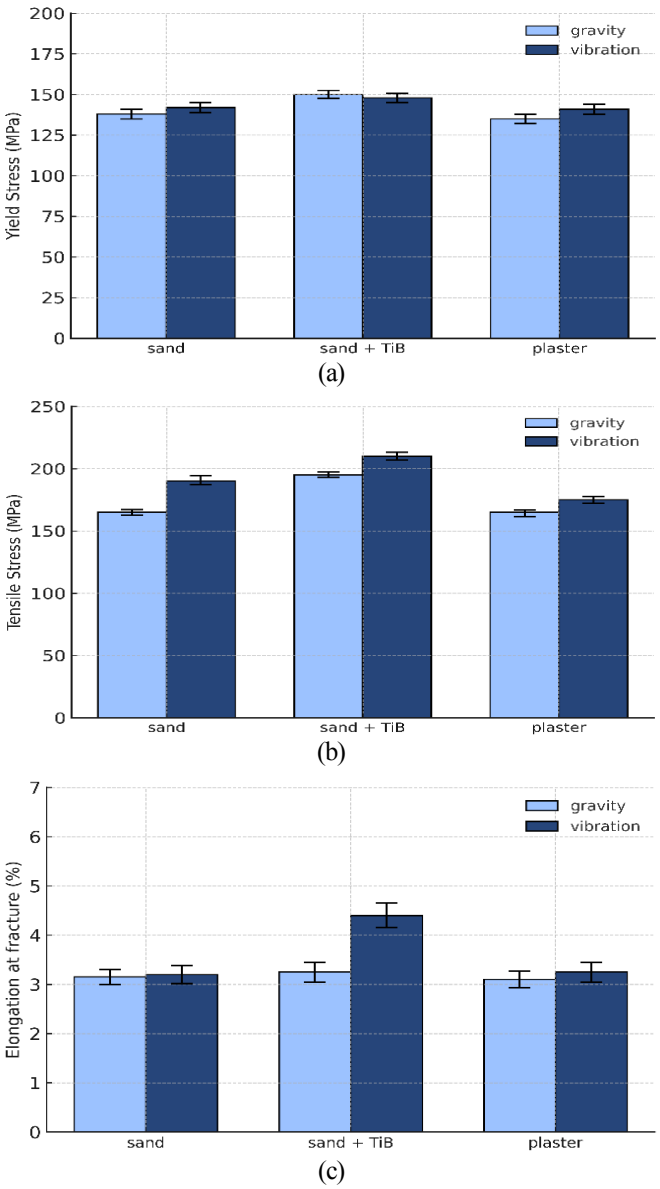


Fig. 6. Mechanical properties of the cast samples: (a) yield strength, (b) ultimate tensile strength (UTS), and (c) elongation.

The casting made under vibration yielded a strength of 142.64 MPa and a tensile strength of 195.35 MPa. Upon examination of the results, it was found that the highest tensile strength of 210.14 MPa was observed in both the grain refiner and sand molded samples that were solidified under vibration. In the plaster mold casting test, the yield strength was measured at 134.60 MPa, and the tensile strength was measured at 166.68 MPa. The test specimens that were solidified under vibration showed higher values with yield strength at 142.48 MPa and tensile strength at 174.76 MPa. These results are consistent with previous findings reported by Uslu and Yetgin [6], Wang and Apelian [36], and Ayar et al. [42], which demonstrated that the combined use of grain refinement and mechanical vibration enhances grain refinement, reduces porosity, and improves the mechanical strength of Al–Si casting alloys. The difference in values is thought to be due to solidification time and grain size. Studies have shown that increasing solidification rates and refining grain size can lead to an increase in mechanical values [43, 44].

4. CONCLUSION

A356 aluminum alloy was cast into sand and plaster molds under three conditions: without additives, with grain refiner addition (0.2 wt.% Al–5Ti–1B), and with mechanical vibration during solidification. The effects of these parameters on microstructure and mechanical properties were systematically investigated.

- An increase in section thickness reduced the cooling rate, resulting in coarser and more heterogeneous dendrites. The addition of the grain refiner promoted heterogeneous nucleation and refinement of the dendritic structure, while mechanical vibration enhanced this effect by promoting dendrite fragmentation. Consequently, the combined use of vibration and grain refiner produced a finer and more homogeneous microstructure.
- The hardness values of the samples varied between 50.1 and 62.3 HBN. In sand molds, hardness increased from 52.3HBN (without additives) to 59.3 HBN with TiB addition, while mechanical vibration resulted in 58.5 HBN. Due to the lower thermal conductivity of plaster molds, slower solidification led to the lowest hardness of 50.12 HBN, whereas applying vibration raised this value to 54.28 HBN.
- Tensile test results revealed that the combined use of grain refiner and mechanical vibration significantly improved both yield and ultimate tensile strength (UTS). The highest UTS of 210.14 MPa was recorded in sand mold castings with both TiB addition and vibration, corresponding to an approximately 25% increase compared to unmodified castings. This improvement is attributed to grain boundary strengthening and dendrite fragmentation caused by the synergistic effect of grain refinement and vibration.
- The combined application of grain refinement and mechanical vibration proved to be an efficient and practical approach for enhancing the microstructure, reducing porosity, and improving both hardness and tensile strength of A356 aluminum alloy castings. This synergy offers a reliable method for improving casting quality in industrial applications such as automotive and aerospace components.
- Future Work: Further studies are recommended to optimise vibration frequency and amplitude, to investigate the effects on fatigue and wear behaviour, and to extend this approach to other Al–Si alloy systems with different cooling rates and mold materials.

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