

Effect of Mechanical Vibration on the Microstructure and Mechanical Properties of LM6 Reinforced with 6wt.%Cu

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ABSTRACT

Eutectic aluminium-silicon alloy (LM6) is widely used in industrial applications due to its excellent casting characteristics and good corrosion resistance. Due to its low strength and hardness, its use is limited in some applications that require high mechanical properties. To enhance the properties of LM6, various methods are used, such as adding alloying elements, heat treatment, or specific casting techniques. The mechanical properties of this alloy are intrinsically linked to its morphological features that occur during the hardening stage. This paper investigates the effect of applying mechanical vibration during solidification on the microstructure and mechanical properties—specifically tensile strength and hardness—of LM6 reinforced with 6 wt.% Cu, followed by heat treatment. During this study, using a sand casting mould under different vibration frequencies to prepare the test samples. Microstructure analysis, and tensile and hardness tests were performed. Experimental results demonstrated that mechanical vibration induces significant grain refinement and a highly homogeneous distribution of the silicon phase within the aluminium matrix. These microstructural modifications notably improve the alloy's tensile strength and hardness compared to non-vibrated samples. Consequently, these findings highlight mechanical vibration as a highly effective processing technique for enhancing the mechanical properties of LM6 alloys reinforced with 6wt.% Cu for high-performance engineering applications.

Keywords: LM6, Mechanical Vibration, Microstructure, Tensile Strength, Hardness.

تأثير الاهتزاز الميكانيكي على البنية المجهرية والخواص الميكانيكية لسبائك LM6 المعززة بنسبة وزن 6% من النحاس

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ملخص البحث

تُستخدم سبيكة الألومنيوم-السيليكون الإيوتكتيكية (LM6) على نطاق واسع في التطبيقات الصناعية نظراً لخصائصها الممتازة في الصب ومقاومتها الجيدة للتآكل. ونظراً لانخفاض قوتها وصلادتها، فإن استخدامها محدود في بعض التطبيقات التي تتطلب خصائص ميكانيكية عالية. ولتحسين خصائص LM6، تُستخدم طرق مختلفة مثل إضافة عناصر سبائكية،

وعملية المعالجة الحرارية، أو استخدام بعض التقنيات أثناء عملية الصب. يرتبط الأداء الميكانيكي لهذه السبيكة ارتباطاً جوهرياً بخصائصها المورفولوجية التي تحدث أثناء مرحلة التصلب. تبحث هذه الورقة البحثية في كيفية تأثير تطبيق الاهتزاز الميكانيكي أثناء التصلب على السمات الميكروية الرئيسية، بما في ذلك حجم الحبيبات، وتوزيع الأطوار، وشكل المكونات. وبالتالي، فإنها تبحث في تأثير تطبيق الاهتزاز الميكانيكي أثناء التصلب على الخصائص الميكانيكية، مثل قوة الشد والصلابة، لـ LM6 المدعم بنسبة 6% من النحاس متبوعاً بالمعالجة الحرارية. خلال هذه الدراسة، تم استخدام قالب صب رملي بترددات اهتزاز مختلفة لإعداد عينات الاختبار. وأجري تحليل للبنية الميكروية واختبارات الشد والصلابة. أظهرت النتائج التجريبية أن الاهتزاز الميكانيكي يؤدي إلى تحسين ملحوظ في بنية الحبيبات وتوزيع أكثر تجانساً لطور السيليكون داخل مصفوفة الألومنيوم. وتؤدي هذه التعديلات في البنية المجهرية إلى تحسين ملحوظ في مقاومة الشد وصلابة السبيكة مقارنةً بالعينات التي لم تتعرض للاهتزاز. وتُبرز هذه النتائج إمكانات الاهتزاز الميكانيكي ك تقنية معالجة فعالة لتحسين الخواص الميكانيكية لسبيكة LM6 المدعمة بنسبة 6% من النحاس، وذلك لتطبيقات هندسية عالية الأداء تتطلب مواصفات دقيقة.

الكلمات الدالة: LM6، الاهتزاز الميكانيكي، البنية المجهرية، قوة الشد، الصلابة.

1. Introduction

Eutectic aluminium-silicon alloys (LM6) are widely recognized for their appropriate properties, making them essential in various industrial applications, particularly in the automotive and aerospace sectors. These alloys are characterized by their unique micro-structure, which consists of a fine distribution of silicon crystals within the aluminium matrix [1]. The combination of aluminium and silicon provides beneficial attributes such as excellent casting characteristics, high corrosion resistance, and a lightweight nature, making them suitable for manufacturing high-performance components like engine blocks and transmission housings [2]. Due to its low strength and hardness, its use is limited in some applications that need high mechanical properties [3]. Other elements such as magnesium, copper, nickel, manganese, and tin are added to alloys for use in specific applications [4]. Copper plays a role as a strengthening agent in aluminium alloys [5]. The mechanical properties of these alloys can be significantly influenced by processing techniques, which allows for the optimization of the microstructure to enhance tensile strength and overall performance [6].

The control of microstructure is remarkable for improving the mechanical properties of eutectic Al-Si alloys [7]. The eutectic composition, typically around 12.6% silicon, results in a lower melting point and improved fluidity, enhancing the casting characteristics of the material [8]. However, conventional casting methods can result in coarse, circular silicon structures and casting defects like porosity, which can be detrimental to the mechanical integrity of the alloy. To overcome these limitations, various refinement techniques have been explored. Recent studies have focused on the effects of applying mechanical vibration during the solidification process [9]. Mechanical vibration is an innovative approach that can significantly influence the microstructure and mechanical properties of cast alloys. The application of vibration during solidification promotes the refinement of the solidification structure, leading to a more uniform distribution of phases [10]. The proposed mechanisms include the fragmentation of dendrites, increased nucleation sites, and improved feeding to prevent shrinkage porosity. Research indicates that mechanical vibrations can lead to a notable increase in tensile strength, potentially by as much as 20-30% compared to non-vibrated castings, depending on the casting methods and vibration parameters [11]. The vibration frequency is a critical parameter that must be optimized to achieve the desired microstructural characteristics and, then, the best mechanical performance [12].

In this area, some studies have used vibration in various casting methods. In a gravity die casting mould, Mishra [10] used mechanical vibration at a frequency of 15 Hz to study the microstructure, tensile

strength, and hardness of Al-7.15% Si alloy (LM25). They found that the micro-grain structure of the aluminium alloy has improved at 15 Hz of vibration; the grain size has reduced, and a fine-grain structure has been obtained. Therefore, the mechanical properties, such as tensile strength and hardness, increased at 15 Hz of vibration. Using a die steel casting mould by [13], LM6 was used under mechanical vibration at 5, 10, 15, 20, and 25 Hz. They found that dendrite grain size and porosity were reduced as the vibration frequency increased. Therefore, the hardness, tensile strength, and elongation increased. In a graphite casting mould, Kumar et al. [14] was applied mechanical vibration at frequencies from 40 Hz to 150 Hz to study the grain size and morphology of Al-6wt%Cu alloy (LM27). They found that as the frequency of vibration increases, refinement increases. Therefore, the hardness of the casting also increases as frequencies go from 40 Hz to 150 Hz. The effect of copper addition followed by a heat treatment process on the morphology and properties of LM6 was studied by [7]. They added different contents of copper powder (3 wt.%, 6 wt.%, and 9 wt.%) to LM6, followed by solution heat treatment. They found that the change in eutectic morphology and grain size was due to applying a heat treatment to LM6 reinforced with copper, therefore getting top readings in the tensile strength and hardness of the casting at 6 wt.%

A review of the literature reveals that various studies have confirmed the advantages of adding some elements and using vibration to enhance the mechanical properties of different eutectic aluminium-silicon alloys such as LM6, LM25, and LM27. Nevertheless, it is notable that only limited research has been reported regarding the effect of mechanical vibration on the microstructure and mechanical properties of LM6 alloys. Thus, this study aims to investigate the effects of mechanical vibration on the microstructure of the heat-treated LM6 reinforced with 6 wt.% Cu. Consequently, its effects on the mechanical properties. In this experimental work, tensile test specimens were prepared from an LM6 alloy reinforced with 6 wt.% Cu using a carbon dioxide sand casting method. The casting moulds were subjected to different frequencies of mechanical vibration during solidification of the casts. Then the samples were subjected to solution heat treatment. Finally, the microstructure was analysed, and the hardness and tensile strength of the specimens were tested; the results were compared to those of the non-vibrated ones.

2. Experimental Work

The methodology adopted for this experimental work includes the following steps: material preparation, fabrication of sand moulds, casting of the specimen, application of mechanical vibration during solidification, solution heat treatment procedure, microstructural analysis, and mechanical testing.

2.1 Materials Preparation

LM6 alloy was used as a main material, reinforced with copper powder. The chemical composition of the Al-Si eutectic alloy is listed in Table 1. The copper powder was used with 6wt.% and particle size of 62 μm . The composition of copper powder is shown in Table 2. Tensile test specimens were produced using the CO₂ sand casting method according to the ASTM B557M standard, as shown in Figure 1.

Table 1: Chemical composition of LM6 alloy by weight %, [15]

Element	Al	Si	Cu	Mg	Fe	Mn
Wt.%	85.95	12.0	0.1	0.1	0.6	0.5

Element	Ni	Zn	Sn	Ti	Pb	other
Wt.%	0.1	0.1	0.05	0.2	0.1	0.2

Table 2: Chemical composition of copper powder by weight %. [7]

Element	Cu	Fe	Pb	S	Zn	Sn	other
Wt%	99.4	0.023	0.029	0.003	0.006	0.003	0.32

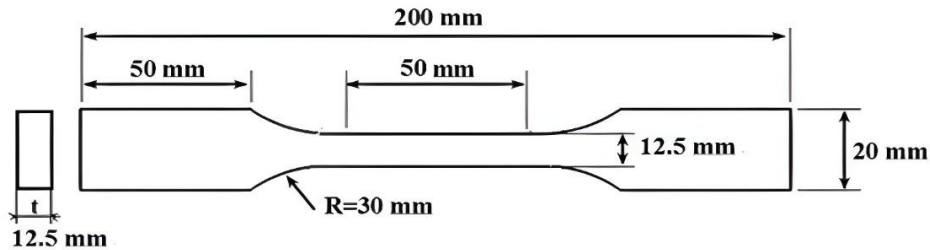


Figure 1. Tensile specimen, [16]

2.2 Sand Moulds Preparation

The casting moulds used in this work were prepared by mixing 20 kg sand with 800 ml sodium silicate and 400 ml water. The mixture was then poured and rammed in a prepared wooden frame containing patterns of tensile specimens. Finally, CO₂ was injected to further harden the sand, thus obtaining the sand mould, as shown in Figure 2.

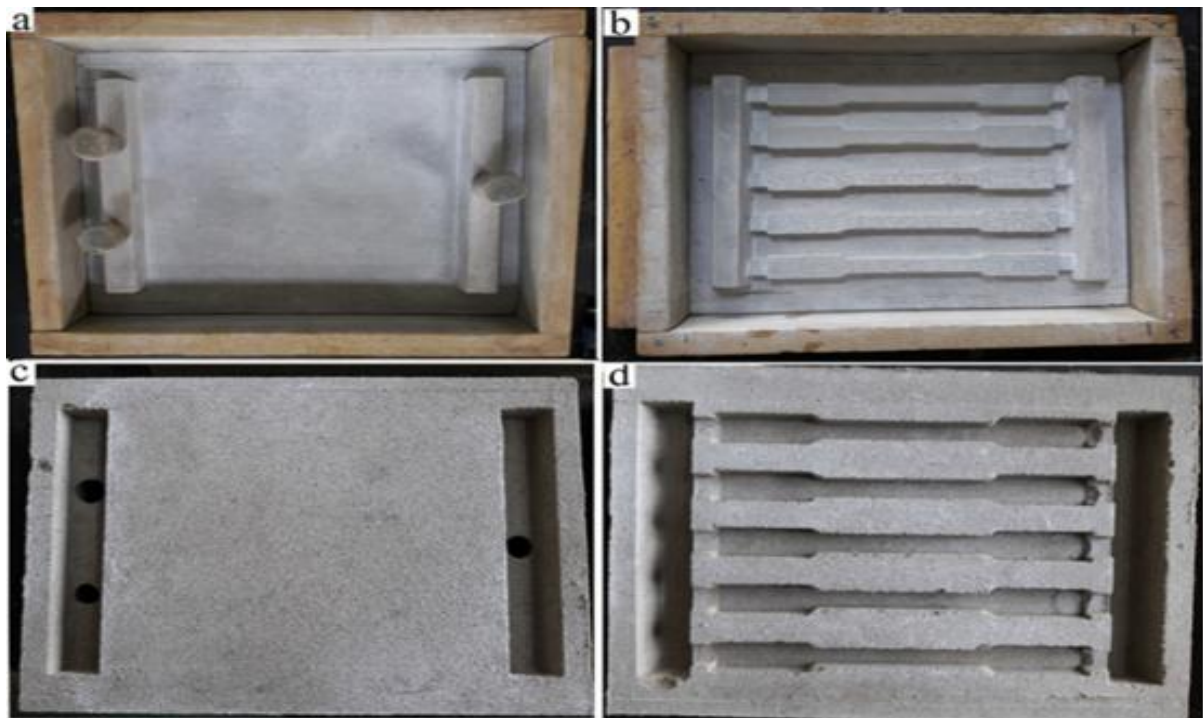


Figure 2. Wooden pattern; a) Cap consisting of gate and risers, b) Drag consisting 5 patterns of dog-bone shapes. Sand mould; c) The upper half Mould, d) The lower half mould [7]

2.3 Melting and Pouring

In the induction furnace, 3.6 kg of LM6 was melted at about $700 \pm 5^\circ\text{C}$. The 200°C preheated 216 grams (6 wt.%) of copper powder was added to the molten metal and stirred for 2 mints at 200 rpm to obtain a homogeneous mixture. The molten metal was poured into the sand moulds under different vibration frequencies (0 Hz, 5 Hz, 10 Hz, and 15 Hz) and then left to solidify and cool, as shown in figure 3a.

Next, the sand mould was broken to eject the castings. Then the castings were cleaned using a grinding machine. The finished samples are shown in Figure 3b.

2.4 Heat treatment

The produced specimens were subjected to solution heat treatment to investigate the effect of solution treatment on the mechanical properties of LM6 reinforced with 6wt.% Cu. The aim of the conducted heat treatment was to precipitate copper particulates in the grain matrix rather than concentrating them at grain boundaries, thereby achieving a more homogeneous intermetallic phase distribution. Copper is one of the few elements that have high solubility in Al. The maximum solubility of copper in aluminium is 5.65 wt.% at 548 °C [17]. Solution heat treatment was carried out in an electric furnace at 490 ± 2 °C for 6 hours, followed by quenching in hot water (60 ± 2 °C), immediate ageing at 155 ± 2 °C for 5 hours, and finally air-cooling.

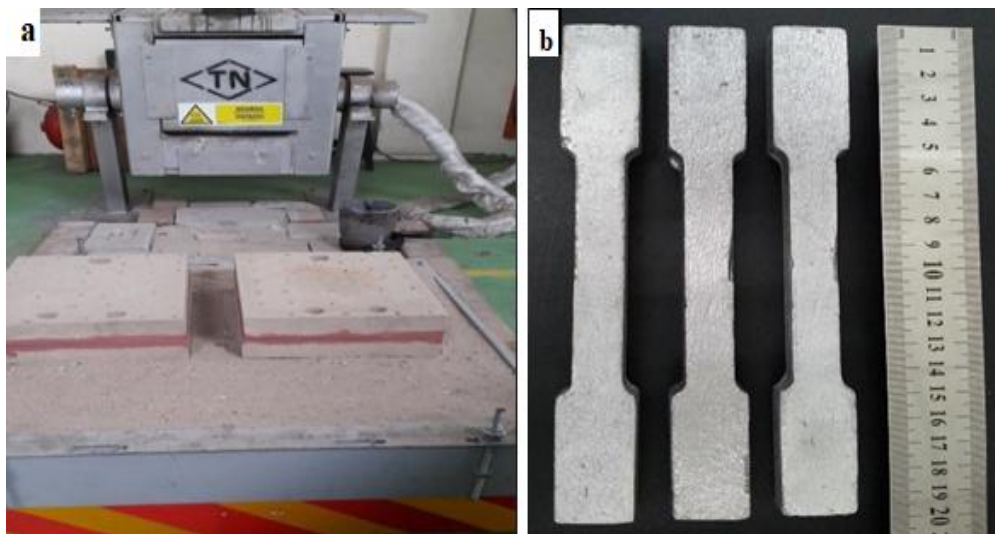


Figure 3. a) Induction furnace with two sand moulds, b) Finished tensile specimens.

2.5 Micro-structural Analysis

The morphological structure of the sample's surface was studied using optical microscopy. Four samples were prepared for different frequencies (0 Hz, 5 Hz, 10 Hz, and 15 Hz). The processes started with sectioning, followed by mounting in cold epoxy resin, then grinding with silicon carbide emery paper under different grades (180, 400, 800, 1200, and 2000 grit size), respectively, and finished with mechanical polishing. Then, these samples underwent microstructure testing under optical microscopy at 50× magnification, as shown in Figure 4.

2.6. Mechanical Properties

Two mechanical properties were studied, namely hardness and tensile strength. The evaluation of these properties depends on the micro-structure features that were affected by applying mechanical vibration during solidification stage. During the preparation of samples in this study, the micro-structure was affected by change frequencies 0, 5, 10, and 15 Hz and under a fixed amplitude of 0.5mm.

2.6.1. Tensile test

By using universal testing machine, the tensile properties for fabricated specimens were tested. Tensile tests were performed at a 1mm / min cross-head speed under the capacity of 10 Tons. The applied load and responded elongation data were collected by the software attached to the testing machine for further

analysis. The tensile test was performed for tension testing of cast aluminium alloys according to ASTM B557M. Figure 5 displays the tensile test steps.

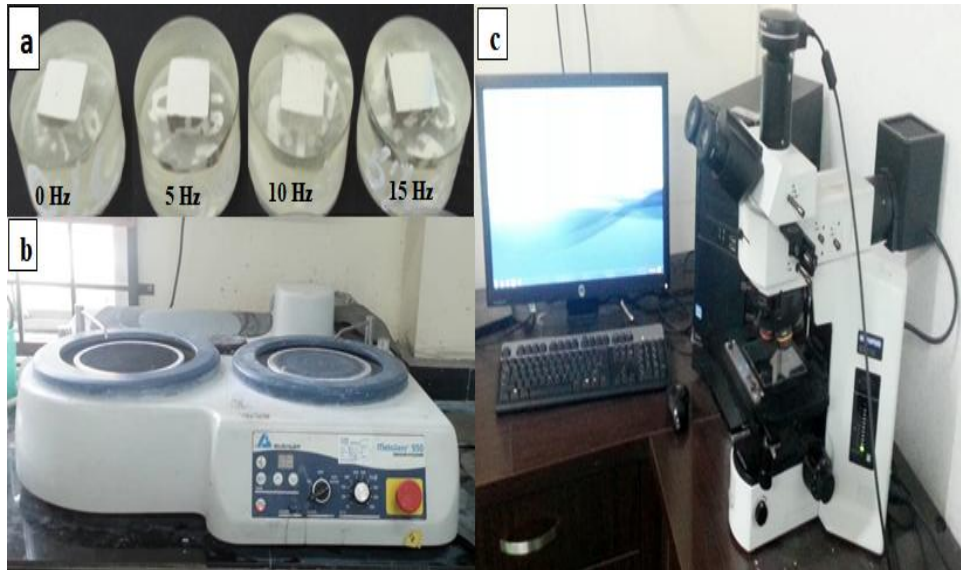


Figure 4. a) Mounted samples, b) Polishing Machine, c) Optical Microscope

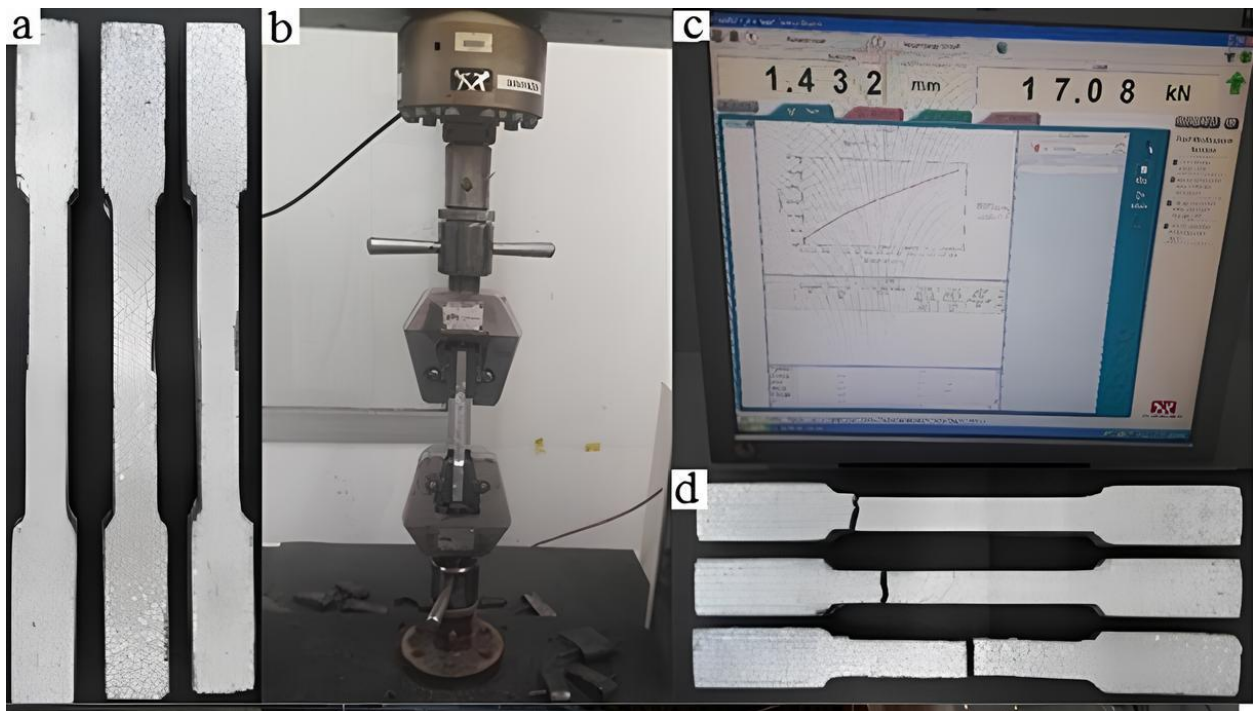


Figure 5. Tensile test procedure (a) Specimens before fracture, (b) Tensile test machine (c) monitor display, (d) specimens after fracture.

2.6.2. Hardness test

Rockwell hardness test was conducted on each specimen using a hardness testing machine, as shown in figure 6. The test scale was set at HRB, meaning 100 kgf. Ten hardness readings were taken at random for each sample. Rockwell hardness number was gained by calculating the average amount of obtained data. The Rockwell hardness test was conducted according to ASTM E18.



Figure 6. Rockwell hardness test machine and a specimen under the test.

3. Results and Discussion

The subsections below present the results of laboratory experiments, including microstructural analysis and mechanical tests. The microstructural analysis was performed by optical microscopy, while mechanical tests were conducted using hardness and tensile testing machines.

3.1. Micro-structure Analysis

The application of mechanical vibration had a profound impact on the micro-structure of LM6 reinforced with 6wt.%Cu. In the non-vibrated control sample, the micro-structure was characterized by coarse, circular eutectic silicon particles within large primary α -Al dendrites. In contrast, the vibrated samples exhibited a significantly refined micro-structure. As the vibration frequency increased, the grain size decreased progressively. These outcomes are consistent with the findings of Al-ethari et.al [13]. Furthermore, mechanical vibration modified the morphology and distribution of the eutectic silicon phase. The coarse needle-like silicon particles observed in the control sample were transformed into a finer, more fibrous or globular morphology in the vibrated samples.

When applying different vibration frequencies during solidification, a slight change in the micro-structure features was observed. Figure 7 shows the micro-structure features of LM6 reinforced with 6wt.%Cu under 0, 5, 10, and 15 Hz. The figure displays slight changes in morphology structure due to different frequencies. Primary silicon experienced little changes from a big size plate into a smaller one, while the eutectic silicon that was coarse needle-like transformed into medium needle-like.

3.2. Mechanical Properties

The following subsections address the results of mechanical testing performed on the samples, including tensile and hardness tests.

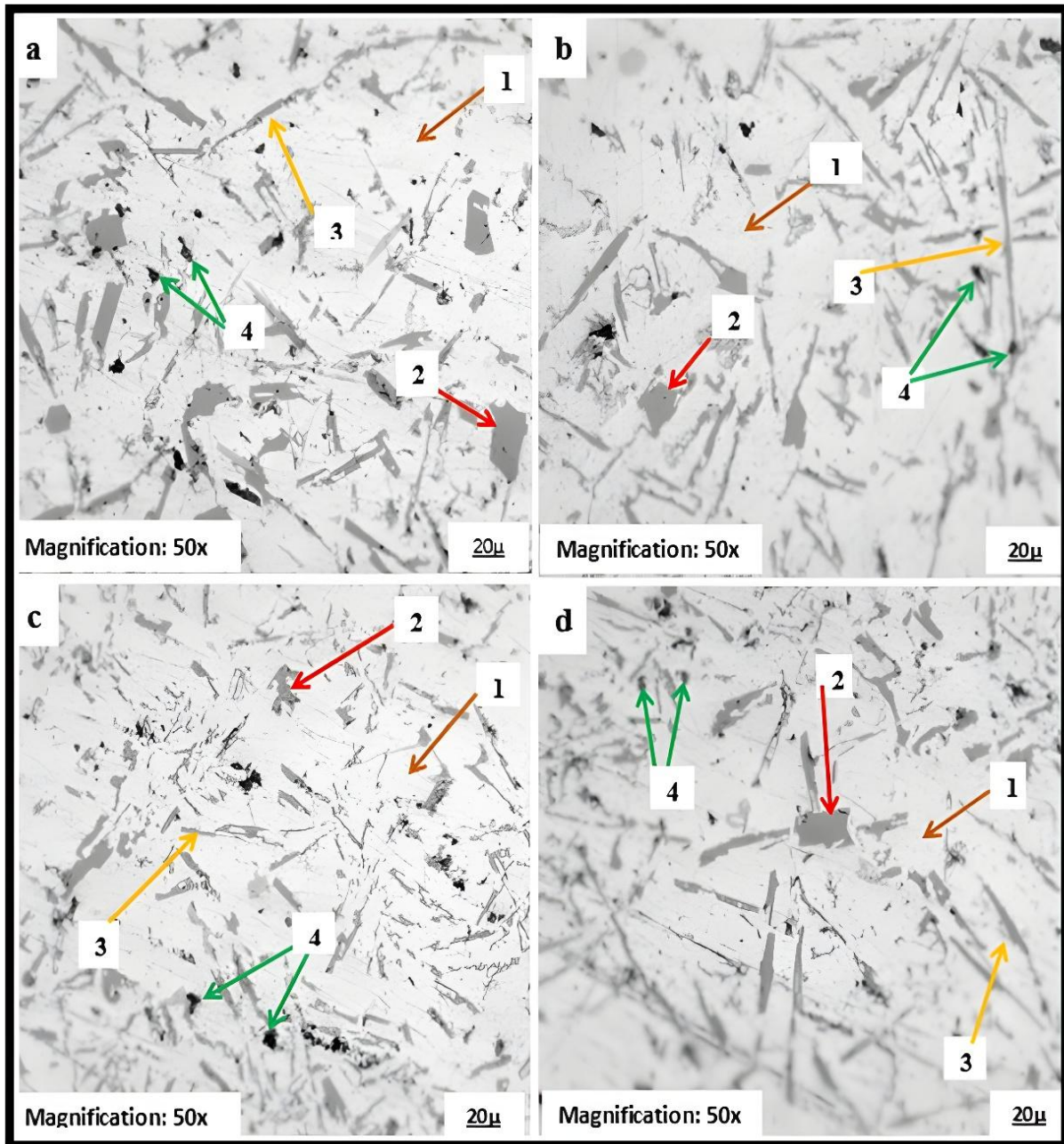


Figure 7. Micro-structure of LM6 under applying different frequencies vibration 1- α -Al primary, 2- primary Si, 3- eutectic Si, 4-copper

3.2.1. Tensile Strength

The micro-structural refinements achieved through mechanical vibration translated directly into enhanced tensile properties. The tensile strength of LM6 reinforced with 6%Cu increased significantly with the application of vibration. This improvement is attributed to the combined effects of grain refinement and the modification of the eutectic silicon morphology. The experimental results align with findings from previous studies [10, 13,14], which have consistently shown a positive correlation between micro-structural refinement and the tensile strength of LM6 reinforced with 6%Cu.

Figure 8 noted that applying vibration during the solidification stage for LM6 reinforced with 6%Cu increases tensile strength, especially at 10 Hz, which is clearly changing by 6.4%, while the increment percentage of tensile strength from 0Hz to 15Hz is just 4.5%.

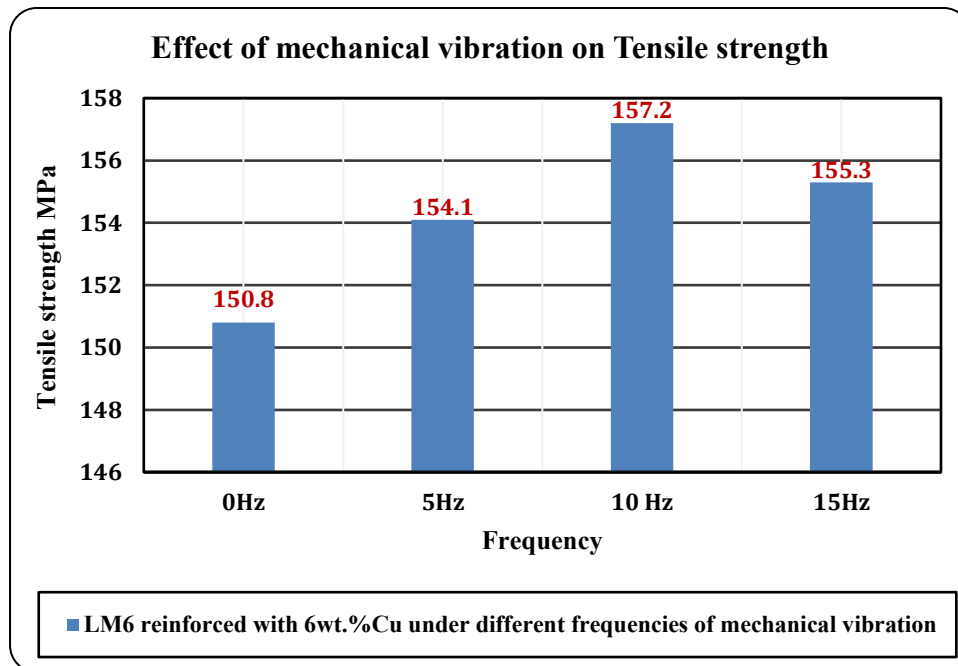


Figure 8. Tensile strength of LM6 under applying different vibration frequency

3.3. Hardness

Figure 9 shows that when applied different frequencies, the hardness was increased, particularly at 10Hz due more refinement grain structure during the solidification stage. The hardness of 5Hz, 10Hz, and 15Hz were increased by 2.5%, 5.2%, and 3.3%, respectively. The hardness was increased with increasing vibration frequency, the maximum hardness at 10Hz that was 58.4 HR.

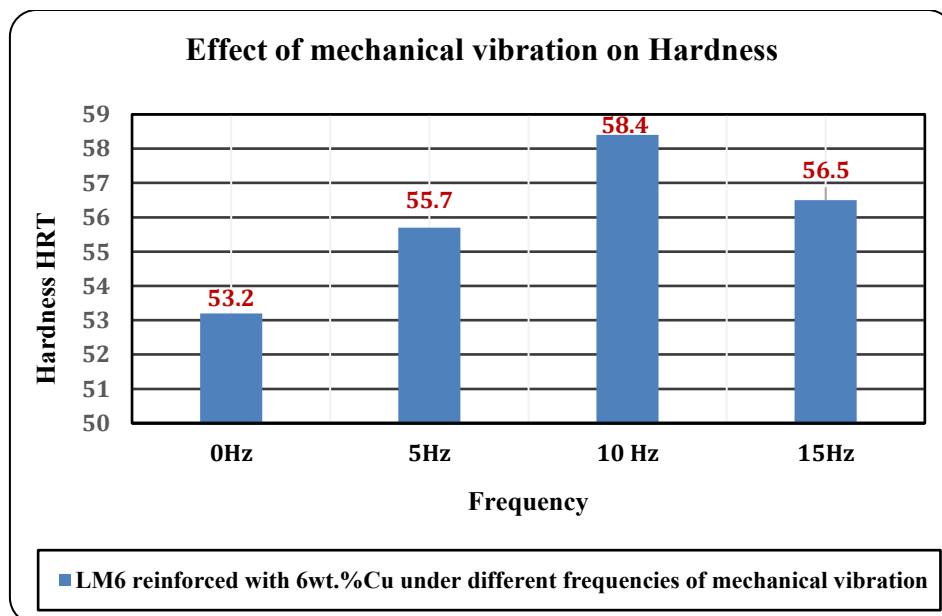


Figure 9. Hardness of LM6 under applying different vibration frequency

The above figures show that by applying 10 Hz mechanical vibration, the grain size became smaller and the silicon eutectic had a more uniform distribution, which resulted in improved tensile strength reaching 157.2 MPa and hardness reaching 58.4 HR. In comparison, by applying 15 Hz, the grain size returned

to being bigger, and the silicon eutectic had a less uniform distribution, which in turn decreased both tensile strength (155.3 MPa) and hardness (56.5 HR). From the microstructure view in Figure 7, as shown in Figure 7c, under vibration at 10 Hz, the morphological components show a more homogeneous distribution and smaller grains compared to those in Figures 7a, 7b, and 7d. At 15 Hz vibration, it returns to a less homogeneous distribution and larger grain size, as shown in Figure 7d. This may be caused by turbulent flow of the molten mass during pouring into the mould.

4. Conclusions

In conclusion, this investigation confirms that the application of mechanical vibration during the solidification stage of LM6 reinforced with 6%Cu is an effective method for refining the micro-structure and enhancing tensile strength and hardness. The key findings indicate that vibration promotes a finer, more equiaxed grain structure and modifies the eutectic silicon phase from a coarse, acicular morphology to a fine morphology. These micro-structural changes are directly responsible for the significant improvements observed in the alloy's mechanical properties. The results underscore the potential of using controlled vibration as a processing tool in the casting industry to produce high-performance Al-Si components for demanding applications in the automotive and aerospace sectors. However, the research reveals that frequency must be tightly controlled, as frequencies both below and beyond 10 Hz yielded suboptimal results in this work. Future work should focus on optimizing vibration parameters for LM6 reinforced with other alloying elements and scaling the process for industrial production.

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