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# Investigation of The Effect of Mechanical Vibration Applied During Solidification on The Microstructure and Properties of Aluminum 356 Alloy

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## Abstract

Manufacturing by casting method in aluminum and its alloys is preferred by different industries today. It may be necessary to improve the mechanical properties of the materials according to different industries and different strength requirements. The mechanical properties of metal alloys are directly related to the microstructure grain sizes. Therefore, many grain reduction methods are used during production or heat treatment. In this study, A356 alloys were molded into molds at 750 °C and exposed to vibration frequency at 0, 8.33, 16.66, 25, and 33.33 Hz during solidification. Optical microscopes images were analyzed in image analysis programs to measure the grain sizes of the samples that solidified after solidification. In addition, microhardness tests of samples were carried out to examine the effect of vibration and grain reduction on mechanical behavior. In the analyzes made, it was determined that the grain sizes decreased from 54.984 to 26.958 µm and the hardness values increased from 60.48 to 126.94 HV with increasing vibration frequency.

**Keywords:** Casting, A356, Aluminum, Vibration

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## 1. Introduction

Since the day it was discovered, aluminum has been followed with interest by different researchers and industries and many studies have been done on it. Aluminum alloys, on the other hand, have been widely preferred in the defense and aerospace industry, as in all other industries, with their low densities and high strength/low-density ratio according to alloy types. Aluminum – Silicon (Al-Si) alloys are highly preferred in fabricated production thanks to their casting ability, high strength/mass ratio, dry abrasive wear and corrosion resistance, and weldability. It is also used in the automotive, aerospace and defense industries. In addition to the mechanical strength of aluminum alloys in the initial alloy state, it is necessary to increase their mechanical properties for some applications. While increasing the mechanical properties, different additional processes can be applied before, during and after manufacturing [1-4].

The grain refinement method is considered an important method to increase the mechanical strength of aluminum alloys. In grain refinement, besides adding grain refiners to the aluminum alloy, the vibration method, which is the main subject of our study, is also used. It was determined that the distances between the dendrite arms were shortened, and the grains became thinner with the application of vibration at different frequencies. The outputs of sample studies on this subject are given below. Different researchers have studied the process of vibration during manufacturing (during solidification) in different vibration aluminum alloys and different vibration times [5-7].

Kocatepe et al., in 2000, during the solidification process of unmodified and sodium-modified A356 aluminum melted at 730 °C, vibration between 15 Hz and 41.7 Hz was applied for 30 minutes. As a result of the investigations, both the shortening effect of the vibration in the solidification time and the thinning of the grain sizes were determined [2].

In the study of G. Chirita et al. in 2009, AlSi 18 aluminum alloy melted at 800°C was preferred. On the other hand, Molten aluminum was poured into molds kept ready at 130°C by preheating and solidification occurred with vibration at 0, 8 and 24 Hz. The samples were tempered at 200 °C for 8 hours as a post-casting process after solidification. In addition to microstructural examinations, tensile tests were applied to the samples obtained. The particle sizes of the sample produced at 8 Hz are the finest; The particle sizes produced at 24 Hz were recorded as the thickest. The same ranking was in question for tensile strength. [8]

In their work published in 2019, Promakhov et al., unlike standard casting, studied the combination of composite material and aluminum. They produced a non-vibrating A356 alloy, vibrating A356 alloy and vibrating $TiB_2$ added A356 aluminum composite sample. As a result of the examination, an improvement was observed in both mechanical properties and microstructure with grain refinement between the non-vibrating and vibrating samples. When the $TiB_2$-added A356 composite sample was examined, it was concluded that the mechanical properties were improved compared to the vibrating A356 aluminum alloy. [9]

In the study published by Selivorstov et al. in 2017, vibration at 100 Hz, 150 Hz and 200 Hz levels were applied to A356 and A 356 with ultrafine powder modifier modification. At 100 and 150 Hz, 20% and 10% improvement were observed in tensile and yield strength, respectively, compared to non-vibration samples. A high porosity structure was observed in the sample solidified at 200 Hz and was excluded from the test. [10]

In 2018, Yüksel examined the effect of vibration on solidification in primary and secondary aluminum (scrap aluminum) parts, both in different cross-sections and in vibratory and vibration-free casting. As a result of the examination, it was observed that the distance between the primary and secondary dendrite arms was shortened by vibration. In addition, it has been stated that the use of secondary aluminum is avoided due to pollution and impurities in the production of critical parts. [11]

In the study published by Sulaiman and Zulkifi in 2018, LM6 and LM26 aluminum alloys melted in a 600 °C furnace were preferred. Sample production was performed by applying 0 Hz, 5 Hz and 9 Hz vibrations, respectively. Hardness and tensile tests were applied to the produced samples, and it was observed that vibration positively affected hardness and tensile strength for both sample types. In addition, the microstructure examination concluded that as the vibration level increased, the fine grain formation and porosity values decreased. [12]

In the study published by Rao et al. in 2019, tensile strength, hardness, compression test values, and abrasive wear values were investigated in Al-18 wt% Si solidifications made by applying vibration at 0 Hz, 10 Hz, 20 Hz, 30 Hz, 40 Hz and 50 Hz frequency, respectively. As a result of the tests and investigations, it was determined that the increase in vibration.[13]

In this study, the microstructure after sanding and polishing for all samples that were vibrated at 0 Hz, 8.33 Hz, 16.66 Hz, 25 Hz and 33.33 Hz with the help of rpm-driven vibration mechanism during the solidification of A356 aluminum. has been examined; porosity, abrasive wear, hardness and friction coefficient data were also calculated.

## 2. Materials and Method

A356 Aluminum alloy samples were adjusted to have a mass of about 2 kg and were respectively melted in an electric resistance furnace at 780±5 °C in the crucible. (Fig. 1.) The material characterization of A356 aluminum alloy according to literature [14] is given in Table 1.

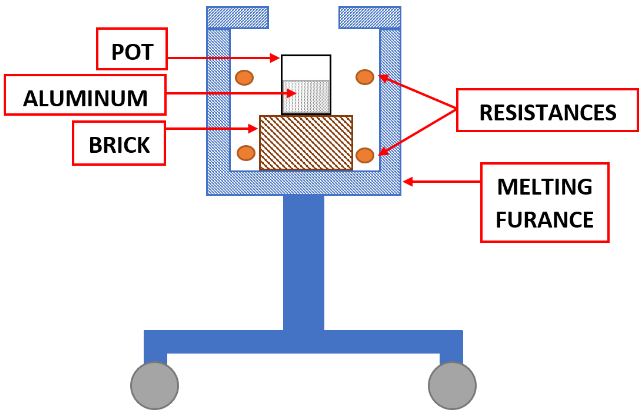



Fig. 1. Electrical Resistance Melting Furnace

Table 1.
The Chemical Composition of A356

| Si | Fe | Cu | Mn | Mg | Zn | Ti | Others | Al |
|---|---|---|---|---|---|---|---|---|
| 6.5-7.5 | 0.15 | 0.20 | 0.10 | 0.30-0.35 | 0.10 | 0.20 | 0.15 | rem |

For casting, glass tubes in a metal cylindrical pot, insulated with soil, were pre-prepared for all samples. In order to minimize the amount of air in the metal structure during casting, the mechanism was prepared so that the angle between the ground and the metal pot was approximately 70°.

Immediately after casting, the sample was quickly placed on a vibrator with an RPM-adjusted horizontal, circular motion mechanism with an interface on which the cylindrical mold would sit, and vibration was applied (except for the non-vibration poured samples). The casting of molten aluminum into the glass tube.

Samples with five different vibration parameters were cast from the A356 alloy melted in the same crucible. The samples were kept on the vibrator for 90 seconds at 0, 500, 1000, 1500 and 2000 rpm, respectively. The vibrations applied from the 1 rpm ~ 0.0167 Hertz equation correspond to 0 Hz, 8.33 Hz, 16.66 Hz, 25 Hz and 33.33 Hz, respectively. The formula for calculation is:

$$RPM = Hz \times 60 \tag{1}$$

$$Hz = \frac{RPM}{60} \tag{2}$$

After the solidification was completed, the samples were left to cool at room temperature for approximately one hour and were taken out of the glass tubes as a single piece. After cooling, it was removed from the cylindrical pods and dimensional adjustment was made by turning operation. Specimens were cut to 15mm length and mounted for easy sanding, polishing and inspection.

In order to examine the effect of vibration on the porosity of the material, porosity test was applied to each type of sample. The masses of the samples in air and water are weighed with the help of Sartorius CPA224S model precision balance in Kırıkkale University casting laboratory, and firstly, their true density;

$$\rho_{exp.} = \frac{G_{dry}}{G_{dry} - G_{wet}} \times \varphi \tag{3}$$

$\rho_{exp.}$. is the actual density of the sample after production, $G_{dry}$ is the dry weight, $G_{wet}$ is the wet weight, and φ is the density depending on the water temperature.
Calculated with the formula. In order to find the porosity percentage;

$$\%_{porosity} = \frac{\rho_{teoritical} - \rho_{exp}}{\rho_{exp}} \times 100 \tag{4}$$

Formula has been used. In the calculations, the theoretical density of A356 was taken as 2.685 g/cm3 [13].

After the mounting process, all samples were subjected to sanding and polishing. After the polishing process, images were taken from different parts of the samples with the help of Nikon ECLIPSE MA100 optic microscope. In addition, the distance between the 2nd dendritic arms for all samples was calculated with the help of ImageJ program.

In order to examine the effect of vibration on the wear resistance of the materials, 40 mt distance length, 400 P sandpaper for each sample was tested at 70 RPM speed and 5N load, in Kırıkkale University casting laboratory wear test device. The wear amounts were calculated by measuring the pre-test and post-test masses of the samples in grams with the help of precision scales.

Depending on the obtained hardness and wear values;

$$w = k \times F_n \times s \tag{5}$$

$$k = \frac{w}{F_n \times S} \tag{6}$$

The friction coefficients of the samples were calculated according to the vibration levels. In the formula 5, w: volumetric loss, k: coefficient of friction, $F_n$: force applied during the wear test (N), and S: the frictional path (m). The mass loss m during the wear test gives the output; The m value and the density (d) value and the v value (the volumetric value of the mass loss) are calculated. The win the formula 5 represents the volumetric value of the mass loss which is the result of mass divided by density. Formula 5 gives the output k depending on Formula 6.

# 3. Research Results and Discussions

## 3.1. Porosity

As a result of the porosity tests, the vibration-free sample's porosity was 7.9740%. In contrast, it was found to be 25 Hz, inversely proportional to the vibration during solidification. It was determined that it decreased up to the vibration frequency—25 Hz. At the vibration frequency, the pore value decreased to 1.1418%. However, it was determined that the porosity value increased to 2.0320% at the vibration frequency of 33.33 Hz. Similar results were reported by Kocatepe et al. (2007) in their study with LM25 alloy [15]. The porosity ratio according to vibration frequency is given in Figure 2.

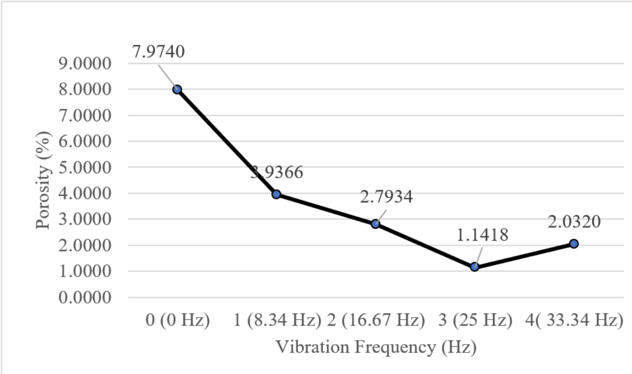
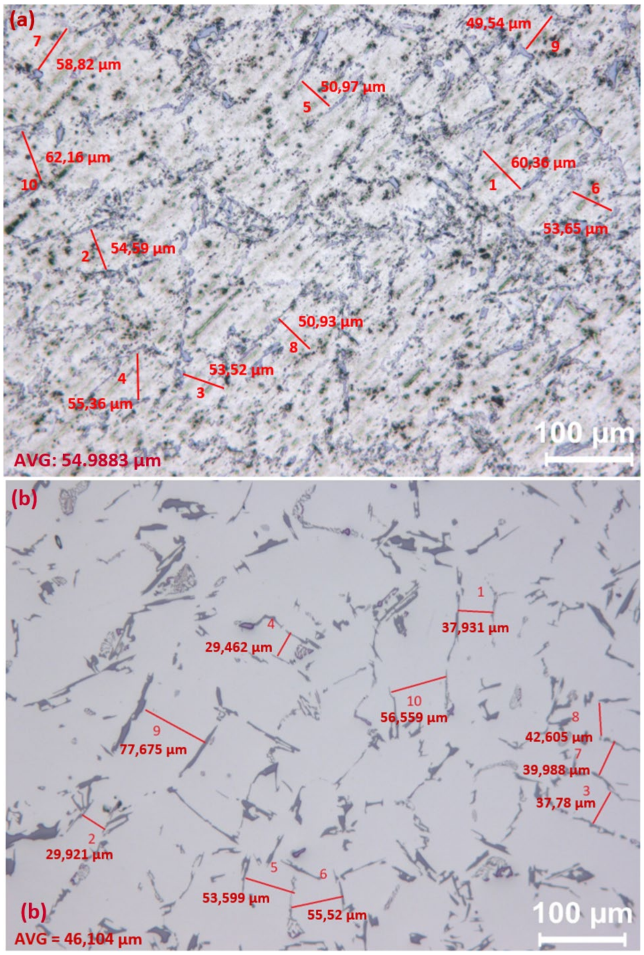



Fig. 2. The Graph of Porosity (%) - Vibration Frequency (Hz)

When we look at the porosity rates of A356 alloys solidified at different vibration frequencies given in Figure 5, it is seen that porosity decreases with increasing vibration rate. Liquid aluminum, which had difficulty moving between the dendrite arms during solidification with increasing vibration, gained the opportunity to infiltrate these areas with the effect of vibration. Thanks to the dendrite arms decreasing with increasing vibration, the closed pore rate decreased and the liquid metal filled the gaps between the dendrite arms.

## 3.2. Microstructure Characteristics

In the microstructure examinations of the samples, shortening was observed in the distances between the second dendrite arms in direct proportion to the vibration rate. In order to verify the shortening data, the distance between the dendrite arms was calculated from 10 different regions for each vibration level with the help of ImageJ program and the averages were taken. According to the vibration types, the microscope images of the samples under 100x zoom and the distance between the second dendrite arms are measured. The data of the measurements and averages of the distances between the dendrite arms are given in Figure 3; the graphical representation of the results is given in Figure 4.



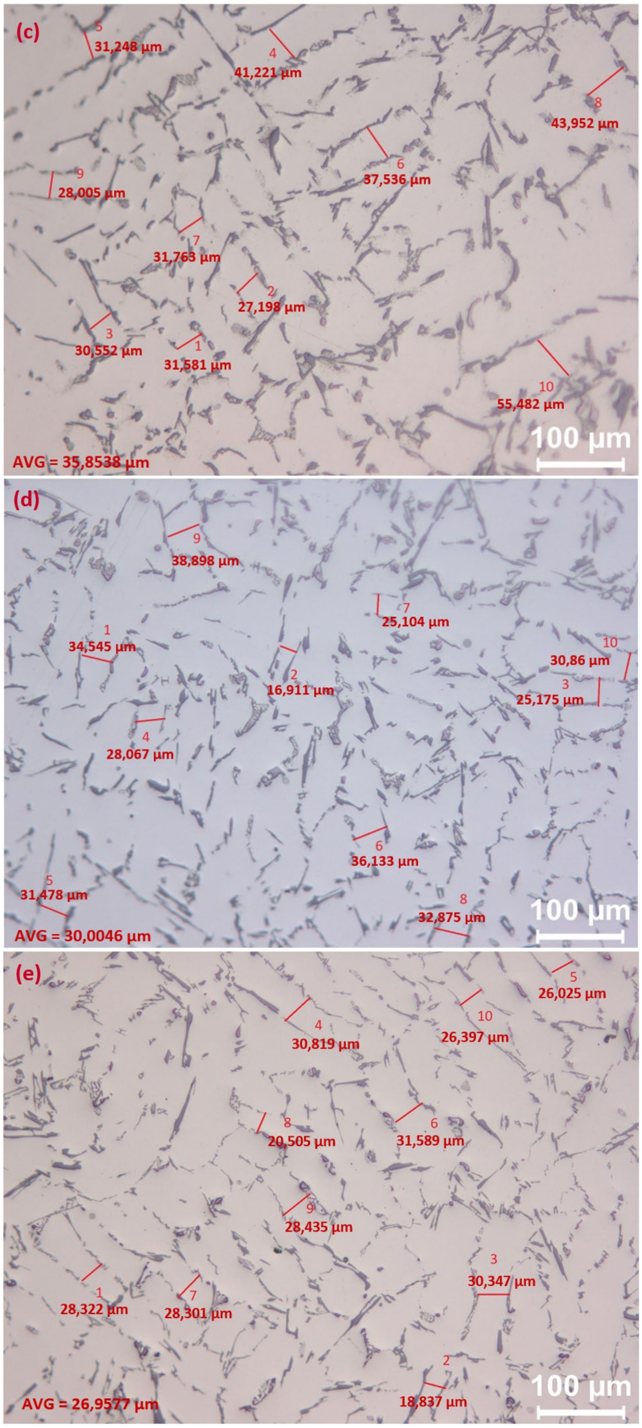




Fig. 3. Microstructure image of the tested A356 Alloy samples (a) Vibration Free Sample; (b) 8.34 Hz Vibrated Sample; (c) 16.67 Hz Vibrated Sample; (d) 25 Hz Vibrated Sample; (e) 33.34 Hz Vibrated Sample.

Figure 4 shows that the distance between the secondary dendrite arms shortens with increasing vibration frequency during increasing solidification. While the distance between the secondary dendrite arms was approximately 55 microns in the vibration-free solidified A356 sample, this distance decreased to approximately 27 microns at 33.34 Hz vibration.

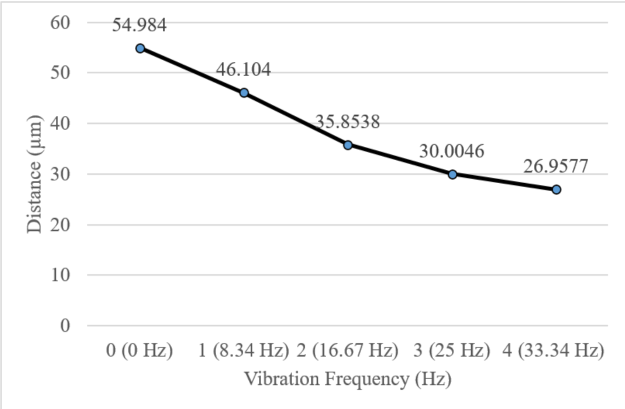



Fig. 4. The Graph of Distance (µm) - Vibration Frequency (Hz)

In the vibration frequency - secondary dendrite arms length graph given in Figure 4; it is seen that the secondary dendrite arms become smaller. Therefore, the grains in the microstructure become smaller. The shrinkage in the dendrite arms allowed more molten aluminum to enter between them, thus reducing the porosity rate, as seen in Figure 2.

## 3.3. Hardness Measurement

Hardness values in Vickers (HV) were taken from 5 different regions for the samples solidified in each different vibration type and the average data for each type of sample were calculated. The graph of the Vickers hardness data is given in Figure 5.

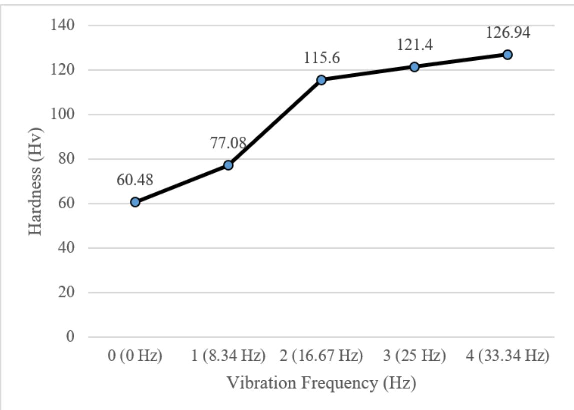



Fig. 5. The Graph of Hardness (HV) - Vibration Frequency (Hz)

When the hardness graph according to the vibration frequency given in Figure 8 was examined, it was determined that the Vickers hardness value increased with increasing vibration. This situation occurred due to the decrease in the distance between the secondary dendritic arms and the shrinkage of the grains. The increase in hardness values inversely proportional to the decreasing distance between the secondary dendrite arms indicates that vibration also achieves grain reduction during solidification.

## 3.4. Wear Test

Abrasive wear resistance test data of samples solidified at different vibration frequencies are shown in Figure 6. When the graph is examined, it can be seen from the microstructure images given in Figure 3 that the size of the dendrite arms decreases with increasing vibration rate. This situation also shows that the grains of the alloy have become smaller in the microstructure. Decreasing grain sizes causes the hardness and brittleness of the material to increase, according to the Hall-Petch equation [16]. The mass loss in the sample during wear is expected to decrease inversely proportional to increasing hardness values. In Figure 6, it is seen that the mass loss of the sample solidified without vibration decreased up to 25 Hz vibration, while a slight increase occurred at 33.4.

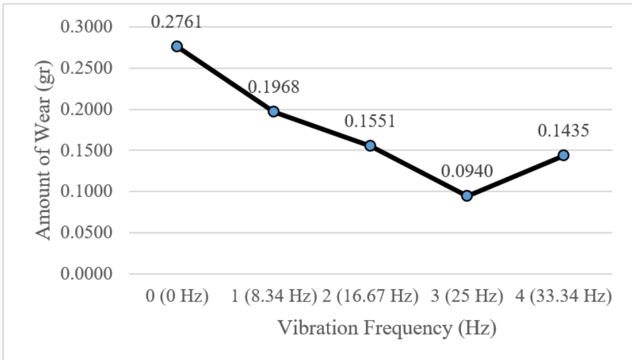



Fig. 6. The Graph of Amount of Wear (gr) - Vibration Frequency (Hz)

# 4. Conclusions

In line with the calculations, when the porosity data is examined, the porosity value of the sample solidified without vibration is more non-porous than all vibrating levels; It was observed that the porosity level of the sample solidified by vibration at 25 Hz was less porous than the sample at 33.33 Hz.

In line with the data obtained, it was determined that the effect of vibration on the microstructure was positive, as in other studies, and it was observed that the distance between the dendrite arms was shortened. Ten measurements for each type of sample were performed with the help of ImageJ program and averaged. The mean dendrite lengths (µm) of the samples solidified at vibration-free, 8.34 Hz, 16.67 Hz, 25 Hz and 33.34 Hz are 54.984, 46.104, 35.854, 30.005 and 26.958, respectively.

When the results were analyzed in terms of hardness, the averages of five hardness measurements in Vickers (HV) for each of the samples solidified at vibration-free, 8.34 Hz, 16.67 Hz, 25 Hz and 33.34 Hz, respectively, were 60.48, 77.08, 115.6, 121.4 and 126.94. As a result of the obtained outputs, it was concluded that the increase in vibration level affects the hardness positively and the increase in vibration level is directly proportional to the increase in hardness.

As a result of the examinations made specifically for the wear data, although an improvement was observed in the samples solidified at Vibration-Free, 8.34 Hz, 16.67 Hz, 25 Hz in accordance with the distance between the dendrite arms and hardness data, the solidified at 25 Hz in the sample solidified at 33.34 Hz was observed. More wear was observed than the sample.

Since the inputs in the coefficient of friction calculation are the volumetric equivalent of the data in grams obtained in wear and the hardness data, the outputs are similar to the wear data graphics and outputs, and the friction coefficient of the sample solidified at 33.34 Hz is higher than the friction coefficient of the sample solidified at 25 Hz.

When the general outputs are examined, it is concluded that the effect of vibratory solidification up to 33.34 Hz on the microstructure and hardness is positive, and the vibration to be applied during solidification will have a positive effect on strength and similar properties, considering the geometry of the part to be produced.

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