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The Effect of Grain Refiner and Mechanical Vibration on Feedability in Sand and Plaster Mold Casting of Etial 177 Aluminum Alloy

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Abstract

Aluminum alloys are widely used in industry due to their many engineering advantages. In aluminum alloys, the final product properties emerge during the solidifacation process. For this reasons, the goal in casting aluminum alloys is to obtain a fine-grained structure by using grain refining alloys such us Ti and B. There ara also alternative methods for achieving a fine grain structure. In this study, the effects of grain refiner addition and mechanical vibration on the feedability of Etial 177 aluminum alloy cast in sand and plaster molds were investigated. A model with different solidification times was designed and castings were made in molds prepared using this model. Liquid metal cleaning, sand and plaster casting, density measurement by Archimedes' principle, cross-section and surface examinations, and pore measurement techniques were used in the study. When the results were examined, it was determined that the feedability values changed depending on the solidification time and the amount of pores decreased in fine-grained structures. It was observed that mechanical vibration has a positive effect on the internal structure, and it was determined that the pore value decreased even more in castings with grain refiner addition compared to castings without addition.

Keywords: Etial 177, Sand mold, plaster mold, Feedability, Grain refinement, Mechanical vibration.

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1. Introduction

Aluminum, which is the second most abundant metal in the earth's crust, is widely used in today's industry with its advantageous properties. Aluminum and its alloys, which are the most preferred metal after steel, maintain their importance thanks to their mechanical properties and their usage areas in industry are increasing (Zeytin 2000). It is widely used in motor vehicles such as private vehicles, public transportation vehicles preferred aluminum alloys are also used in the aerospace industry. Aluminum alloys, whose strength and impact properties have been improved with new designs and additive components, have taken their place as an important material in the defense industry (Başer 2013). Aluminum alloys are widely used in the automotive and aerospace industries due to their high strength, easy castability and corrosion resistance. It is one of the most widely used non-ferrous metals in the world and is used in many sectors with energy recovery and environmentally friendly manufacturing (Tokatlı et al. 2022). It has long been known that grain refinement applications, which are widely used in aluminum alloys for development studies, have positive effects. The addition of Ti at some scale to the molten metal results in a significant reduction in the grain structure, which can make the alloy easier to cast. This process can be clearly seen in the grain structure on the etched surface of the samples without addition and with some Ti and B addition (Çolak and Kayıkçı 2009). With the addition of 0.15% Ti, $TiAl_3$ compounds are formed in the molten metal and the melting temperature of pure aluminum increases from 660°C to 665°C. In this way, it is observed that a heterogeneous fine-grained structure is spontaneously formed on the aluminum $TiAl_3$ compound without the need for any supercooling (ΔT) during the cooling period

(Sigworth 1984). In addition to grain refinement processes, modification studies are also carried out in foundries (Çolak, 2019). In experimental studies, the microstructure and mechanical properties of the liquid metal are affected by the alloying elements (Cu, Ni, Ti, Mn, etc.) added. Pressure, cooling rates, casting temperatures, vacuum treatment, mechanical vibration, etc. can be counted among these factors. These factors also affect the microstructure, good feedability and mechanical properties of the materials (Davis et al. 1990), (Elliott 1990).

As a result of the mechanical vibration process, which is accepted to increase the mechanical properties of aluminum as well as Ti and B elements, which are accepted as grain refiners, especially grain and phase sizes are reduced and the gases dissolved in the molten metal can be removed from the liquid metal by the effect of surface transport. The fluidity of the molten metal is therefore improved and the slowdown in heat transfer due to the segregation occurring at the mold and metal interface can be reduced (Hasırcı 2017). Mechanical vibration is one of the factors that should have a frequent continuity. When applied at high amplitude and wide time intervals, negative effects (turbulence formation, gas (air) cavity formation, mold distortion, etc.) can be seen. When vibration is applied under appropriate conditions, it is seen that results similar to grain refinement and modification processes can be obtained. This method is also an easy and low-cost process that can be used in all casting methods (Lin et al. 2000),(Minkoff, 1983).

It is known that the addition of grain refining mastic alloy and mechanical vibration in the casting of aluminum alloys will reduce the grain size and consequently increase the feedability and reduce the porosity, which is also known in the literature (Chen and Zhang 2010). One of the main purposes of grain refinement is to reduce the amount and size of porosity in the material (Sigworth and Kuhn, 2007). In the casting of aluminum alloys, the mechanical stirring process to ensure the homogeneity of the molten metal in the mechanical stirring method is mostly provided by a drill or impeller system (Fan 2002), (Figueredo 2001). Stirring is applied during the solidification period in order to form a non-dendritic microstructure. However, many problems have been encountered in the applications of mechanical mixing method. The electromagnetic mixing method was developed to solve the problems encountered in mechanical mixing. In this technique, rods with dendritic-free internal structure can be produced with electromagnetic stirring created in the casting line. It has been reported that the products manufactured by this method have a particle size between 30μm-100μm A study in which the effect of vibration during the solidification process of the A356 alloy was investigated and a comparison was made with the casting part solidified in a sand mold normally at different vibration intensities and without vibration was examined. As a result of the examination, it was seen that solidification under vibration had a positive effect on the properties of A356 aluminum casting alloy by reducing the grain size (Çolak and Balcı 2016). One of the conditions that have an effect on grain size is solidification time. Solidification time can be calculated by the Chvorinov formula, which ratios the volume (V) of the casting to the surface area (A). The equation obtained with this relation is $t=k(V/A)^2$. While t in the equation is the solidification time in minutes, k is the equation constant that varies depending on the casting alloy and mold material (Chvorinov 1940).

Under the basic basic integrity of the study is the issue of improving the properties of aluminum, and the concept of another branch of this improvement is the concept of feedability. In the production of Al alloys by casting, the timing of solidification and the design of the molds are very important. During the transition from liquid to solid state, Al alloys shrink in percentages ranging from 3.5% to 8.5% by volume, depending on their chemical composition. This volumetric shrinkage can be supported by feeders that can be placed in the required dimensions in places that seem appropriate in the design of the molds. As a result of the volumetric shrinkage not being adequately fed by the feeders, voids occur in the structure formed after solidification. Shrinkage, also known as shrinkage, which is one of the problems experienced in aluminum casting processes, can cause more than one casting product to be scrapped. In order to obtain robust parts, the amount of shrinkage in macro and micro dimensions must be reduced (Çolak and Arslan, 2018).

In addition to improving the properties of aluminum, mold materials are also available in the casting industry to support this improvement in a positive way. Economical and readily available sand molds are widely used for casting metals. Sand mold casting is a metal casting method with sand as the mold material. The mechanical properties of the parts manufactured in the casting process are proportional to the mold and mold materials in which the casting process is performed. Sand mold material, which is cost-effective and easily accessible as mold material, is the most widely used mold material. The molding steps are performed by compacting the sand material around a casting model and then removing the casting model from the mold. Approximately 60% of metal casting processes are performed by sand mold casting (Çalık et al. 2022). The biggest advantage of the plaster-mold method, which is another mold material, is known as surface smoothness. However, solidification times are prolonged due to low heat transfer. Cooling plates can be placed in areas where rapid cooling is required. However, the low gas permeability and fragility of the gypsum mold material are disadvantages (Altıparmak 2007).

In this study, castings will be made with Etial 177 alloy in sand and plaster molds prepared with a ladder-shaped model designed to produce different solidification times. The effects of castings without addition, grain refiner addition and mechanical vibration on feedability will be investigated. In addition, different solidification times will also occur depending on the geometry of the ladder model in the experiments, so that the effects of solidification time on feedability will be discussed.

2. *Materials and Methods*

In this study, Al-Si based Etial 177 alloy with a wide solidification range was cast to exhibit different solidification times according to changing casting conditions. For this purpose, the ladder model, whose dimensions and solid model image are given in Figure 1, including different section thicknesses specially designed for varying casting conditions, was used.

The dimensions of the rectangular prism shaped model given in Figure 1 are 20x20 mm lower step, 30x30 mm middle step and 50x50 mm upper step. Modulus calculations were made for each step of the model. As a result of the calculations, while the modulus value for the lowest part was 0.33 cm, the modulus in the thickest section was calculated as 0.83 cm. Thus, it was determined that each step has varying modulus values (Kayikçi 2008).

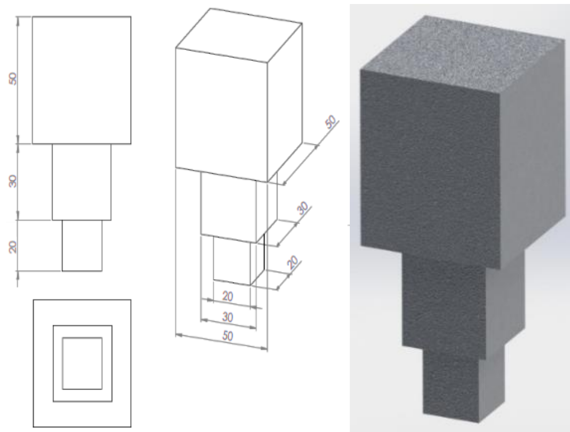

Figure 1. Model dimensions and solid model image.

Free model was used for the preparation of the molds. In the preparation of wet mold sand, 3-5% bentonite and 1-2% coal dust were added to dry silica sand with a grain size of 90-110 AFS and 5-7% water was added. After the necessary additions to the silica sand, mold material was obtained by homogeneous mixing. In the preparation of gypsum molds, the material called casting gypsum, which is sold commercially in the market and mainly used in the jewelry industry, was used. Gypsum mold slurry was obtained by mixing gypsum with water in the same ratio. By dissolving the gypsum material in water, the mold material was obtained in slurry consistency and poured into the degree in which the models were placed. Graphite was sprinkled as a mold release agent for easy removal of the model from the mold. Then, the molds of the models were formed with the prepared casting plaster. When the plaster molds reached a certain level of solidification and hardening, 2 hours after the gypsum slurry was poured into the degree, the models were removed. The plaster molds were then kept in the oven at 150°C for 24 hours. After firing, the molds were removed from the oven before casting, the runner connections were opened, the molds were made ready for casting and the stages were closed. Before casting, the mold was kept on the 80°C mold heater until casting to prevent moisture from the environment. Castings were made with alloys prepared in accordance with the experimental parameters.

Melting processes were carried out in the electric resistance furnace in our laboratories. SiC crucible with a capacity of 8 kg was used as a crucible in the furnace. In the study, castings were made in sand molds without addition, with grain refiner addition and under vibration in the same way. In addition, castings were made in gypsum molds in a total of 6 different changing parameters, including normal and under vibration. Al5Ti1B master alloy with 0.2% Ti was used for grain refiner addition. After the added alloy was melted in the furnace, nitrogen flushing was performed for 5 minutes with a graphite lance immersed in the crucible at 720°C to clean the liquid metal and then castings were made. For the casting experiments under mechanical vibration, the setup given in Figure 2 was prepared and the molds were solidified under vibration with the help of the setup. The vibration was turned on after filling the liquid metal into the mold and applied until the end of solidification. The sand mold was fixed to a plate to which an electric motor was connected with L-shaped profiles. The electric motor used is 130 W and 7000 rpm. In order for the electric motor to create vibration, vibration was provided with a weight attached to the rotor part of the motor.

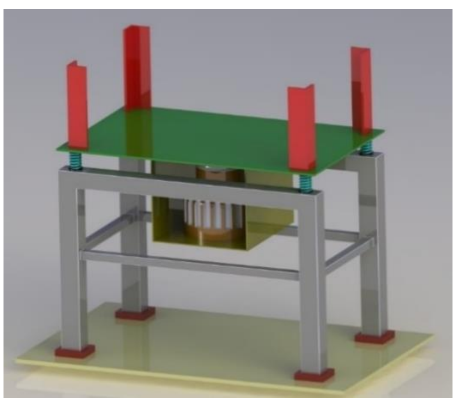

Figure 2. Illustration of the setup for solidification under mechanical vibration (Çolak and Balcı, 2016)

After cleaning, the RPT (Reduced Pressure Test) gas measurement test was applied to check the condition of the liquid metal. In this test method, the liquid metal is solidified under vacuum and then the sample is cut vertically in the middle and examined. The aim of the castings made within the scope of the study is to ensure that the gas level is at acceptable levels. Liquid metal cleaning was continued when necessary.

Following the casting tests, 2 ladder models were removed from each mold after solidification and separated from the runners. The demolded samples were first subjected to density measurements. Subsequently, one of the ladder model samples was cut vertically to check for depressions and the other one was cut horizontally for density measurement and pore determination from each step. The surfaces of the vertically cut specimens were sanded and transferred to the computer environment with the help of a scanner and the setup prepared for depression analysis in cross-section. Density measurements were made to determine the amount of pores in the inner cross-sections of the cast specimens under varying casting conditions and, accordingly, the feeding ability of the cast specimens removed from the mold. According to Archimedes' principle, each sample was immersed first in air and then in pure water and weighed in water. From the determined weights, the weight of the sample in air (m_h), the weight in water (m_s), the density of pure water at room temperature (d_s) and the density of the cast sample (d_n) were calculated according to the following formula (Taylor at al. 1999).

$$\mathbf{d_n = \frac{m_h}{m_h - m_s} \, x \, d_s} \qquad \text{(Equation 1)}$$

3. Experimental Results and Evaluation

3.1. Control of Chemical Composition Compliance

The chemical composition analysis results of the alloys used in casting experiments and the samples taken for the control of the amount of grain refiner addition are given in Table 1.

When the chemical composition values given in Table 1 are examined, it is determined that the alloys are within the standard composition range. In the experiments with grain refiner addition, Ti target ratios were found to be appropriate. It was targeted to add Ti at a rate of 0.2% for grain refinement, and since the critical threshold value for Ti addition is 0.15% Ti, it was determined that this ratio was achieved in all experiments.

Table 1. Chemical analysis result of alloys (% wt)

Alloy	Si	Fe	Cu	Mn	Mg	Zn	Ti	B	Sr	Al
Etial177	7.12	0.121	0.012	0.006	0.345	0.014	0.010	0.002	0.003	Rem.
Etial177+ TiB	7.01	0.122	0.008	0.007	0.364	0.011	0.192	0.011	0.004	Rem.

3.2. Liquid Metal Cleanliness Control Results

The formation of pores in the casting of aluminum alloys is due to various effects. These can occur due to shrinkage due to insufficient supply during solidification, due to gases dissolved in the melt, due to shrinkage and gas action. Pore formation in the samples included in the study will negatively affect the results. Due to this situation, in order to prevent pores due to dissolved gases, nitrogen cleaning was performed before liquid metal casting. Since the study compares pore formation based on underfeeding, possible gas-induced porosity will affect the results. For this reason, liquid metal cleaning process was carried out. After cleaning with nitrogen, the liquid metal was subjected to RPT test and the suitability of the cleaning was checked. The images of the specimens that were pressure tested after solidification are given in Figure 3. Figure 3 shows the cross-sectional surface results of the RPT sample taken after nitrogen purging for the alloy under all casting conditions. In all castings, it is understood that liquid metal cleaning process is suitable to prevent gas-induced porosity formation in the casting. Thus, it is thought that the possible porosities in the castings will not be gas- induced. Similar results were observed in the studies on liquid metal cleaning in the literature and the suitability of the liquid metal quality was confirmed (Dispinar and Campbell 2011), (Dışpınar and Campbell 2009).

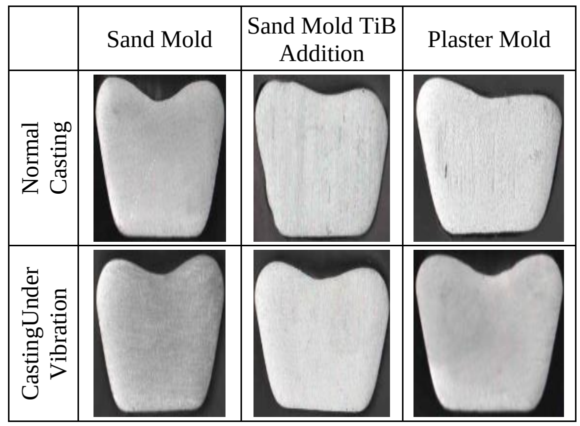

Figure 3. RPT specimen cross-sectional images obtained before casting tests.

3.3. Density Measurement and Pore Values

Table 2 gives the density and porosity results obtained after cutting the runners of the samples obtained from the casting experiments.

Table 2. Density measurement and pore values of cast samples as a whole.

Casting Method	Sample Name	Weight in air (g)	Weight in water (g)	Experimental Density (g/cm^3)	Theoretical Density (g/cm^3)	Calculated Pore (%)
Sand Mold	Gravity Sand Casting	380.20	233.78	2.59	2.68	3.28
Sand Mold	Casting Under Vibration	384.26	238.12	2.62	2.68	2.06
Sand Mold	Sand Casting with TiB Addition	381.46	236.84	2.63	2.69	2.12
Sand Mold	Under Vibration with TiB Addition	378.24	237.12	2.68	2.69	0.54
Plaster Mold	Gravity Plaster Casting	370.07	224.37	2.53	2.68	5.40
Plaster Mold	Casting Under Vibration	386.45	238.42	2.61	2.69	3.12

When the values given in Table 2 are examined, it is observed that the density and calculated pore values of the cast samples vary depending on the casting conditions. While the pore value in the sample was 3.28% in the normal casting test in the sand mold, it was determined that the pore value was 2.06% in the casting samples obtained by solidifying the same alloy under vibration. It is understood that the vibration acting on the casting molds during solidification has a positive effect on the internal structure of the casting and therefore on its feeding. It was found that the pore values decreased even more in grain refiner added castings made in sand molds compared to similar castings. It was measured that the pore value decreased from 3.28% in normal casting without addition to 2.1% with the addition of grain fining and from 2.06% to 0.54% in casting without addition under vibration. It is thought that the increase in feedability and the decrease in the pore value in the cast structure in both grain refiner addition and vibration casting experiments are related to grain size. In the casting of aluminum alloys, grain size will decrease with the addition of grain refining mastic alloy and mechanical vibration, and accordingly, feedability will increase and porosity will decrease, which is also known in the literature (Chen et al. 2010).

In normal castings made in gypsum molds, the amount of pores was 5.4% in normal casting and 3.12% in castings solidified under vibration. As in the sand mold casting experiments, it was determined that the amount of pores decreased as a result of solidification under vibration in gypsum mold casting experiments. However, among all casting tests, the most pores were found in the gypsum mold casting specimens. This is thought to be related to the lower heat transfer coefficient of the gypsum mold compared to the sand mold and the later solidification in the mold. Modulus castings that solidify later are expected to form larger grain structures. The lowest porosity value was observed in the test results both with the addition of grain refiner and solidified under vibration. Therefore, it was observed that the most effective factor in the feeding of the castings and the resulting pore values within the scope of the experiments was the reduction in grain size. In addition, the cast samples were cut at each section level and density measurements were made. The lower part is coded as thin, the middle section as medium, and the uppermost region as thick, with density measurements conducted. The results obtained are given graphically in Figure 4.

As can be seen in the graph given in Figure 4, different densities and accordingly different values of pores appeared in the sections of the sample under all test conditions. Depending on the solidification time, the amount of pores in the lower parts with the thinnest cross-section was found to be low depending on the solidification time, while it was found to increase in the middle and upper parts. This is related to the solidification time, also known as the modulus criterion in castings (Kayıkçı and Akar 2007), (Şirin and Çolak 2009). Depending on the casting test conditions, mold material and section thickness, the parts that solidify earlier have a finer grained structure and it is observed from the related results that the amount of pores decreases and the feedability increases. For example, the pore value of the sample obtained under normal casting conditions in the sand mold was measured as 1.92% in the lowest small part, 2.38% in the middle part and 4.14% in the top part. As a result of the density measurements made on the whole sample for the relevant part, the pore value was found to be 3.28% as given in Table 2. When the sample obtained under the same conditions was cut horizontally, different pore values were found at each level. This difference reveals the difference in density due to the whole sample and solidification time.

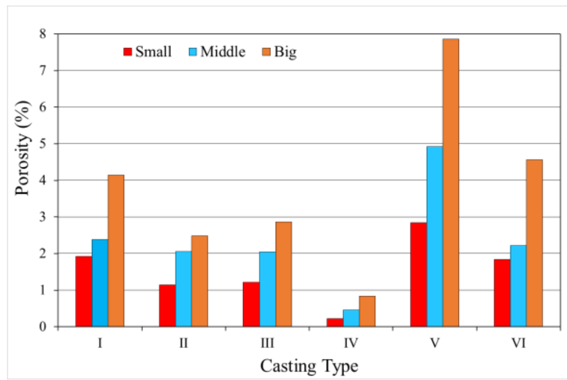

Figure 4. Pore values depending on casting sample section thicknesses. (I- Gravity Sand Casting, II- Casting Under Vibration, III- Sand Casting with TiB Addition, IV-Under Vibration with TiB Addition, V- Gravity Plaster Casting, VI- Casting Under Vibration)

3.4. Examination of the Cross-Sectional Surfaces of the Castings

In order to examine the pore condition and surface depression on the cross-sectional surfaces of the cast specimens, the specimens separated from the sprue connections were cut vertically in the middle and scanned images were obtained after sanding the surfaces. Figure 5 shows the scanned cross-sectional surface images of the specimens obtained from the experiments performed under normal casting conditions and Figure 6 shows the cross-sectional images of the cast specimens solidified under vibration.

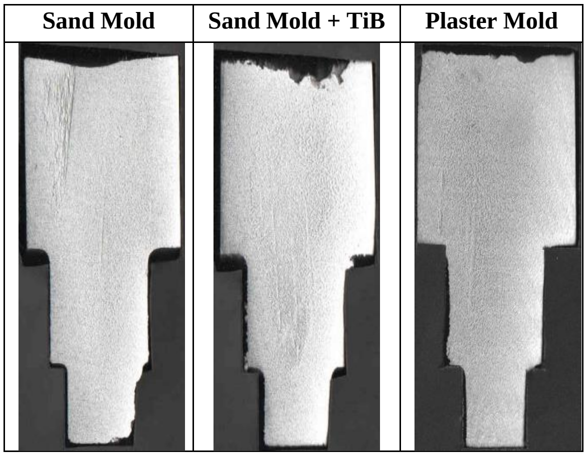

Figure 5. Cross sectional images of casting test speciment solidified under normal conditions.

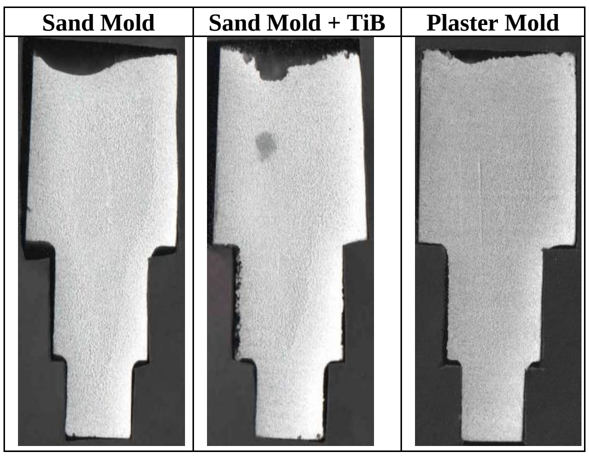

Figure 6. Cross sectional images of casting test specimen solidified under vibration.

When the cross-sectional surface scans of the cast samples given in Figure 5 and Figure 6 were examined, it was seen that the parts started to solidify from the bottom section, depending on the geometry of the cast samples. It is observed that the solidification direction continues and solidification occurs in the thickest section upper regions of the part. Therefore, shrinkage occurred on the casting surface under all casting conditions. Depending on the changing casting conditions, the shrinkage on the surface varies. This situation is thought to be related to the fact that the feed path remains open depending on the grain size, as expressed in the density measurements. When the existing literature on the subject is investigated, it is known that the addition of grain refiners increases the feedability in castings (Lee et al.1990), (Sabau and Viswanathan 2002). It is also known that mechanical vibration has a grain refining effect and reduces the grain size in castings (Kao and Chang 1996; (Sabau and Viswanathan 2002). In the examinations made according to the depressions on the casting surface, depending on the grain size, the shrinkage shape was observed to be conical downwards in some castings and wide in the castings with small grain sizes. Despite the pore values revealed according to the density measurement results in the cast samples, it is seen as if there is no shrinkage in the cross-sectional surface scanning picture. This situation shows that there is no macroporosity in the casting and possible shrinkages may occur as micropores. It is thought that this situation will be revealed in microstructure examinations in castings.

4. *General Results*

The results obtained from the experiments are listed below;

- It was determined that there were depressions on the surfaces of the RPT test samples and the liquid metal quality was appropriate in the cross-sectional surface examinations.
- It has been observed that the density and calculated porosity values in the casting samples vary depending on the casting conditions.
- It has been determined that the vibration affecting the casting molds during solidification has a positive effect on the internal structure and therefore the nutrition of the casting.
- It has been determined that the porosity values in castings made in sand molds with the addition of grain refiners decrease even more than in castings without additions.
- Among all casting tests, the highest porosity occurred in plaster mold casting samples. This is related to the fact that the heat conduction coefficient of the plaster mold is lower than the sand mold and the solidification in the mold is slower.
- It has been determined that the amount of pores in the thinnest-sectioned lower parts of the casting samples is low, depending on the solidification time, and increases in the middle and upper parts.
- It was observed that, depending on the geometry of the cast specimens, the parts started to solidify from the lower section and the solidification orientation continued and solidification took place in the upper regions of the part with the thickest cross-section.

5. *Acknowledgement*

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