Wasit Journal of Engineering Sciences

Journal homepage: https://ejuow.uowasit.edu.iq

The Influence of Casting Die Vibration On The Microstructure and Mechanical Properties of Aluminum Alloys: Review

Adnan A. Ugla[1], Jwad K. Hassan[1*]

Affiliations
[1]Department Mechanical Engineering Department, College of Engineering, Advanced Nano-Technology Research Group, University of Thi-Qar, An-Nasiriya

Correspondence
Jwad.k.Hassan
jwad.s@utq.edu.iq

Received
16-May-2024
Revised
12-Augest-2024
Accepted
15-Augest-2024

Doi:https://doi.org/10.31185/ejuow.Vol12.Iss4.560

Abstract

This study provides a review of the aluminium alloy that was produced through the vibrated casting die. The combined effect of vibration is a subject that deserves attention. Several researchers discovered that the die vibration has reduced the microstructure's grain size and produced a more consistent casting structure. One way to apply motion is through mechanical vibration. It has proven to be relatively less expensive than electromagnetic vibration and ultrasound methods. It is one of the important methods used to improve the mechanical properties and grain size of aluminum alloys. When applied with appropriate intermittent ultrasonic treatment, ultrasonic vibrations can also reduce porosity formation in aluminium alloys and improve the grain size. Since the mechanism of microstructure during solidification involves an extreme change in pressure and temperature of the melt, the thermal convection resulting from this method can cause local changes in temperature and composition, thereby promoting the diffusion of the solute. Electromagnetic vibration (EMV) is one of the vibration methods used on aluminum alloys. Examining the microstructure as a function of vibration frequency during the process on the molten liquid, we discovered that as the vibration frequency rises, the microstructure and its average grain sizes diminish to a minimum. Increasing the intensity of the variable and constant magnetic fields further refines the grains.

Keywords: Aluminium alloys, Vibration, mechanical properties , ultrasonic, electromagnetic vibration.

الخلاصة:

تقدم هذه الدراسة مراجعة لسبائك الألومنيوم التي تم إنتاجها من خلال قالب الصب المهتز. إن التأثير المشترك للاهتزاز هو موضوع يستحق الاهتمام. اكتشف العديد من الباحثين أن اهتزاز القالب قد قلل من حجم حبيبات البنية الدقيقة وأنتج بنية صب أكثر اتساقًا. إحدى طرق تطبيق الحركة هي من خلال الاهتزاز الميكانيكي. لقد ثبت أنها أقل تكلفة نسبيًا من طرق الاهتزاز الكهرومغناطيسي والموجات فوق الصوتية. إنها واحدة من الطرق المهمة المستخدمة لتحسين الخصائص الميكانيكية وحجم حبيبات سبائك الألومنيوم. عند تطبيقها مع المعالجة بالموجات فوق الصوتية المتقطعة المناسبة، يمكن للاهتزازات فوق الصوتية أيضًا تقليل تكوين المسامية في سبائك الألومنيوم وتحسين حجم الحبيبات. نظرًا لأن آلية البنية الدقيقة أثناء التصلب تنطوي على تغيير شديد في ضغط ودرجة حرارة المصهور، فإن الحمل الحراري الناتج عن هذه الطريقة يمكن أن يسبب تغييرات محلية في درجة الحرارة والتكوين، وبالتالي تعزيز انتشار المذاب. الاهتزاز الكهرومغناطيسي (EMV) هو أحد طرق الاهتزاز المستخدمة في سبائك الألومنيوم. عند فحص البنية الدقيقة كدالة لتردد الاهتزاز أثناء العملية على السائل المنصهر، اكتشفنا أنه مع ارتفاع تردد الاهتزاز، تتضاءل البنية الدقيقة وأحجام حبيباتها المتوسطة إلى الحد الأدنى. يؤدي زيادة شدة المجالات المغناطيسية المتغيرة والثابتة إلى تحسين الحبيبات بشكل أكبر.

1. INTRODUCTION

In recent years, there's been a rise in the use of aluminum alloys as structural materials. This is primarily due to their advantageous characteristics, including a high strength-to-weight ratio and simplicity of manufacture, excellent workability, great ductility, exceptional thermal conductivity, high resistance to corrosion, and appealing appearance. The appearance is distinguished by its unaltered, unprocessed state. Therefore, the building sector currently accounts for 25% of worldwide aluminium production. The ease of extrusion facilitates Aluminium alloy is a highly adaptable structural material that enables the creation of intricate cross-sectional forms, making it ideal for constructing structures that are not feasible with conventional materials like concrete or steel. Its exceptional corrosion resistance makes it ideal for use in marine environments without the need for surface protection, and it requires minimal maintenance at a low cost. Their exceptional endurance enables the construction of structures that can retain their inherent qualities even in the face of significant temperature fluctuations. Recent technological advancements have emerged within the context of sustainability and efforts to mitigate climate change. This has resulted in the development of groundbreaking aluminium structural solutions that surpass steel and concrete in terms of environmental and economic efficiency. In particular, improvements in the manufacturing process of aluminum alloys have resulted in a reduction of over 75% in energy consumption since 1995. Therefore, the sector's carbon footprint has been reduced by approximately 40%. Furthermore, he asserted that North America produces a greater quantity of aluminum [1-3]. Alloying elements like copper, zinc, manganese, magnesium, silicon, and lithium, along with alloy treatment, primarily strengthen aluminum. These treatments, which include mechanical vibration, ultrasonic vibration, and electromagnetic vibration, significantly enhance the properties of cast aluminium alloys, including mechanical properties, tensile strength, hardness, and impact. They also improve physical properties such as microstructure, reduce grain size, and disperse alloy dendrites. Typically, a four-character numerical code (Table 1) identifies aluminium and its compounds. The first digit in the code represents the main alloying ingredient, except for the AA1XXX series, which shows the purity of aluminum. The second number represents changes in the contamination boundaries. A minimum percentage of aluminium is required for the AA1XXX series and several other aluminum alloys. The third and fourth digits denote the set (for subsequent strings). A four-digit number, including a decimal point, designates Al castings, alloys, and their alloys (Table 2). The digit 1 in the first number represents high-pure aluminum. The second and third figures represent the minimum percentage of aluminum. For cast alloys, the fourth digit following the decimal point is 1, while for cast materials, it is 0 [4-6].

Table 1 AA: Designation of wrought aluminum and its alloys [1-2]

Alloying Elements	Series Designation
Pure aluminum	AA1XXX
Copper	AA2XXX
Manganese	AA3XXX
Silicon	AA4XXX
Magnesium	AA5XXX
Magnesium and silicon	AA6XXX
Zinc	AA7XXX

Table 2: AA Designation of Cast Aluminium and its alloys [1-2]

Alloying Elementa	Series Designtion
Pure aluminum	AA1XX.X
Copper	AA2XX.X
Silicon,with coper and or	AA3XX.X
Magnesium	AA4XX.X
silicon	AA5XX.X
Magnesium	AA6XX.X
Zinc	AA7XX.X
Lithium	AA8XX.X

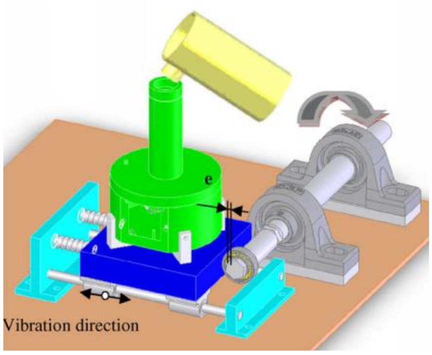
2. STRENGTHENING OF ALUMINIUM ALLOYS METHODS

Solid-state precipitation is a highly effective technique for enhancing the strength of engineering alloys. This process is present in all categories of alloys, but it holds particular significance for aluminium alloys. The effective dispersion of high-strength aluminium alloys, found in aeroplanes, trains, and mobile phones, contributes to their strength. Solid-state nucleation and growth processes compose the sediments. The key to achieving high strength is the creation of a dense and tightly packed arrangement of deposits that can effectively withstand disintegration forces. Aircraft and, increasingly, automobiles extensively use high-strength aluminium alloys to create lightweight composites. To get greater strength in aluminium alloys, a process of high-temperature "baking" (ranging from 120° to 200°C) is necessary. This process results in the formation of a large number of nanoparticles through solid-state deposition. According to our research, putting the material through controlled cyclic deformation at room temperature is enough to make holes in it that allow a very precise distribution of solute groups measuring between 1 and 2 nanometers to easily form. Therefore, the material exhibits enhanced strength and elongation qualities in comparison to traditional heat treatments, despite a much reduced curing time. Compared to traditional heat treatments, the created microstructures exhibit a higher level of homogeneity and do not exhibit any areas without deposits. Consequently, we expect these alloys to demonstrate greater resistance to damage [7-9]. Studies have revealed that the presence of both manganese and magnesium in a solid solution results in a nearly linear relationship between concentration and strength in commercial alloys at a specific strain. This differs from high-purity AL Mg binary alloys, where there is a corresponding dependence on concentration. Researchers have discovered that the presence of manganese in a solid condition significantly increases the strengthening impact per atom compared to manganese alone, as evidenced by the higher initial work hardening rate and yield stress. The amplification effect becomes more pronounced when comparing commercially available alloys to those with high purity levels. Manganese traces of elements and atoms, possibly silicon, in the solid solution are thought to have a synergistic or cumulative effect that leads to this further improvement [10]. To avoid elaborating on the techniques employed to enhance the mechanical properties of aluminium alloys, this study confined itself to scrutinizing research articles about vibration-based property enhancement. This review has edited several methods employed to enhance the mechanical characteristics of alloys:

3.MECHANICAL VIBRATION

In the highly precise manufacturing process of metal casting, a mould forms a cavity, introduces liquid metal into it, and then allows it to cool and harden, thereby hardening the metal within the mould. Out of all the production processes, casting is the most cost-effective method because of its simplified operations. Casting quality depends on the fluid dynamics of the molten metal and other process variables. Casting techniques currently manufacture about 85% of goods. During casting, all metals and alloys undergo a critical process known as solidification. Solidification is the process of giving rigidity and shape to an object. Nowadays, hardening technology has made rapid progress. The aircraft industry, automotive, chemical, and metal equipment sectors currently use castings in high-security components [11]. Current technologies suggest that the casting process, including the solidification phase, subjects the mould to vibrations. We use this important strategy to improve the shape of castings, polish their surface, and reduce material shrinkage [12]. Factors such as mould conditions, casting temperature, and vibration frequency are process variables that are likely to have an impact. The effect of cast iron on its microstructure and properties is obvious [13]. It is important to know the selection factors mentioned above to produce sound alloys and overcome the defects that accompany the hardening process. Controlling the constitutive parameters also improves the desired properties while avoiding possible flaws, such as shrinkage, porosity, voids, and trapped air contaminants. One of the best ways to find faults early on in metal die detection is to look at high-frequency vibrations, whose parameters change quickly during the early stages of fault formation. Three basic forms of vibration include ultrasonic vibration, electromagnetic vibration, and mechanical vibration. [14]. Mechanical vibration is considered a straightforward approach out of the three mentioned because of its easily controlled characteristics. Figures 1 and 2. A group of researchers conducted a study on the effects of ultrasonic and electromagnetic vibrations on the casting product [15-18].Mold vibration can alter the cast microstructure of components dating back to 1868. In one of the initial experiments, Sofroni [19] found that the use of mechanical vibration during the steel hardening process led to the smoothing of austenite. Sokolov [20] documented the use of mechanical vibration for grain refining. Campbell [21] conducted a study on mechanical vibration. It improves alloys' mechanical and corrosion properties. Tables 3 and 4 depict the effect of mechanical vibration on microhardness and mechanical properties, respectively. Dommaschk [22] conducted a study on the impact of vibration on pure aluminium and Alwt%SiMg alloys, as well as other non-ferrous alloys. The researcher focused on grain refining and concluded that mechanical vibration could potentially reduce the influence of casting wall thickness on casting properties. SS Mishra [4] studied the impact of mechanical mould vibration on the crystallisation of liquid metallic materials. The results showed that vibration caused a reduction in grain size and led to a more compact and spheroidal grain structure in the casting. Pillai [8] employed low-frequency vibration to investigate the impact on the alloys A356 and Al12Si. He determined that mechanical vibrations enhance the cast component's elongation and density. Dheir [23] employed an electromagnetic shaker to generate mechanical vibrations in a permanent mould. The study's findings suggest that these vibrations facilitate temperature distribution equalization throughout the mold, resulting in a more uniform dendritic structure and reduced porosity in the castings [24].

.



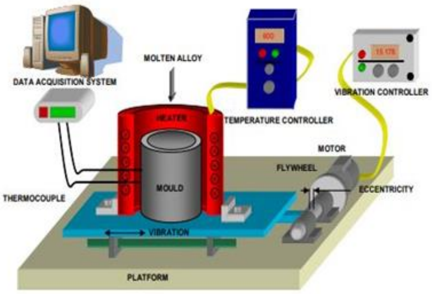


Fig.1 Mechanical vibrating device [25]

Fig.2 Schematic illustration of the apparatus Used in the present study

Table 3: Effect of mould vibration on mechanical properties [27]

Frequency (Hz)	Ultmate Stregnth Tensile (N/Mm²)	Hardnees(Rhb)
0	241	64.25
5	225	88.5
10	212	91.5

Table 4: The Mechanical Properties Of Aluminum Alloy Improve With High Vibration Frequency[28]

Properties	Value	Improvement Ratio
Ultmate Stregnth Tensile	200.82 Mpa	35٪
Yield Stregnth	180.75 Mpa	42٪
Elongation	٪3.42	57٪
Hardnees	86.4 Hbs	28٪

4. EFFECTS OF VIBRATION ON MICROSTRUCTURE

Multiple researchers have discovered that mechanical vibrations alter the typical macrostructures formed during the solidification of metals and alloys. The most frequently observed effect is the inhibition of unwanted dendritic and columnar growth. As vibration frequency increases, the size of zones and the formation of a fine-grained equilibrium structure decrease. Specimens cast with mechanical vibration significantly enhance their mechanical characteristics [27]. Figures3and4.

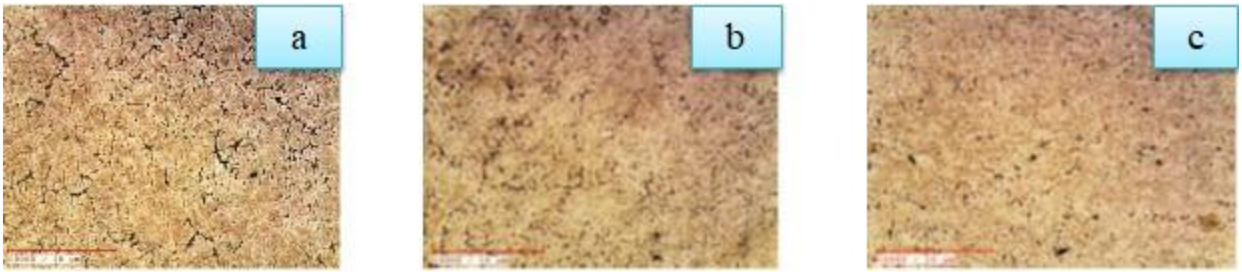


Fig.3 The microstructure of the Aluminum 356 casting without vibration, b. with frequency at 5HZ, and C. with frequency at 10HZ [27]

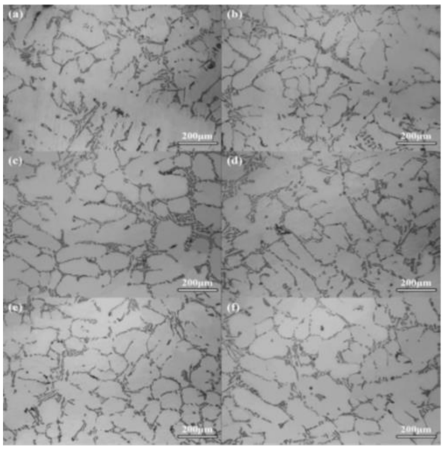


Fig.4 A356 aluminum alloy optical microstructures produced at various vibration frequencies: a) 0 Hz, b) 5 Hz, c) 35 Hz, d) 50 Hz, e) 100 Hz, and f) 120 Hz[28]

5.ULTRASONIC

In recent years, several experiments have focused on bonding reinforced aluminium matrix composites (Al MMCs) with SiCp in order to produce components from these materials. As you connect metal matrix composites (MMCs) with complicated geometries [29–33], the reinforcement particles tend to stick together while they are still molten. When the base metal dissolves, it collects. Sclerosis Even when it is possible to guarantee the even distribution of particles, the fused collector faces a challenge similar to the solidification of poured composite mortar. The solid-liquid contact during the solidification process pushes the melted particles forward, allowing them to break down into granules and interdendritic portions of the matrix [34- 36]. We detected interstices among the particles within the bonding zone. The junction [32] can act as a source of cracks during mechanical testing. We discovered it during the manufacturing process of moulded composite material. The presence of larger dendritic structures during solidification results in particle aggregate formation, whereas smaller dendrites do not. Achieving consistent sphericity results in a more evenly distributed pattern. Therefore, from this perspective, a processing step capable of generating smaller grains can decrease the variability of reinforcement by reducing their size. The solid bond region distribution enhances the mechanical performance of the Al MMC joint. Fig.5 Researchers have extensively investigated the application of ultrasonic treatment to homogeneous alloys, such as Si [37–40] and copper alloys. Research has shown that incorporating ultrasonic vibration onto... Melting eliminates and refines the columnar dendritic structure. The grains exhibit an equilibrated morphology and, in specific situations, transform into spherical grains. There are no dendritic grains [36, 37]. This study looks at how ultrasonic vibration affects grain and particle refinement during the hardening process. The investigation focused on the distribution of the hardened composite filler metal. The objective was to gather pertinent data. We aimed to tackle the strengthening process involved in the joining or casting of metal matrix composites reinforced with SiC. Ultrasonic vibration is a type of vibration that occurs at a frequency higher than human hearing's upper limit, often above 20,000 Hz [41].

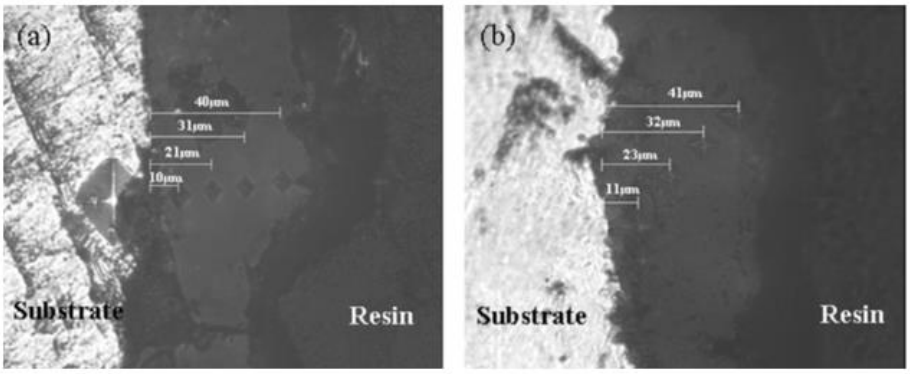


Fig.5 The cross-sectional morphology of hardness testing on 6061aluminuim alloy. (a) with ultrasonic (b) without ultrasonic [42]

The ceramic coating surface of the ultrasonic-acting specimen is rather flat, and the discharge pores are not clearly visible (refer to Fig. 6(a)). In the absence of ultrasonic activity, the specimen's ceramic coating surface displays a distribution of very large discharge pores. The surface is uneven and rough, as depicted in Figure 6 (b). The discharge apertures that use ultrasonic vibrations have a maximum size of approximately 5 mm, which is significantly smaller than those without ultrasonic action (refer to Fig. 6 (c) (d)). Visible microfractures developed on the ceramics surface in the final stage without applying ultrasonic action (refer to Fig. 6 (d)).[42]

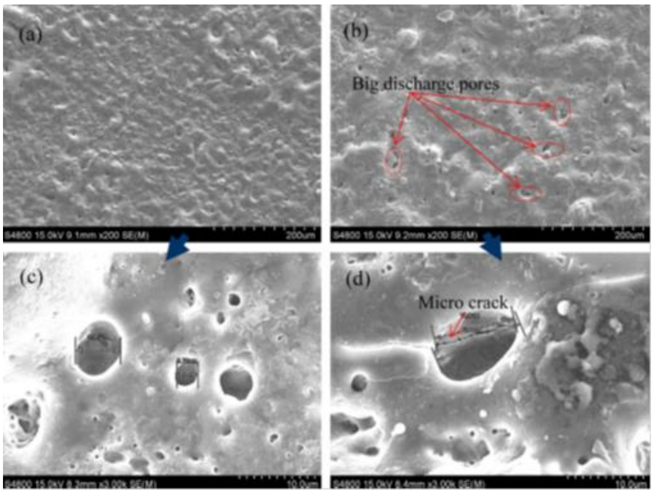


Fig.6 SEM images of surface morphology of coating by MAO 60 min on 6061aluminuim alloy. (a) 200; (c) 3000 with ultrasonic (b) 200;(d) 3000 without ultrasonic [42]

6.ELECTROMAGNETIC

The size, shape, and dispersal of eutectic silicon within the microstructure significantly influence the mechanical characteristics of the Al-Si alloy [43, 44]. These alloys typically undergo inoculation to enhance their mechanical properties [45–47]. Although inoculation can improve the quality of solidified structures, the introduction of additional elements can also damage product recycling. Vibration, whether mechanical, acoustic, or ultrasonic, is an appealing tool due to its various significant impacts. The factors mentioned include grain refining, increased density, degassing, and shrinkage [48–50]. However, this approach faces significant challenges, such as the transmitter's disintegration when exposed to high-temperature molten materials. An alternative technique for refining crystals is to induce electromagnetic vibration directly on a solidifying metal. Vive and Radjai et al. [51–54] improved the quality of structures constructed using aluminium alloys by subjecting them to vibration. The simultaneous application of an alternating current and a static magnetic field to the entire alloy during the solidification process caused this vibration. Nevertheless, applying this approach to large products is difficult due to the electromagnetic skin effect. Iwai et al. [55, 56] introduced an alternative approach for refining, involving the use of an alternating current and a static magnetic field to a specific area of a metal. However, the refining effect is most visible near the electrode. We look into using localised electromagnetic vibrations during the solidification process of a liquid metal using directional solidification in order to get a smooth and even refining structure. It has the potential to become a highly effective method in industrial use. Researchers have investigated the impact of localised electromagnetic vibration on the directed solidification process by examining the composition and mechanical properties of an Al-6%Si alloy after solidification at a speed of 100 m/s [57]. Therefore, we can credit the early work in employing EMV technology for alloy hardening. Vive [58, 59] conducted a study on the microstructure creation of various alloys based on aluminum, specifically focusing on the refining of the aluminium grain solid solution matrix under various operational parameters. Following the groundbreaking research, Asai [60] and Miwa et al. [61-69] investigated the improvement of technology and the solidification behaviour of different metallic systems, including several single-phase solid solution alloys and metals. This was the initial conclusion. Under EMV processing terms, solidification under certain appropriate conditions can improve the microstructures of both alloys and metals.

6.1 Mechanical Property

Figure 7 shows the mechanical properties of Al-6%Si's ductility and tensile strength with and without various electromagnetic vibration treatments. Fig. 7 illustrates that the tensile strength increases from 71 MPa to 114 MPa after electromagnetic vibration treatment (10 T, 10 A), representing a 50% improvement. Similarly, the electromagnetic vibration increases ductility by 2.0 times, from 3.79% to 7.65%. Electromagnetic vibration treatment enhances the mechanical properties of cast Al-6%Si alloy by causing structural refinement [70].

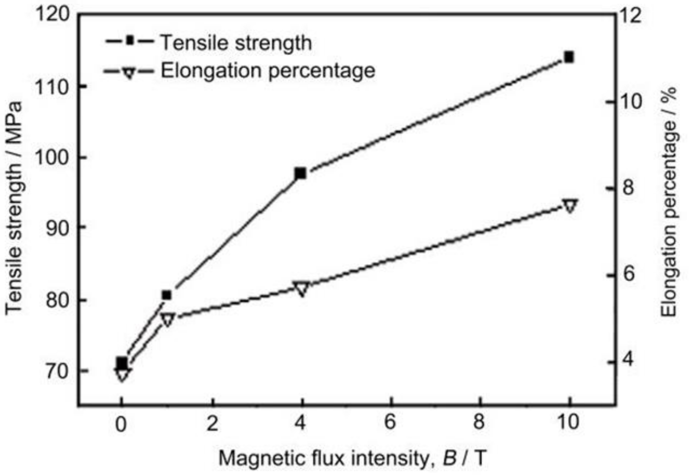


Fig.7 Mechanical characteristics of Al-6%Si without and with different electromagnetic vibration treatments. and the strength of the alternating electrical current is10 A [70]

6.2Microstructure

Figure 8 depicts the microstructure of an Al-6%Si alloy, both with and without electromagnetic vibration treatment. The absence of electromagnetic vibration treatment resulted in the acquisition of coarse primary Al dendrites and flaky eutectic silicon. When electromagnetic vibration was used, it made clear changes: the dendritic structure changed, the grain structure turned into a sphere, and the silicon in the eutectic mixture went from being thin and flat to being long and thread-like [70].

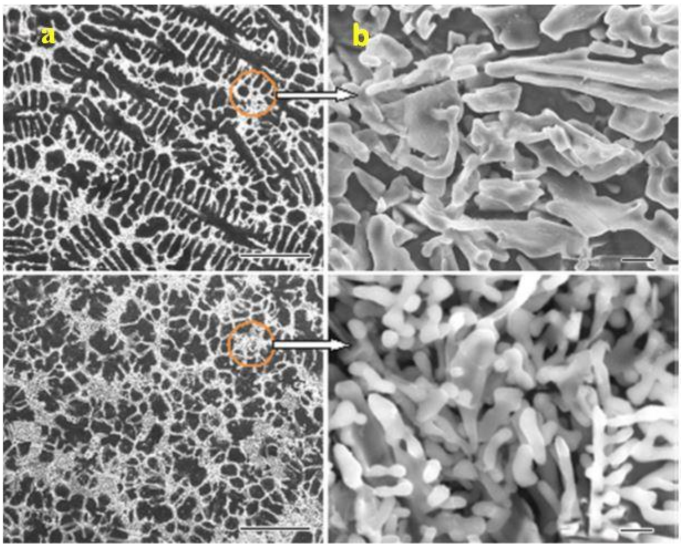


Fig.8 SEM micrographs of Al-6%Si alloy without and with electromagnetic vibration: (a) without electromagnetic vibration treatment (B=0 T, I=0 A); (b) with electromagnetic vibration treatment (B=10 T, I=10)[70]

7.CONCLUSIONS

The impact of mechanical vibration in the mold on the mechanical properties of the cast was evaluated . Based on the experimental results and literature review, we concluded that increasing the vibration of mould casting significantly increased the tensile strength, compressive strength, hardness, and refining of the grain. Table 5 illustrates the effects of vibration on tensile strength [71]. Mechanical vibration improves the microstructure of molten aluminium alloys, as shown in Figure. 9 Ultrasonic technology has demonstrated the ability to process columnar stem structures and non-stem spherical shapes from molten metal. Nonlinear processes produced by the ultrasonic field, such as cavitation and acoustic flow, can have a significant impact on aluminium alloy heat and mass transfer. This can change the grain shape from dendritic to spherical, reducing grain formation. Figure.10 Aluminium alloys also use ultrasonic vibration to reduce porosity formation. [72] Managing the electromagnetic vibration (EMV) of aluminium alloys can improve the hardening microstructure. Figures 11 and 12. The spherical granules' structure has undergone a slight change. There was a noticeable enhancement of tensile strength. By treatments including electromagnetic vibration. We find that the maximum increase in stress occurs at about 50% of strength and 2.0 times the ductility.

Table 5. Mechanical properties of an initial A356 alloy and composites based on it, containing titanium debride particles before and after vibration treatment.[71]

Alloy	**$\sigma_{0.2}$ (MPa)**	**σ_B(MPa)**	**δ(%)**
A356 alloy	67 ± 6	182 ± 8	3.4 ± 0.2
A356 alloy after vibration	121 ± 7	182 ± 7	1.7 ± 0.1
A356 + 0.5 wt% TiB_2 after vibration	151 ± 7	227 ± 10	2.3 ± 0.2

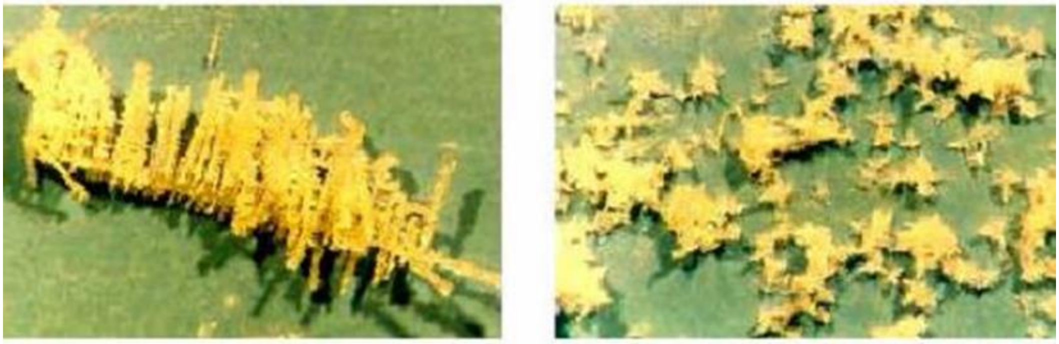


Fig. 9 (a)Without vibration (b) with vibration.[71]

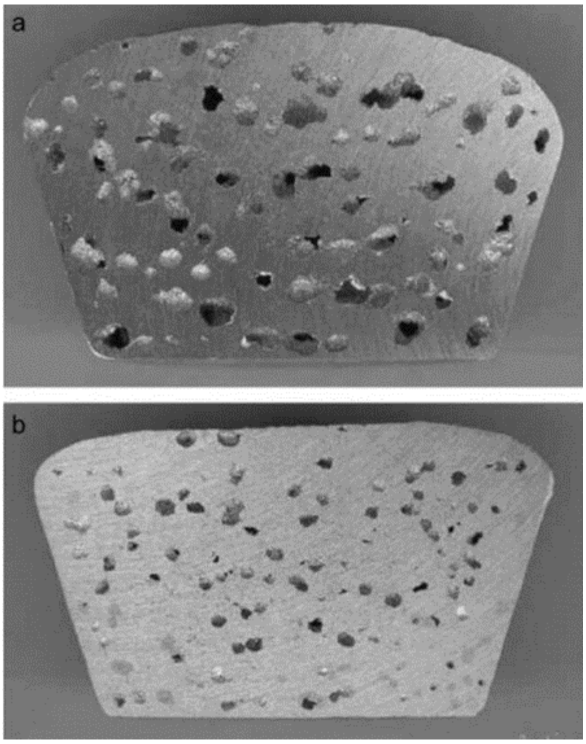


Fig. 10 Porosity in the specimens using the melt prepared at 740C under (a) humidity of 60% and (b) humidity of 40% [72]

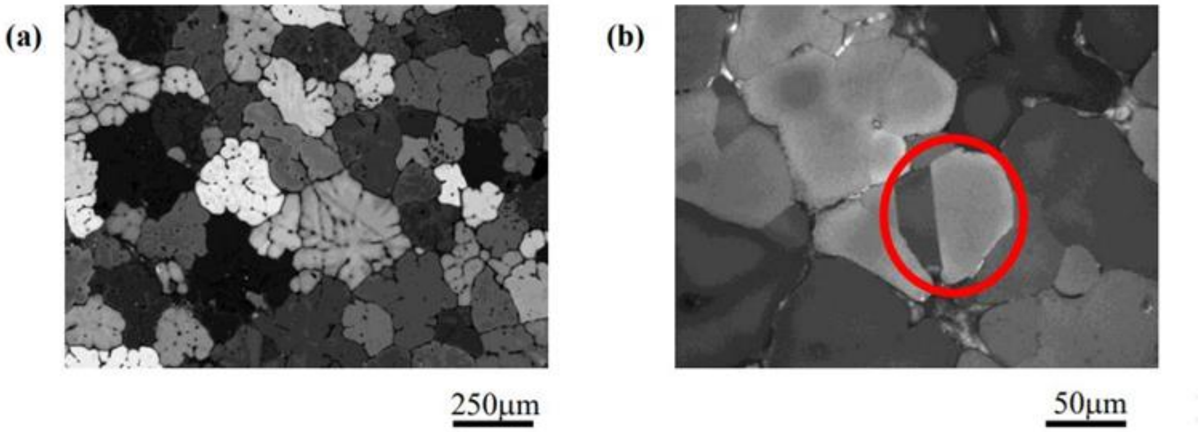


Fig. 11 The microstructure solidified (a) at the usual casting state without EMV showing no crystal twins and (b) with EMV indicating deformation twins in the present face-centered cubic aluminium alloys due to the imposition of Lorentz force [73].

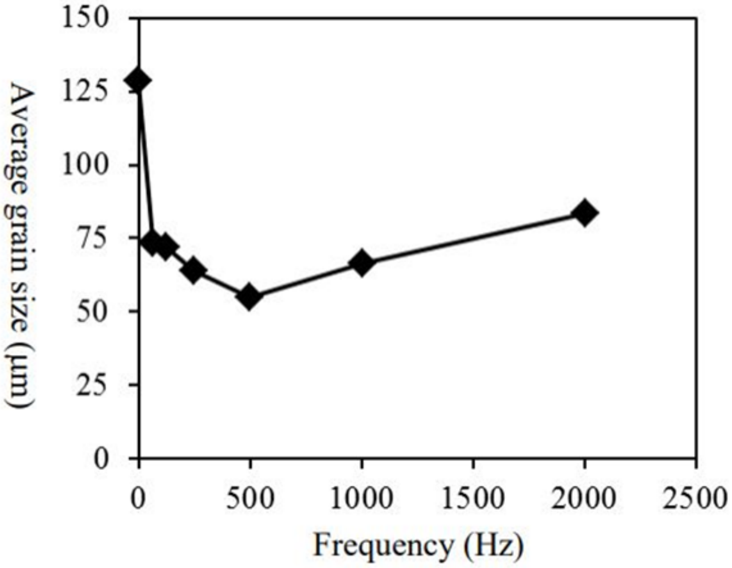


Fig. 12 The measured average grain size of solidified alloys as a function of vibration frequency for the present 7xxx alloys [73]

REFERENCES

1. Schempp, P.; Rethmeier, M. Understanding grain refinement in aluminium welding: Henry Granjon Prize 2015 winner category B: Materials behaviour and weldability. *Welding in the World*. **2015** Nov;59:767-84.
2. Ramachandran, TR. Advances in Aluminium Processing and Its Automotive Application. *InWorkshop Lecture Notes* **2006** (pp. 28-32)
3. Mukhopadhyay, P. Alloy designation, processing, and use of AA6XXX series aluminium alloys. *International Scholarly Research Notices*. **2012**;2012(1):165082.
4. Aluminium in construction [Internet]. All about aluminium; **2019**Available from: https://aluminiumleader.com/application/construc tion/.
5. Aluminum Alloys 101[Internet]. The Aluminum Association; **2019** Avaliable from: https://www.aluminum.org/aluminum-sustaina bility.
6. Georgantzia, E.; Gkantou, M.; Kamaris, GS. Aluminium alloys as structural material: A review of research. *Engineering Structures*. **2021** Jan 15;227:111372.
7. Georgantzia, E.; Gkantou, M.; Kamaris, GS. Aluminium alloys as structural material: A review of research. *Engineering Structures*. **2021** Jan 15;227:111372.

8. Hornbogen, E. Hundred years of precipitation hardening. *Journal of light metals*. **2001** May 1;1(2):127-32.
9. Wilm, AL. Physical metallurgical experiments on aluminum alloys containing magnesium. *Metallurgie*. **1911**;8:223.
10. Ryen, Ø.; Holmedal, B.; Nijs, O.; Nes, E.; Sjölander, E.; Ekström, HE. Strengthening mechanism in solid solution aluminum alloys. *Metallurgical and Materials Transactions A*. **2006** Jun;37:1999-2006.
11. Pîrvulescu, CM.; Bratu, C. Mechanic vibrations generation system and effect on the casting alloys solidification process. *UPB. Sci. Bull. Ser. B*. **2010** Jan 1;72(3):219-32.
12. Deshpande, JU. The effect of mechanical mold vibration on the characteristics of Aluminum alloys *(Doctoral dissertation, Worcester Polytechnic Institute)* **2006.**
13. JACKSON, KA. Mechanisim of growth. *Liquid metals and solidification*. **1958**:174- 86.
14. Mishra, SS.; Sahu, SS.; Ray, V. Effect of mold vibration on mechanical and metallurgical properties of Al-Cu alloy. *IJTRE*. **2015** Sep;3:131-4.
15. Jian, X.; Meek, TT.; Han, Q. Refinement of eutectic silicon phase of aluminum A356 alloy using high-intensity ultrasonic vibration. *Scripta Materialia*. **2006** Mar 1;54(5):893-6.
16. Jian, X.; Xu, H.; Meek, TT.; Han, Q. Effect of power ultrasound on solidification of aluminum A356 alloy. *Materials letters*. **2005** Feb 1;59(2-3):190-3.
17. Abugh, A.; Kuncy, IK. Microstructure and mechanical properties of vibrated castings and weldments: A review. *Journal of Engineering Studies and Research*. **2013**;19(1):7.
18. Pillai, RM.; Kumar, KB.; Pai, BC. A simple inexpensive technique for enhancing density and mechanical properties of Al□ Si alloys. *Journal of Materials Processing Technology***.** **2004** Mar 10;146(3):338-48.
19. Tenali, N.; Kumar, BK.; Ch, Kishor.; Kumar, K. An investigation of effect of mould vibrations on mechanical and metallurgical properties of aluminum 356 casting. *Methodology*.**1980**;230(75):71.
20. Abu-Dheir, N.; Khraisheh, M.; Saito, K.; Male, A. Silicon morphology modification in the eutectic Al–Si alloy using mechanical mold vibration. *Materials Science and Engineering: A*. **2005** Feb 25;393(1-2):109-17.
21. Campbell, J. Effects of vibration during solidification. *International Metals Reviews*. **1981** Jan 1;26(1):71-108.
22. Dommaschk, C. Beitrag zur Gefugebeeinflussung Erstarrender Metallschmelzen Durch Vibration (Contribution to the Influence of Vibration on the Microstructure of Solidifying MoltenMetals) (Doctoral dissertation, Ph. D. Thesis, *University of Freiberg*, Germany).**2003**
23. Tenali, N.; Kumar, BK.; Ch, Kishor.; Kumar, K. An investigation of effect of mould vibrations on mechanical and metallurgical properties of aluminum 356 casting. *Methodology*.**2004**;230(75):71.
24. Tenali, N.; Kumar, BK.; Ch, Kishor.; Kumar, K. An investigation of effect of mould vibrations on mechanical and metallurgical properties of aluminum 356 casting. *Methodology*.**2004**;230(75):71.
25. Kumar, PS.; Abhilash, E.; Joseph, MA. Solidification under mechanical vibration: variation in metallurgical structure of gravity die cast A356 aluminium alloy. *In International Conference on Frontiers in Mechanical Engineering (FIME)* **2010** May 20 (pp. 140-146).
26. Kumar, PS.; Abhilash, E.; Joseph, MA. Solidification under mechanical vibration: variation in metallurgical structure of gravity die cast A356 aluminium alloy. *In International Conference on Frontiers in Mechanical Engineering (FIME)* **2010** May 20 (pp. 140-146).
27. Tenali, N.; Kumar, BK.; Ch, Kishor.; Kumar, K. An investigation of effect of mould vibrations on mechanical and metallurgical properties of aluminum 356 casting. *Methodology*.;230(75):71.
28. Jiang, W.; Chen, X.; Wang, B.; Fan, Z.; Wu, H. Effects of vibration frequency on microstructure, mechanical properties, and fracture behavior of A356 aluminum alloy obtained by expendable pattern shell casting. *The International Journal of Advanced Manufacturing Technology*. **2016** Mar;83:167-75.
29. Wielage, B.; Hoyer, I.; Weis, S. Soldering aluminum matrix composites. *Welding journal*. **2007**;86(3):67-70.
30. Xu, Z.; Yan, J.; Wu, G.; Kong, X.; Yang, S. Interface structure and strength of ultrasonic vibration liquid phase bonded joints of Al2O3p/6061Al composites. *Scripta materialia*. **2005** Oct 1;53(7):835-9.
31. Yan, JC.; Xu, HB.; Xu, ZW.; Ma, L.; Yang, SQ. Modelling behaviour of oxide film during vibration diffusion bonding of SiCp/A356 composite in air. *Materials science and technology*. **2004** Nov 1;20(11):1489-92.
32. Li, Z.; Fearis, W.; North, TH. Particulate segregation and mechanical properties in transient liquid phase bonded metal matrix composite material. *Materials Science and Technology*. **1995** Apr;11(4):363-9.
33. Urena, A.; Gil, L.; Escriche, E.; Gómez, de.; Salazar, JM.; Escalera, MD. High temperature soldering of SiC particulate aluminium matrix composites (series 2000) using Zn–Al filler alloys. *Science and technology of welding and joining*. **2001** Feb;6(1):1-1.
34. Hashim, J.; Looney, L.; Hashmi, MS. Metal matrix composites: production by the stir casting method. *Journal of materials processing technology*. **1999** Aug 30;92:1-7.
35. Garcia-Hinojosa, JA.; Surrapa, MK. Effect of grain refinement treatment on the microstructure of cast Al–7Si–SiCp composites. *Materials Science and Engineering: A*. **2004** Nov 25;386(1-2):54-60.
36. Eskin, GI. Principles of ultrasonic treatment: Application for light alloys melts. *Advanced Performance Materials*. **1997** Apr;4(2):223-32.

37. Jian, X.; Xu, H.; Meek, TT.; Han, Q. Effect of power ultrasound on solidification of aluminum A356 alloy. *Materials letters*. **2005** Feb 1;59(2-3):190-3.
38. Abramov, V.; Abramov, O.; Bulgakov, V.; Sommer, F. Solidification of aluminum alloys under ultrasonic irradiation using water-cooled resonator. *Materials Letters*. **1998** Sep 1;37(1-2):27-34.
39. Jian, X.; Meek, TT.; Han, Q. Refinement of eutectic silicon phase of aluminum A356 alloy using high-intensity ultrasonic vibration. *Scripta Materialia*. **2006** Mar 1;54(5):893-6.
40. Xu, Z.; Yan, J.; Chen, W.; Yang, S. Effect of ultrasonic vibration on the grain refinement and SiC particle distribution in Zn-based composite filler metal. *Materials letters*. **2008** Jun 30;62(17-18):2615-8.
41. Xu, Z.; Yan, J.; Chen, W.; Yang, S. Effect of ultrasonic vibration on the grain refinement and SiC particle distribution in Zn-based composite filler metal. *Materials letters*. **2008** Jun 30;62(17-18):2615-8.
42. Dejiu, S.; Jingrui, C.; Guolong, L.; Donglei, H.; Lailei, W.; Haojie, M.; Yonghong, X.; He, C, Yaqian Y. Effect of ultrasonic on microstructure and growth characteristics of micro-arc oxidation ceramic coatings on 6061 aluminum alloy. *Vacuum*. **2014** Jan 1;99:143-8.
43. Gruzleski, JE.; Closset, BM. The treatment of liquid aluminum-silicon alloys, *American Foundrymen's Society*. Inc. Des Plaines, Illinois, USA. **1990**;19.
44. Kori, SA.; Murty, BS.; Chakraborty M. Development of an efficient grain refiner for Al–7Si alloy and its modification with strontium. *Materials Science and Engineering: A*. **2000** May 15;283(1-2):94-104.
45. Pavlović-Krstić, J.; Bähr, R.; Krstić, G.; Putić, S. The effect of mould temperature and cooling conditions on the size of secondary dendrite arm spacing in Al-7Si-3Cu alloy. *Metalurgija*. **2009**;15(2):106-13.
46. Easton, M.; StJohn, D. Grain refinement of aluminum alloys: Part I. the nucleant and solute paradigms—a review of the literature. Metallurgical and Materials Transactions A. **1999** Jun;30:1613-23.
47. Wang, Q.; Li, YX.; Li, XC. Grain refinement of Al-7Si alloys and the efficiency assessment by recognition of cooling curves. *Metallurgical and Materials Transactions A*. **2003** May;34:1175-82.
48. Jianbo, YU.; Zhongming, RE.; Weili, RE.; Kang, DE.; Zhong, Y. Effects of electromagnetic vibration on the structure and mechanical properties of Al-6% Si alloy during directional solidification. *Acta Metallurgica Sinica (English Letters)*. **2009** Feb 1;22(1):35-9.
49. Jian, X.; Meek, TT.; Han, Q. Refinement of eutectic silicon phase of aluminum A356 alloy using high-intensity ultrasonic vibration. *Scripta Materialia*. **2006** Mar 1;54(5):893-6.
50. Jian, X.; Xu, H.; Meek, TT.; Han, Q. Effect of power ultrasound on solidification of aluminum A356 alloy. *Materials letters*. **2005** Feb 1;59(2-3):190-3.
51. Vivès, C. Effects of electromagnetic vibrations on the microstructure of continuously cast aluminium alloys. *Materials Science and Engineering: A*. **1993** Dec 20;173(1-2):169-72.
52. Vives, C. Crystallization of aluminum alloys in the presence of vertical electromagnetic force fields. *Journal of crystal growth*. **1997** Apr 1;173(3-4):541-9.
53. Radjai, A.; Miwa, K.; Nishio, T. An investigation of the effects caused by electromagnetic vibrations in a hypereutectic Al-Si alloy melt. *Metallurgical and Materials Transactions A*. **1998** May;29:1477-84.
54. Radjai, A.; Miwa, K. Structural refinement of gray iron by electromagnetic vibrations. *Metallurgical and Materials Transactions A*. **2002** Sep;33:3025-30.
55. Sugiura, K.; Iwai, K. Effect of operating parameters of an electromagnetic refining process on the solidified structure. *ISIJ international*. **2004** Aug 15;44(8):1410-5.
56. Sugiura, K.; Iwai, K. Refining mechanism of solidified structure of alloy by electromagnetic refining process. *ISIJ international*. **2005**;45(7):962-6.
57. Jianbo, YU.; Zhongming, RE.; Weili, RE.; Kang, DE.; Zhong, Y. Effects of electromagnetic vibration on the structure and mechanical properties of Al-6% Si alloy during directional solidification. *Acta Metallurgica Sinica (English Letters)*. **2009** Feb 1;22(1):35-9.
58. Vives, C. Electromagnetic refining of aluminum alloys by the CREM process: Part I. Working principle and metallurgical results. *Metallurgical Transactions B*. **1989** Oct;20:623-9.
59. Vives, C. Effects of forced electromagnetic vibrations during the solidification of aluminum alloys: Part I. Solidification in the presence of crossed alternating electric fields and stationary magnetic fields. *Metallurgical and Materials Transactions B*. **1996** Jun;27:445-55.
60. Asai, S.; Application of high magnetic fields in inorganic materials processing. *Modelling and Simulation in Materials Science and Engineering*. **2004** Feb 16;12(2):R1.
61. Radjai, A.; Miwa, K.; Nishio, T. An investigation of the effects caused by electromagnetic vibrations in a hypereutectic Al-Si alloy melt. *Metallurgical and Materials Transactions A*. **1998** May;29:1477-84.
62. Radjai, A.; Miwa, K. Effects of the intensity and frequency of electromagnetic vibrations on the microstructural refinement of hypoeutectic Al-Si alloys. Metallurgical and Materials transactions A **2000** Mar;31:755-62.
63. Radjai, A.; Miwa, K. Structural refinement of gray iron by electromagnetic vibrations. *Metallurgical and Materials Transaction A*. **2002** Sep;33:3025-30.

64. Mizutani, Y.; Kawai, S.; Miwa, K.; Yasue, K.; Tamura, T.; Sakaguchi, Y. Effect of the intensity and frequency of electromagnetic vibrations on refinement of primary silicon in Al-17% Si alloy. *Materials transactions*. **2004**;45(6):1939-43.
65. Mizutani, Y.; Ohura, Y.; Miwa, K.; Yasue, K.; Tamura, T.; Sakaguchi, Y. Effect of the electromagnetic vibration intensity on microstructural refinement of Al-7% Si alloy. *Materials transactions*. **2004**;45(6):1944-8.
66. Mizutani, Y.; Kawata, J.; Miwa, K.; Yasue, K.; Tamura, T.; Sakaguchi Y. Effect of the frequency of electromagnetic vibrations on microstructural refinement of AZ91D magnesium alloy. *Journal of Materials Research.* **2004** Oct;19(10):2997-3003.
67. Mizutani, Y.; Tamura, T.; Miwa, K. Microstructural refinement processof pure magnesium by electromagnetic vibrations. *Materials Science and Engineering*: A. **2005** Dec 15;413:205-10.
68. Mizutani, Y.; Miwa, K.; Tamura, T.; Nakai, Y.; Otsuka Y. Grain refinement of tough pitch copper by electromagnetic vibrations during solidification. *Materials transactions*. **2006**;47(7):1793-7.
69. Mizutani,Y.; Tamura, T.; Miwa, K. Effect of electromagnetic vibration frequency and temperature gradient on grain refinement of pure aluminum. *Materials transactions.* **2007** Mar 1;48(3):538-43.
70. Jianbo, Y.U.; Zhongming, R.E.; Weili, R.E.; Kang, D.E.; Zhong, Y. Effects of electromagnetic vibration on the structure and mechanical properties of Al-6% Si alloy during directional solidification. *Acta Metallurgica Sinica (English Letters).* **2009** Feb 1;22(1):35-9.
71. Promakhov, V.V.; Khmeleva, M.G.; Zhukov, I.A.; Platov, V.V.; Khrustalyov, A.P.; Vorozhtsov, A.B. Influence of vibration treatment and modification of A356 aluminum alloy on its structure and mechanical properties. *Metals*. **2019** Jan 15;9(1):87.
72. Meek, T.T.; Han, Q.; Jian, X.; Xu, H. Ultrasonic processing of materials. *Univ. of Tennessee, Knoxville, TN (United States)*; **2005** Jun 30.
73. Li, M.; Tamura, T.; Omura, N.; Murakami, Y.; Tada, S. Microstructure refinement of commercial 7xxx aluminium alloys solidified by the electromagnetic vibration technique. In *IOP Conference Series: Materials Science and Engineering* **2016** Mar 1 (Vol. 117, No. 1, p. 012048). IOP Publishing.