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Investigating the Role of Pouring Temperature, Heat Treatment and Mold Preheating Temperature on the Hardness and Microstructure of the Inner Surface of Al-15Mg_2Si In Situ Composite Pipe Fabricated by Centrifugal Casting Method

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ABSTRACT

This study aims to place Mg_2Si reinforcing particles in the inner wall of aluminum matrix composite tube and optimize the microstructure and hardness of the mentioned wall using temperature parameters. Upon application of Al-Si alloy, creation of in-situ Mg_2Si particles in this alloy system, and production of the pipe as a result of the low density of Mg_2Si particles based on the centrifugal casting method, these reinforcing particles would be accumulated in the inner wall of the pipe. In this study, the effect of dissolution, aging, mold preheating, and pouring temperature on the hardness of the inner wall of Al-15 wt. % Mg_2Si alloy was investigated, and the most optimal manufacturing conditions as well the interaction among the variables were determined using Design Expert software to achieve the highest hardness. Of note, the most effective variable among the mentioned variables was heat treatment temperature, and the best temperature was about 535 °C. According to the findings, the best pouring temperature was obtained as around 700 °C; hence, a higher temperature is needed to preheat the mold to obtain reinforcement with uniform placement.

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1. INTRODUCTION

Compared to the ordinary alloys and unreinforced materials, composite materials have significant features owing to which, application of these advanced materials in different industries has increasingly grown. The main objectives of the developing composite materials can be summarized as follows: reducing the weight, elevating the strength-to-weight ratio, enhancing the elastic modulus, decreasing the thermal expansion coefficient as well as improving the thermal shock resistance, yield strength, creep resistance at high temperatures, fatigue properties at high temperature, and wear properties. Composites have a combination of properties that do not exist in metal, ceramic, and polymer materials alone;

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therefore, composites give us design power and this feature makes them unique.

The in-situ process is one of the common methods for producing cast aluminum matrix composites, which is thermodynamically stable where the reinforcing phase is basically formed in situ from the matrix by germination and growth. Special attention has been paid to these composites in recent years owing to their stable interface, ease of production, diverse mechanical properties, and low price. Unlike non-in-situ methods that always face problems such as non-wetting of reinforcing particles, control of the interface between particles and the ground, improper distribution of the particles, and agglomeration of the reinforcing particles, the in-situ method creates stable interfaces between the particles and the ground while its properties are mechanically suitable, and the manufacturing method is also simple [1].

1.1. Introduction of Al-Mg2Si Composite

Aluminum alloys are the most widely used light materials for use in the automotive industry to lighten the weights, enhance efficiency in fuel consumption, and reduce CO_2 gas. In the last 50 years, the amount of using aluminum alloys and other light alloys in different industrial applications has notably increased. Significant amounts and types of aluminum alloys are commonly used in the automotive industry in different parts such as engine cylinders, body, chassis, manifold, wheels, and decor. Due to the decrease and limitations in energy resources and the increase in the consumption of goods and energy in the world today, increasing applications of aluminum alloys owing to their lightweight and easy production and shaping (compared to other metals such as steel) in industries have gained more significance than before. In general, efficiency enhancement of aluminum alloys is classified into two groups: 1) increasing productivity by controlling the production process and 2) increasing productivity by improving the alloy characteristics. Al-Si alloys with a high percentage of Mg are cast-in-situ composites that have an Al matrix and hard Mg_2Si particles as the reinforcement. The Al-Mg_2Si alloys enjoy several advantages such as uniform distribution of reinforcing phase, high wettability of particles, and low cost of production that make them very suitable alternatives to the Al-Si alloys used in aerospace and automotive industries and other industries as well. Among the reinforcing materials that are used in the form of particles in metal-based composites, Mg_2Si has the lowest density; hence, it has a high potential to be used as a reinforcement in aluminum-based composites to reduce weight. In addition, the Mg_2Si compound is a semiconductor that has an FCC structure with lattice parameter a=0.6351 nm. This intermetallic composition is characterized by the melting temperature of 1083°C, density of $99.1*10^3$ Kg m^{-3}, high hardness value of 4500 NMm^{-2}, low thermal expansion coefficient of 7.5*10-6 k^{-1}, and relatively high elastic modulus of 120 GPa. It should be noted that in terms of properties and freezing behavior, there are many similarities between Mg_2Si and Si and between Al-Mg_2Si and Al-Si systems as well [2].

1.2. Centrifugal Casting

One of the new methods for shaping materials is centrifugal casting, which has been effectively used in different industries. In this method that functions based on the application of centrifugal force, the mold is movable and rotating, and the melt is added to it during the rotation of the mold which is generally made of steel, graphite, and stainless steel. This method is employed to produce a variety of parts such as all types of gas and water lines pipes, annular parts, pipe wall insulation, engine cylinders, pistons, train wheels, etc. In this method, the force is more concentrated in the outer wall part and by moving towards the inner wall, the centrifugal force is reduced, which leads to the accumulation of heavier particles in the outer wall and tendency of the lighter particles to be accumulated in the inner part of the final piece. The advantages of this method compared to the traditional casting method are briefly listed as follows: high manufacturing speed; high quality of the final part in terms of dimensional accuracy, suitable final surface, and low porosity on the surface; fast freezing with high metallurgical quality; and simple method as well as low machining required.

Upon using Al-Si alloy, creating in-situ Mg_2Si particles in this alloy system, and producing pipes through centrifugal casting method, these reinforcing particles will be accumulated in the inner wall of the pipe due to the low density of Mg_2Si particles. The tribological properties of the inner wall of the pipe could be improved by optimizing the microstructure and morphology of Al-Mg_2Si with additives and heat treatment cheaply and efficiently [3].

All metals capable of static casting can benefit from centrifugal casting for manufacturing; for example, alloy and carbon steels, heat and corrosion-resistant steels, gray cast iron, steel with a high percentage of alloy elements, non-ferrous metals, as well as non-metallic materials such as ceramics, glass, plastics and in general, any material that turns into a liquid phase can be manufactured based on this method [4]. In the centrifugal casting process, the fluidity behavior of the melt plays an important role in determining the quality of the final product. Viscosity is one of the important physical characteristics of the melt, which has an important effect on the flow behavior of the melt as well as the flow patterns inside the mold [5]. Many parameters are effective in the centrifugal casting process, including melt temperature, mold temperature, mold thermal conductivity, mold rotation speed, mold size, temperature and loading time in the mold, to name a few [6]. The rotation speed of the mold is one of the most important influencing parameters, which is directly related to the freezing speed of the molten metal. When the cylindrical mold is filled by the melt at different speeds, different flow patterns namely Ekman, Cote, and Taylor flows are formed [7]. The solidification rate of the molten metal in centrifugal casting is of high importance because of its great impact on the determination of mechanical and microstructural properties. The solidification rate of pure metal in centrifugal casting is measured by grain size and in Al-Si alloys by Secondary Dendritic Arm Spacing (SDAS). Areas with higher solidification speed have small equiaxed grains while areas with lower solidification speed have grains with higher roughness than others [8].

Zhai et al. [۹] employed the centrifugal casting method to create an FGM composite reinforced with in-situ particles of Mg2Si and added Si to increase the hardness of the pipe's inner wall. The results showed that with the accumulation of Mg_2Si and Si particles in the inner wall, the hardness improved significantly.

1.3. Mold Rotation Speed

An important factor in centrifugal casting is to maintain the inner circular shape against gravity, longitudinal tearing, and stresses during rapid solidification of the molten metal against the mold surface. Compared to other parameters, the mold rotation speed is the main and most influential parameter affecting the solidification rate and particle distribution in alloys under centrifugal force.

Upon increasing the rotation speed of the mold, the shrinkage defect decreases while the tensile strength increases [10]. As the mold rotation speed increases, the thickness of the Mg_2Si-rich layer decreases, but the volume fraction of the Mg_2Si-rich layer increases, and the segregation of reinforcement particles intensifies [11]. Arefkhani et al. investigated the effect of mold rotation speed on the microstructure and hardness of Al-WC composite made by the centrifugal casting method. The best rotation speed of the mold for proper positioning of the reinforcement and creating the highest hardness was determined to be 1500 rpm [۱۲]. Nirumand et al. investigated the effect of mold rotation speed on the hardness and mechanical properties of Al-15 wt. %Mg_2Si alloy made by centrifugal casting method. Upon increasing the mold rotation speed, the thickness of the area containing the reinforcement decreased while its compression and hardness increased [۱۳].

1.4. Pouring Temperature

If the temperature of the molten metal or its fluidity is too high, the molten metal will not reach the speed of the mold quickly and the solidification time will also increase. Changing the pouring temperature affects the microstructure and distribution of particles in the casting. Low melt temperatures lead to maximum grain refinement and coaxial structures while higher temperatures promote columnar growth in many alloys. However, it should be noted that scientific considerations limit the used temperature range. Increasing the pouring temperature causes an increase in the grain Size and Dendritic Arm Distance (SDAS), particle separation, and solidification time. The pouring temperature must be high enough to satisfactorily flow the metal while avoiding the formation of rough structures and the increased risk of hot tearing due to overheating.

Morgan et al. [۱۴] investigated the effect of centrifugal casting parameters on the microstructure of Al-SiC composite. The results showed that increasing the pouring temperature leads to the production of denser pieces with better mechanical properties. Slower metal feeding speed and mold rotation speed reduce heat accumulation and metal volume before solidification.

Different factors were found to be effective in the separation of particles and their distribution in the part obtained from centrifugal casting including the pouring temperature, mold temperature, and G number ($G=\omega^2 R/g$ where R is the radius of the tube in meters, ω the rotation speed of the mold in revolutions per second, and g the centrifugal force). At the pouring temperature of 720 °C, mold temperature of 90 °C, and $G > 60$, the reinforcement particles accumulate in the inner layer. However, under the same conditions except for $G < 40$, the reinforcement layer is not formed, and the particles are spread on the cross-section [۱۵].

Increasing the pouring temperature leads to an improvement in the tensile strength and reduction in both hardness and tribological properties [۱۶].

Asan et al. [۱۷] investigated the effect of mold preheating temperature, pouring temperature, and pouring height on the mechanical properties of $Al_{12}Si$ alloy. According to their results, the most important parameters involved in their test were the pouring temperature, pouring height, and mold preheating temperature. The results showed that increasing the pouring temperature and decreasing the pouring height play a key role in maintaining the fluidity of the melt and better filling the mold and the properties of the final part.

Yisi et al. [۱۸] investigated the effect of pouring temperature on the microstructure of Al-5 wt. % Mg_2Si semi-solid hypoeutectic composite. The results showed that lowering the pouring temperature improved both α-Al structure and eutectic cell (α-Al+Mg_2Si) and reduced the formation of dendritic phases.

1.5. Mold Temperature

The temperature of the mold is an important parameter that affects the heat transfer rate of the melt and consequently the freezing rate in centrifugal casting. A change in the freezing speed causes a change in the mechanical properties of the centrifugal casting parts. At high freezing speeds, the possibility of creating shrinkage porosity becomes more than usual. On the contrary, when freezing happens gradually, the possibility of creating shrinkage porosity decreases. For this purpose, it is recommended to preheat the centrifugal casting molds up to a higher temperature range.

1.6. Heat Treatment Of Aluminum Alloys

The dissolution operation is normally performed at a high temperature close to the eutectic temperature of the alloy, which can homogenize the casting microstructure, dissolve intermetallics such as Al_2Cu, Mg_2Zn, and Mg_2Si, and make the eutectic Si spherical [١٩-٢٠]. In Al-Si-Mg alloys, Mg_2Si dissolves easily due to the high penetration rate of magnesium in aluminum while the microstructure and amount of magnesium affect the dissolution process [١٩,٢١].

Zedi et al. [٢٢] performed the dissolution operation at 520 °C for 6 hours and aging operation at 200 C for 6 hours in Al-10 wt. % Mg_2Si alloy. They reported the formation of the Mg_2Si phase from long rods to pseudo-short and spherical fibers changed shape. In a study, the effect of heat treatment on the morphology of primary and eutectic Mg_2Si was investigated. The results showed that the initial Mg_2Si morphology did not change much with the increase in the heat treatment temperature. In addition, since the penetration started from these areas into the background, the sharp corners were rounded and the eutectic Mg_2Si network was partially broken.

After the dissolution operation for 6 hours at 520 °C and 6 hours of aging at 200 °C, the morphology of eutectic Mg_2Si changed from long rods to short and round fibers. Moreover, the morphology of a part of eutectic Mg_2Si became spherical and crushed and the tensile strength improved by 26 % compared to the state without heat treatment.

2. MATERIALS AND METHODS

Figure 1 shows the flow chart of this research.

2.1. Primitive Material

In this research, Iralco pure aluminum ingot with 99.85% purity, magnesium ingot with 99.8% purity, and silicon with 99% purity were used to make Al-15%wt Mg_2Si in-situ composite.

2.2. Composite Manufacturing Method

To make Al-15%wt Mg_2Si (Al-9.5 Mg-5.5 Si) composite, aluminum was first melted in an induction furnace at 700 °C and then, the preheated silicon and magnesium pieces were added to it and kept at this temperature for 15 minutes. Next, it was molded and cooled down by room temperature. To make 2 Kg of this alloy, 1750 g of aluminum, 200 g of magnesium (including waste), and 115 grams of silicon are required. Due to the creation of a vortex in the casting in the induction furnace, there is no need to stir the resulting alloy.

To check the microstructure of the resulting alloy and ensure the proper formation of Mg_2Si as well as the absence of iron in the aluminum background, the obtained alloy was sampled, polished, and etched.

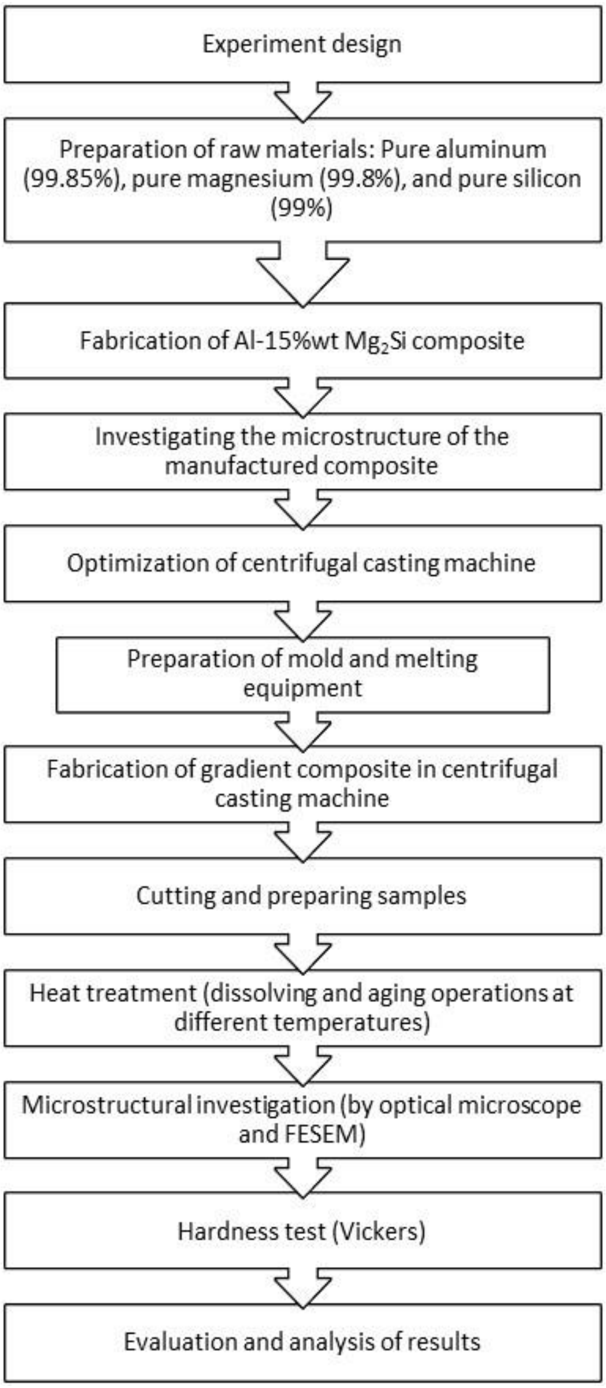

Figure 1. The flowchart of the path of this research

Finally, the prepared samples were examined by an optical microscope. The resulting alloy was used in centrifugal casting and remelted. For this purpose, a vertical centrifugal casting machine with the rotation speed of 1500 rpm was used. Followed by preheating the mold (at two temperatures of 150 and 300 °C), the said melt was cast at different pouring temperatures inside the rotating mold.

2.3. Construction Equipment

2.3.1. Induction Furnace

To make Al-15 wt. % Mg_2Si composite and to remelt the alloy for use in the centrifugal machine and tube forming, a medium frequency induction furnace was used.

2.3.2. Centrifugal Casting Machine

The mold of the device is made of cast iron with the inner diameter of 5 cm and length of 12 cm. The end of the mold was blocked by a cap with a muscle. A 1 HP single-phase electric motor was used to create rotational movement in the mold. To control the rotation speed of the mold, changing the ratio of the pulleys of the motor head and the shaft was used. The mold rotation speed can be calculated using Equation (1) [۲۳].

$$N2 = N1 * D1/D2 \qquad (1)$$

In Equation (1), N1 is the nominal speed of the motor (inserted on the electric motor), D1 the diameter of the motor, D2 the diameter of the motor installed on the mold shaft, and N2 the rotation speed of the mold.

Given that the desired rotation speed of the mold was considered fixed in this research and according to the nominal speed of the machine (900 rpm), two 6 and 10 cm pulleys were used to achieve the rotation speed of 1500 rpm. Figure 2 shows the image of the centrifugal casting machine used in this research.

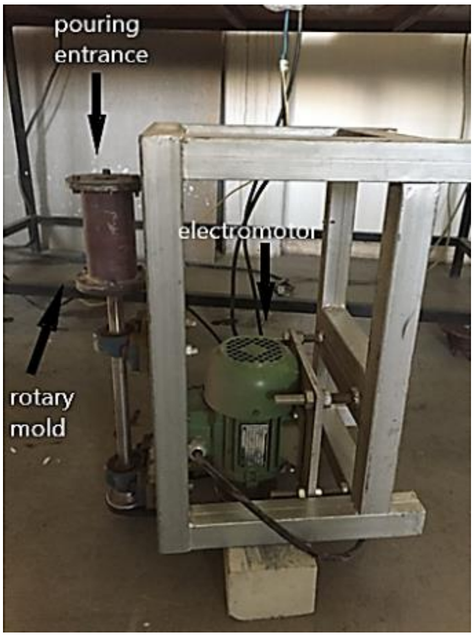

Figure 2. Side view of the centrifugal casting machine

2.3.3. Cutting Samples

To prepare the samples for the hardness test as well as microstructural investigations, it was necessary to prepare the inner surface of the composite pipes, which was done by cutting the samples with a band saw in larger dimensions and then sizing the samples with a grinding stone.

2.4. Preparation of Samples for Metallography

For this purpose, heat-treated samples are prepared at different temperatures and after that, sanding papers from P-80 to P-1500 were used to observe the microstructure by optical microscope and Scanning Electron Microscope (SEM). Polishing the samples was done using coarse sandpaper under water flow and was continued until the softest sandpaper. After changing each sandpaper, the sample was rotated 90 degrees. As the sandpaper became softer, the pressure applied to the samples on the polishing machine decreased, and this continued until the last deep scratches on the samples disappeared. Finally, to polish the surface of the samples, the samples were polished with felt and aluminum oxide on the polishing machine.

To observe the morphologies of the Mg_2Si particles and Mg_2Si phase in the alloy based on the characteristics of the Al-15 wt. % Mg_2Si alloy and that of the Mg_2Si phase, there was a need for deep etching. For this purpose, the samples were deeply etched in an aqueous solution containing 10% by weight of sodium hydroxide (NaOH) for 8 minutes [۲٤]. After that, the samples were washed with 90% ethanol and dried with a hair dryer.

2.5. Preparing the Mount

The shape and size of the pieces cut from the pipe were taken into account while carrying out the hardness test on the samples at ambient temperature, hence inevitable use of mounts. For this purpose, epoxy resin and hardener were used at the ratio of 2:1. After stirring for 5 minutes, this mixture was poured into a mount mold and heated at 70°C for further 30 minutes to solidify.

2.6. Equipment for Analyzing and Checking Mechanical Properties

After preparing the samples in the metallography laboratory, the microstructure of the composite was examined by an optical microscope. The samples were examined from 50 to 500 times magnification. Also, the cross-section of the samples was examined in terms of the thickness from the outer wall to the inside, and the distribution of the reinforcing phase (Mg_2Si) along the thickness was examined and photographed. Further, Image J software was used to measure different phases and microstructure measurements.

2.7. Field Emission Microscope (FESEM)

The field emission microscope device of Razi Metallurgy Research Institute was used due to its high resolution and quality that make it suitable to investigate the morphology of the reinforcement. The EDX analysis was also used to check the chemical composition of the surface of the parts.

2.8. Design expert software

Design Expert is a test design and results analysis software that works with the response surface method and provides powerful tools to ideally test your process, mixture, or combination of factors and components. The matching of the experimental and predicted results is done by ANOVA analysis and at the end, the prediction equations of the results can be extracted. Design Expert 10 software was also utilized in this study to design the experiment and analyze the results.

Akbarpour et al. investigated and optimized the hardness of Cu/SiC composite using the RSM method, and their experimental results were in good agreement with the predicted results [۲۵].

3. RESULTS AND DISCUSSION

Figure 3 shows the cross-section of the sample along the thickness. As shown in this figure, the Al-15 wt. % Mg_2Si gradient composite was successfully fabricated through the centrifugal casting method, and the reinforcing particles were placed in the inner wall of the cylinder. According to the deep etching and in order to determine the morphology of the reinforcement, the middle parts that contain the aluminum matrix and are empty of the reinforcement are corroded by the etching solution. These parts in this figure are depicted in dark color, showing the accumulation of the reinforcement in a dense manner in the inner wall.

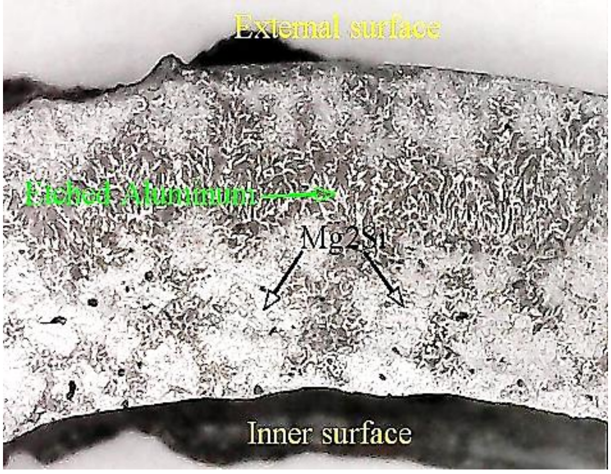

Figure 3. Image of a cross-section of the cylinder along the thickness of Al-15 wt. % Mg_2Si composite

The design of the experiment was done using Design Expert 10 software and based on the Central Composite Design mode, the variables and levels of which are listed in Table 1. It should be noted that the tests were performed in two blocks with preheated molds at two different temperaturees.

TABLE 1. Table of variables and levels of each variable

Name	units	Low	High	-alpha	+alpha
melt T	°C	650	750	600	800
heat treatment T	°C	500	570	465	605
Aging T	°C	170	210	150	230

The design table of the conducted tests is according to Table 2.

TABLE 2. Test design table and results

Std	Block	Run	Factor 1 B: Melt T °C	Factor 2 D: Heat Treat. T °C	Factor 3 E: Aging T °C	Response Hardness HV
1	300C (Block 1)	1	650	500	210	101
2	300C (Block 1)	14	650	500	170	77
3	300C (Block 1)	9	750	500	170	132
4	300C (Block 1)	4	750	500	210	103
5	300C (Block 1)	18	650	500	170	78
6	300 C (Block1)	24	650	500	210	100
7	300C (Block 1)	15	750	500	210	106
8	300C (Block 1)	5	750	500	170	125
9	300C (Block 1)	13	650	570	170	120
10	300C (Block 1)	19	650	570	210	127
11	300C (Block 1)	21	750	570	210	96
12	300C (Block 1)	23	750	570	170	100
13	300C (Block 1)	16	650	570	210	128
14	300C (Block 1)	17	650	570	170	115
15	300C (Block 1)	7	750	570	170	105
16	300C (Block 1)	20	750	570	210	96
17	300C (Block 1)	22	700	535	190	104
18	300C (Block 1)	8	700	535	190	104
19	300C (Block 1)	11	700	535	190	108
20	300C (Block 1)	3	700	535	190	105
21	300C (Block 1)	10	700	535	190	104
22	300C (Block 1)	2	700	535	190	104
23	300C (Block 1)	6	700	535	190	103
24	300C (Block 1)	12	700	535	190	100
25	150C (Block 2)	32	700	535	190	102
26	150C (Block 2)	33	700	535	190	103
27	150C (Block 2)	35	800	535	190	71
28	150C (Block 2)	25	800	535	190	71
29	150C (Block 2)	34	700	535	190	104
30	150C (Block 2)	31	700	535	190	104
31	150C (Block 2)	27	700	465	190	98
32	150C (Block 2)	29	700	535	150	101
33	150C (Block 2)	30	700	535	230	103
34	150C (Block 2)	28	700	535	190	97
35	150C (Block 2)	26	700	535	190	97

As observed in Table 2, 35 samples were made with different levels of variables, and the hardness of each sample was measured. It should be noted that the accuracy and correctness of the results were checked using ANOVA, and the predicted results matched the experimental results by 89.9 %. The final equation (Equation 2) is used to predict the results for hardness and is shown in the following:

$$
\begin{array}{ll}
\text{Hardness} & = \\
-4246.32931 & \\
+9.15665 & * \text{ melt T} \\
+2.84456 & * \text{ heat treatment T} \\
+4.10392 & * \text{ aging T} \\
-7.25000\text{E-}003 & * \text{ melt T} * \text{ heat treatment T} \\
-7.93750\text{E-}003 & * \text{ melt T} * \text{ aging T} \\
-2.67856\text{E-}003 & * \text{ melt T}^2 \\
+2.19494\text{E-}003 & * \text{ heat treatment T}^2 \\
+3.87126\text{E-}003 & * \text{ aging T}^2
\end{array} \tag{2}
$$

Figures 4-8 demonstrate the cross-sectional images of the samples along the thickness with different pouring temperatures. At four pouring temperatures (650, 700, 750, and 800 °C), the samples were made with a mold preheat temperature of 300 °C, and a series of samples were made according to the test design (pouring temperature 700 °C) in a mold with the preheating temperature of 150 °C. On the outer surface of the samples, as expected, there is a small amount of reinforcement, and the presence of small amounts of reinforcement in the outer wall is the result of the recoil of the reinforcement particles caused by the melt turbulence and collision with heavier particles such as excess silicon. During the rotation of the mold, several Mg_2Si particles are directed to the outer wall, and another reason is the limited time of the reinforcement (low freezing range) to move in the melt and reach the inner wall due to rapid freezing. The points close to the mold have the highest freezing speed, thus limiting the time for the movement of the reinforcement, which is why there are more amounts of reinforcement in the outer wall in the sample with the pouring temperature of 650 °C. As we move towards the inner wall of the tube, the amount of reinforcement increases, which are mainly primitive Mg_2Si particles. The reason for the presence of more reinforcing particles in the form of primary Mg_2Si is because during freezing, the first phase that germinates is primary Mg_2Si, which kinetically has enough time to germinate and be placed in the inner wall. In Figures 5, 6, and 7, the pouring temperature ranges from 700 to 750 °C, which provides more opportunity for the reinforcement to move in the melt and reach the inner wall during freezing due to the higher fluidity and greater freezing range. In Figure 8, with an increase in the pouring temperature up to 800 °C, the particles in the inner wall will not be well distributed mainly due to the high fluidity of the melt as well as the reduction of friction between the melt and the mold. This prevents the speed of the melt from reaching the speed of the mold in a short time, and the centrifugal force does not play a role well during freezing. As a result, the reinforcement is not placed well in the inner wall [۲۶]. In addition, the clustering of the reinforcing particles is evident, which originates from the high temperature of the pour.

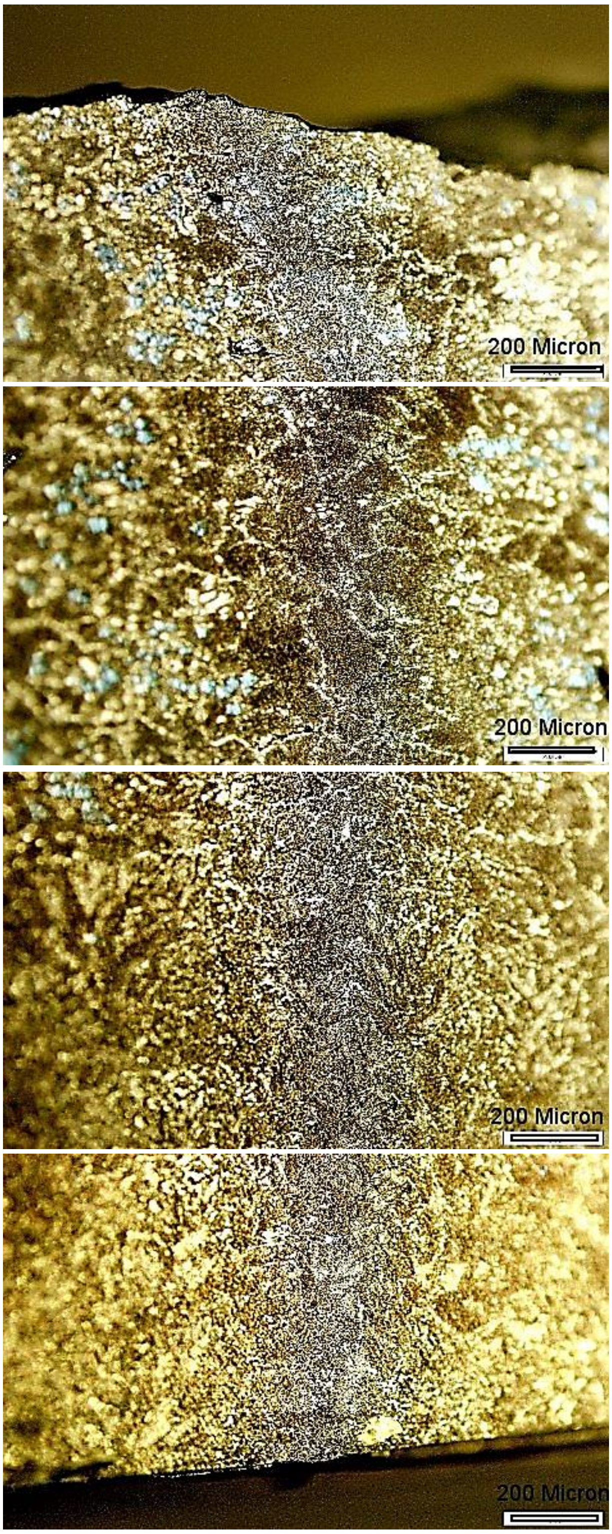

Figure 4. Distribution of reinforcing particles along the thickness from the outer wall to the inside (up to down) for the pouring temperature of 650 °C

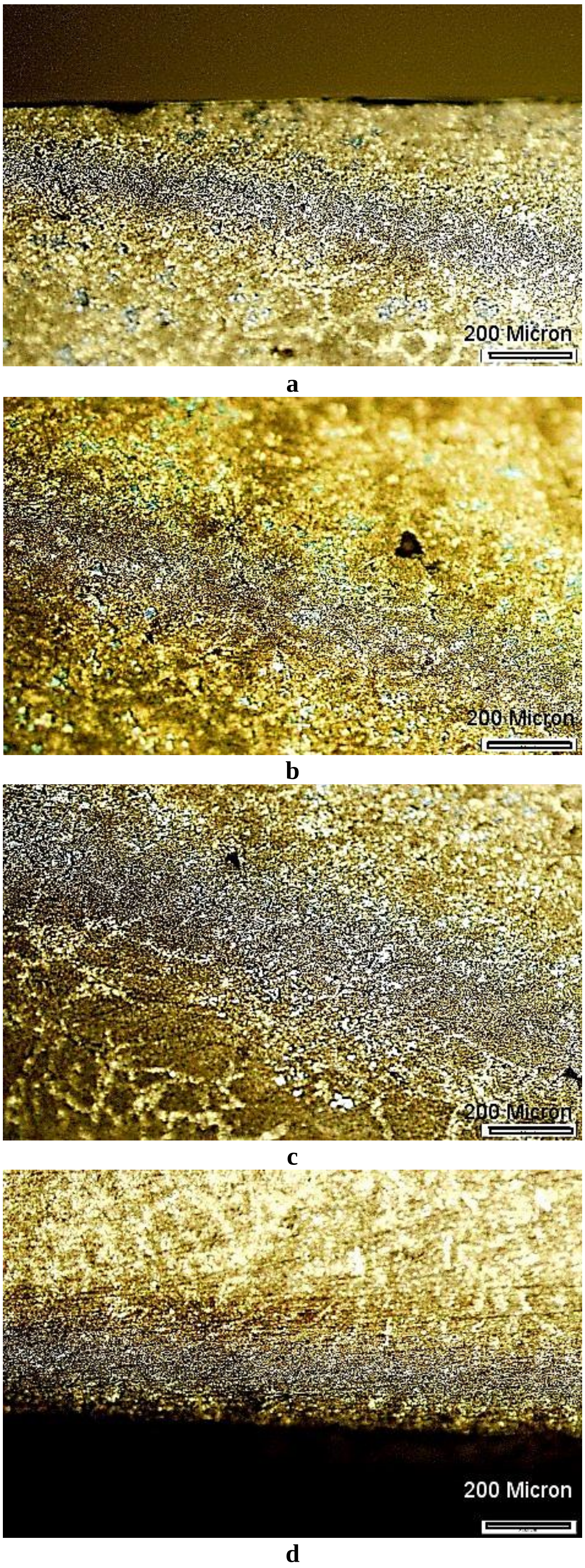

Figure 5. Distribution of reinforcing particles along the thickness from the outer wall to the inside (a to d) for the pouring temperature of 750 °C

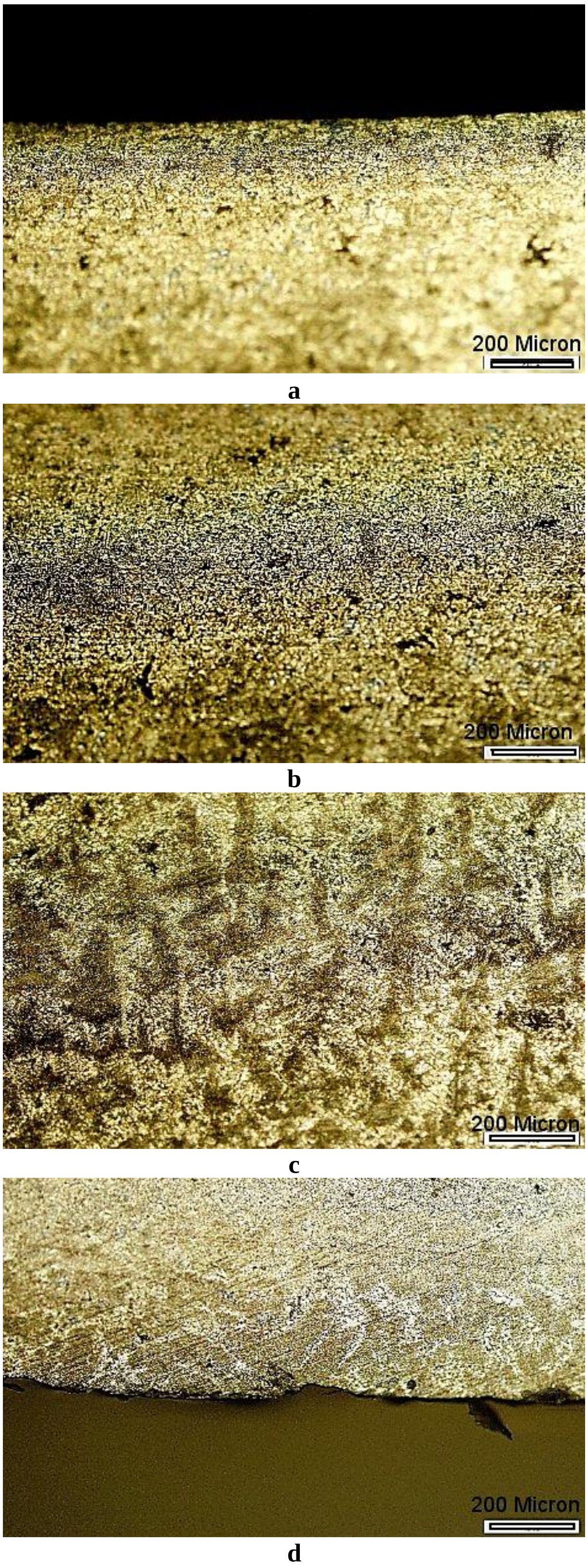

Figure 6. Distribution of reinforcing particles along the thickness from the outer wall to the inside (a to d) for the pouring temperature of 700 °C and preheat 300 °C

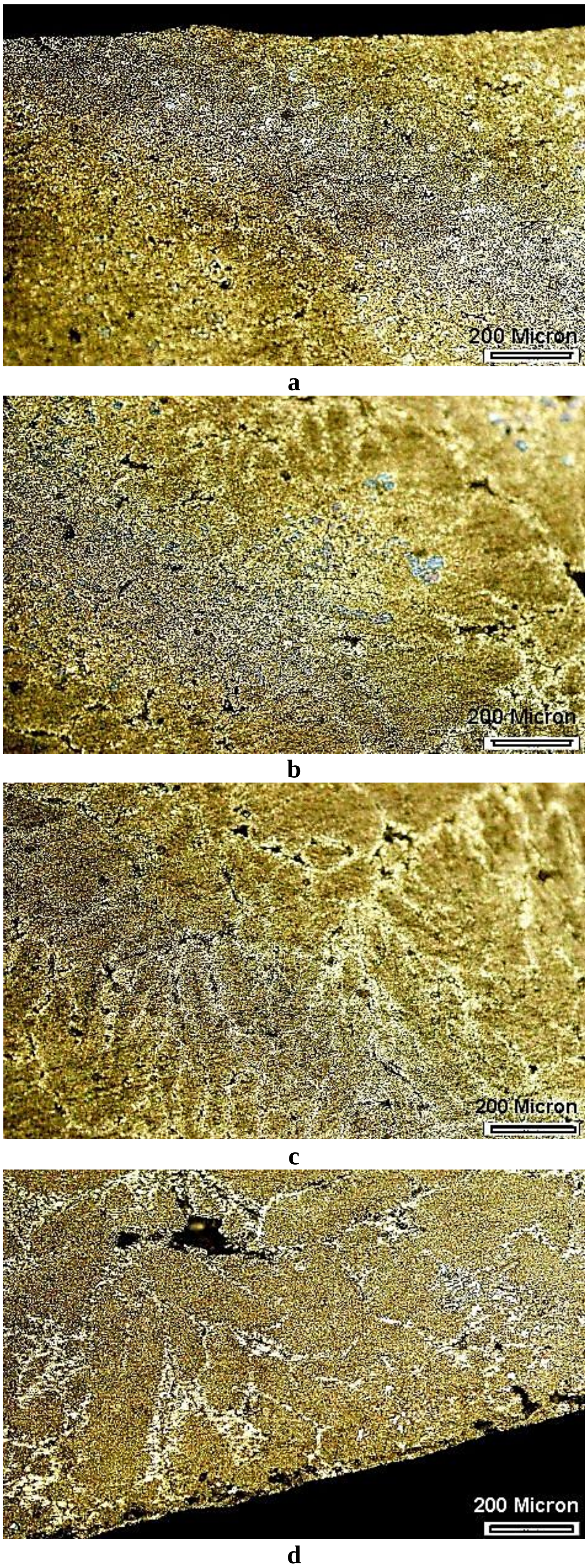

Figure 7. Distribution of reinforcing particles along the thickness from the outer wall to the inside (a to d) for the pouring temperature of 700 °C and preheat 150 °C

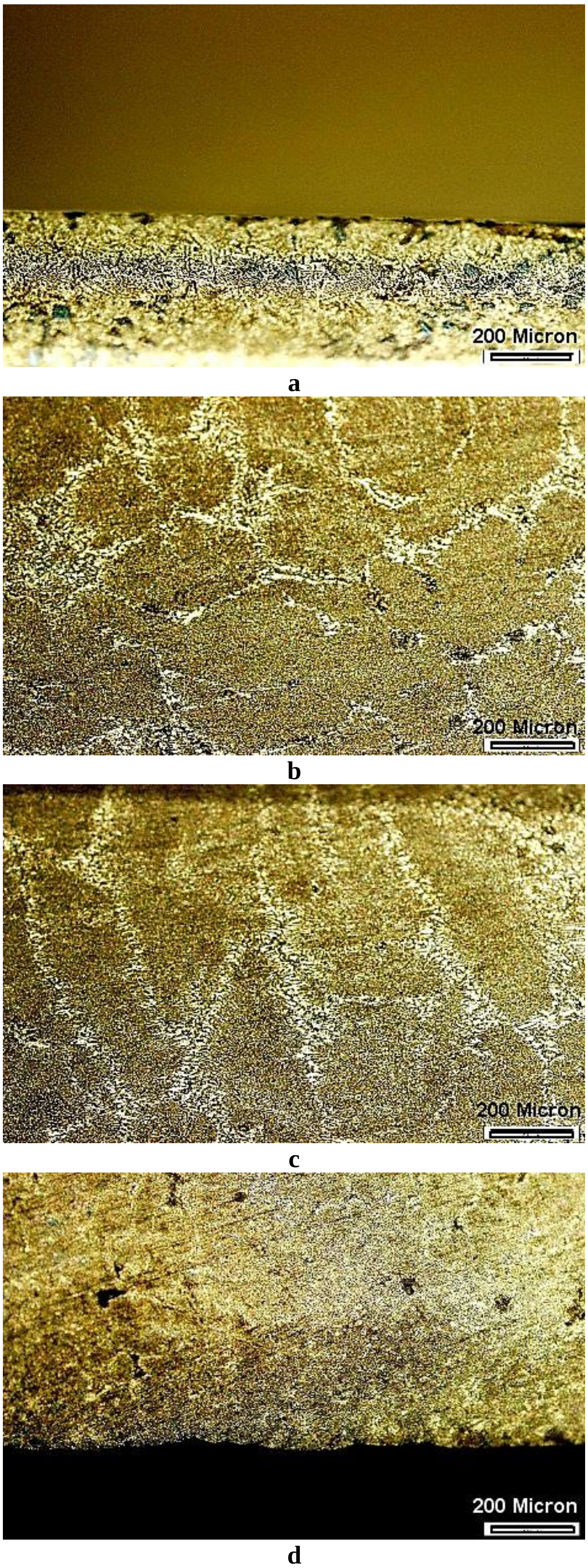

Figure 8. Distribution of reinforcing particles along the thickness from the outer wall to the inside (a to d) for the pouring temperature of 800 °C

Depending on the amount and shape of the reinforcement particles in the inner wall, the hardness values of the samples vary. For example, at the temperature of 650 °C, the non-uniform distribution of the reinforcement and its lower density in the inner wall can have the opposite effect on hardness.

The role of heat treatment in modifying the morphology and consequently optimizing the mechanical properties is undeniable. According to the conducted studies, the amount of wear resistance and in some cases, the amount of hardness increased by performing heat treatment. In Al-Mg_2Si composites, there are three types of reinforcing phases namely the primary and secondary Mg_2Si as well as the eutectic Mg_2Si where the primary Mg_2Si phase appears as polygonal or rough blocks, and the eutectic phase appears as feather or rods. The secondary Mg_2Si appears in the form of fine particles in the aluminum matrix, which is generally obtained after aging in hardenable alloys. Conducting dissolution heat treatment (properly) and rapid quenching led to the loss of rough reinforcing particles, and the rounding of the sharp corners of the primary Mg_2Si, as well as the polymorphic phase or eutectic rods with long rods, turned into a fine fibrous phase or particles, hence improvement in both toughness and wear properties. At higher pouring temperatures, the size of the primary Mg_2Si particles is larger than and the distance between the eutectic compounds is greater than the others. As the pouring temperature decreases, the size of the primary Mg_2Si particles and distance between eutectic arms decrease. This change in morphology will lead to an increase in both hardness and brittleness and a decrease in the ductility and toughness.

Figure 9 shows the light microscope images of the microstructure of the inner surface of the pipe made by the above composite with a pouring temperature of 650 °C, a dissolution temperature of 500 °C, and an aging temperature of 210 °C. Due to the low dissolution temperature and the lack of complete dissolution, it can be seen that the primary Mg_2Si phase retains its rough shape and sharp corners to a large extent, and the eutectic Mg_2Si is still present in the structure in the form of long rods. Also, due to the low pouring temperature, we see the porosity caused by premature freezing as well as the massive accumulation of reinforcing particles are seen, which could lead to the non-uniformity of the hardness distribution on the surface of the part and the high and low hardness with a large difference in different parts of the surface are seen. Similar results were reported by Rajaravi et al. [27].

Figure 10 shows the light microscope images of the microstructure of the inner surface of the above composite with a pouring temperature of 650 °C, a dissolution temperature of 570 °C, and an aging temperature of 210 °C. It can be seen that due to the high dissolution temperature and the proper dissolution of the reinforcing particles in the matrix, the sharp corners of the primary Mg_2Si particles are rounded and the eutectic phase has changed from the state of long rods to the form of microscopic fibers and particles.

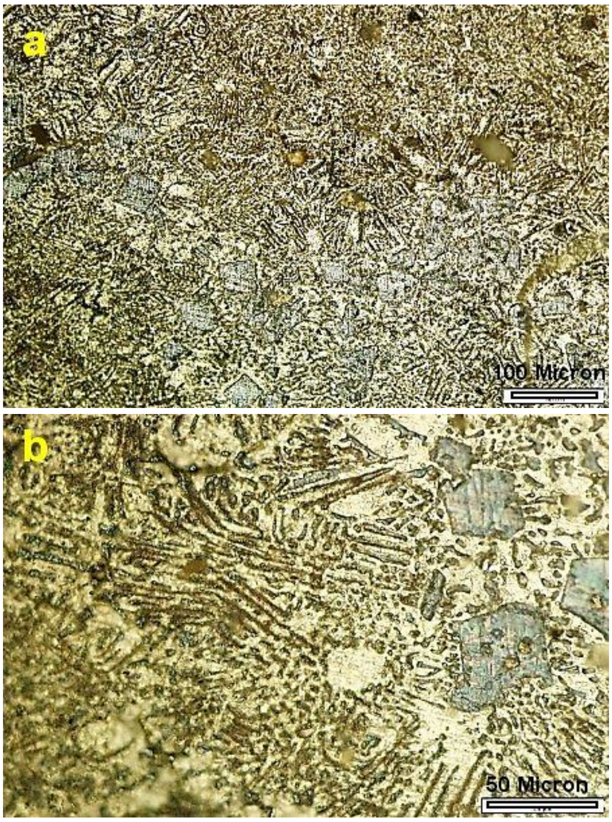

Figure 9. Light microscope image of the inner surface of the sample with a pouring temperature of 650 °C and a dissolution temperature of 500 °C and an aging temperature of 210 °C a) magnification 200x b) magnification 500x

Figure 11 shows the morphology of the reinforcement on the inner surfaces of two samples with a pouring temperature of 700 °C and dissolution and aging temperatures of 535 and 190 °C at two different preheat temperatures.

According to the lower preheat temperature of the mold in sample B (150 °C), it can be seen that the size of the primary Mg_2Si reinforcing particles is smaller compared to the second sample with a preheat temperature of 300 °C (A) which comes from the smaller freezing range and also the larger freezing rate. Also, in sample B, due to the limited range of freezing, more solidification porosity is observed.

Figure 12 shows the comparison of the microstructure of the internal surfaces of two samples at two pouring temperatures of 750 and 650 °C with the same heat treatment process (dissolution temperature of 570 and aging temperature of 210 °C) and the same mold preheating temperature.

It is evident from the images that the distribution of the primary Mg_2Si phase in the sample with a higher pouring temperature is more uniform in comparison with the inner surface of the sample, and the average size of the primary Mg_2Si particles in the sample with a higher pouring temperature is smaller.

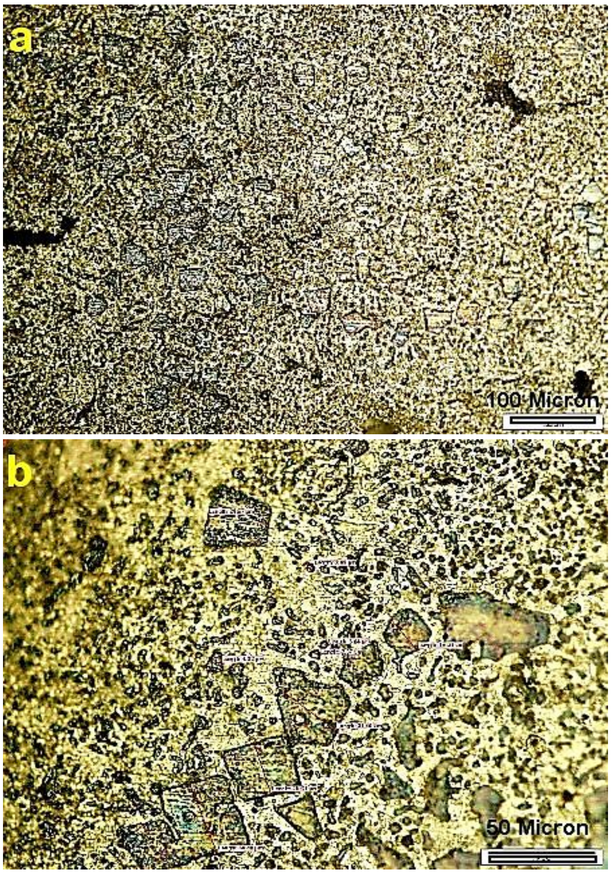

Figure 10. Light microscope image of the inner surface of the sample with a pouring temperature of 650 °C and a dissolution temperature of 570 °C and an aging temperature of 210 °C a) magnification 200x b) magnification 500x

Figure 13 shows the FESEM image of the sample poured at a temperature of 750 °C and a dissolution temperature of 570 °C.

As can be seen from this figure, the morphology of the reinforcing particles (primary Mg_2Si) has changed from rough to polygonal with rounded and spherical corners. The EDS analysis of the reinforcement is also shown in Figure 14.

According to the microstructure images and hardness tests, the highest hardness value is obtained in the sample with the heat treatment temperature of 535 °C and pouring temperature near 700 °C, which depends on the amount, shape, and size of the reinforcement in the inner wall.

Figure 15 shows the simultaneous effect of heat treatment temperature (dissolution) and pouring temperature on the hardness of the inner wall of different samples.

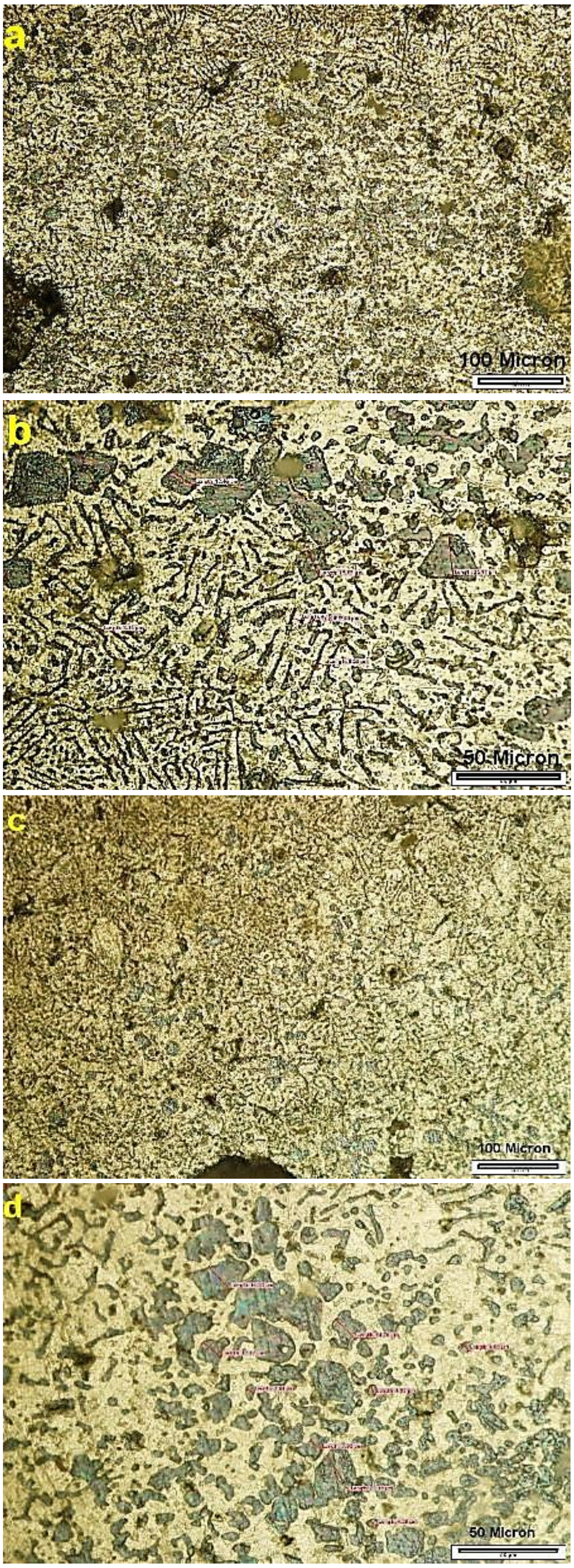

Figure 11. Light microscope image of the inner surface of the sample with a pouring temperature of 700 °C, a dissolution temperature of 535 °C, and an aging temperature of 190 °C a and b) mold temperature 300 °C c and d) mold temperature 150 °C

According to this shape, as the temperature of the heat treatment increases, the hardness of the samples improves significantly, which originates from the modification of the morphology, disappearance of thebrittle corners of the reinforcement, and improvement in the interface between the reinforcement and the ground.

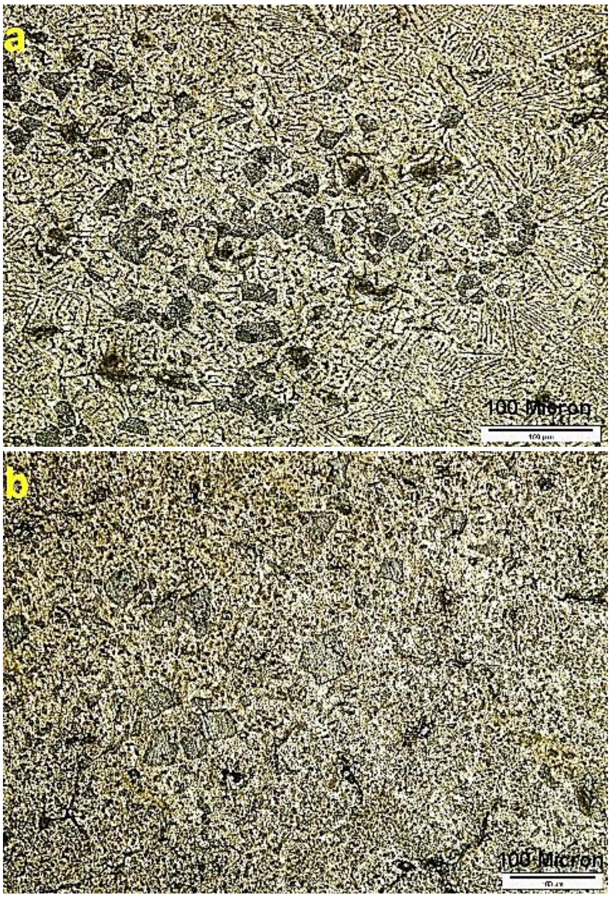

Figure 12. The microstructure of the internal surfaces of two samples at two pouring temperatures of 750 and 650 °C with the same heat treatment process (dissolution temperature of 570 and aging temperature of 210 °C) and the same mold preheat temperature a) 750 °C b) 650 °C

As the pouring temperature increases, the hardness first increases and then decreases. As the pouring temperature increases, on the one hand, the shape and size of the reinforcing particles become larger and rougher than usual, which leads to a decrease in hardness. On the other hand, at low pouring temperatures, due to the small freezing range and insufficient opportunity for the reinforcement to be placed in the inner wall, the reinforcements are not well distributed in this area. Internally, the hardness is low. It should be noted that at high temperatures, with the increase in the fluidity and decrease in melt viscosity, the friction between the mold and melt decreases, and the melt does not reach the speed of the mold in a short time, hence lack of effective placement of the reinforcement in the inner wall and a reduction in hardness.

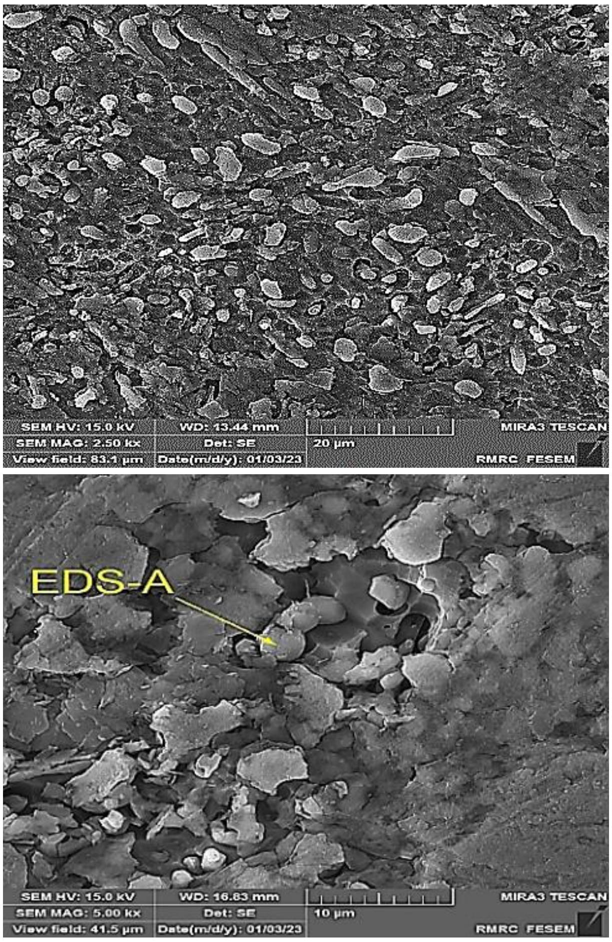

Figure 13. FESEM image of the reinforcement located on the inner surface of the sample poured at 750 °C and dissolution temperature of 570 °C

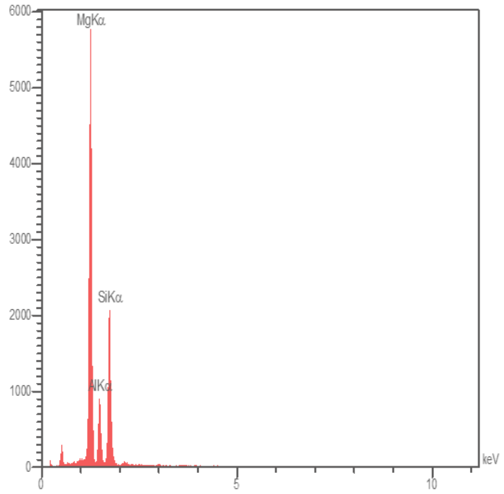

Figure 14. EDS analysis of the reinforcing particle shown in Figure 13

Figure 16 shows the simultaneous effect of aging temperature and pouring temperature on the hardness of the inner wall of different samples. As seen in the figures, hardness improves with the increase in the pouring temperature up to 700 °C and then it decreases [۲۸].

Of note, the change in the aging temperature does not have much effect on the hardness, which seems normal given the application of pure aluminum. According to Figures 15 and 16, the slope of the RSM diagram is higher for the heat treatment variable, which indicates the greater effect of this parameter on the response (hardness) than that of other variables.

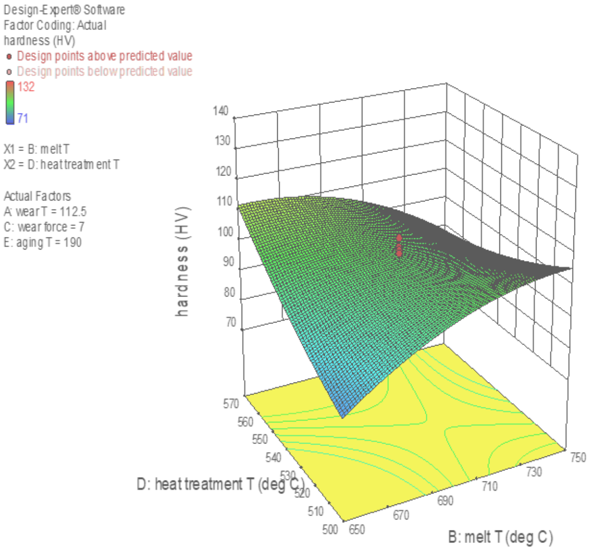

Figure 15. The simultaneous effect of pouring temperature and heat treatment (dissolution) temperature on the inner wall hardness of Al-15 wt. % Mg_2Si gradient composite tube

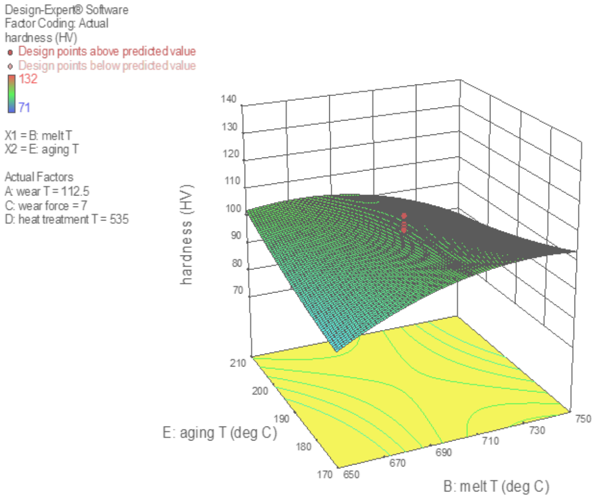

Figure 16. The simultaneous effect of aging temperature and pouring temperature on the hardness of the inner wall of Al-15 wt. % Mg_2Si gradient composite pip

According to Table 3 derived from Design Expert the values with the P-VALUE less than 0.05 have a significant effect while those greater than 0.1 do not have a significant effect on the desired response (hardness). In order to check the mutual effect of different variables, the P-VALUE of those two variables should be taken into consideration. According to the ANOVA table, the two variables of pouring and dissolution temperatures can be identified as the variable affecting the response (hardness). It should be mentioned that the effect of aging treatment is not much significant, as discussed earlier.

TABLE 3. ANOVA table

Source	Sum of Squares	DF	Mean Square	F Value	p-value Prob > F	
Block	804.82	1	804.82			
Model	5735.55	20	286.78	89.19	< 0.0001	Significant
A-melt T	15.89	1	15.89	4.94	0.0446	
B-heat treatment T	277.37	1	277.37	86.26	< 0.0001	
C-aging T	3.38	1	3.38	1.05	0.3243	
AB	2575.56	1	2575.56	801.00	< 0.0001	
AC	1008.06	1	1008.06	313.51	0.1543	
BC	5.06	1	5.06	1.57	0.2317	
A^2	1023.06	1	1023.06	318.17	< 0.0001	
B^2	112.26	1	112.26	34.91	< 0.0001	
C^2	72.87	1	72.87	22.66	0.0004	
Residual	41.80	13	3.22			
Lack of Fit	7.80	4	1.95	0.52	0.7263	Not Significant
Pure Error	34.00	9	3.78			
Corr. Total	6582.17	34				

Regarding the mutual effects of the variables, pouring and heat treatment temperatures were introduced as the variables that have significant mutual effects.

4. CONCLUSIONS

1. The experimental results of this study were in good agreement with those anticipated by ANOVA (above 89%).
2. Among the variables introduced in this study, the temperature of heat treatment (dissolution) had the greatest effect on the hardness of the Al-15Mg_2Si composite, and the best result was obtained at the temperature of about 535 °C.
3. The preheat temperature of the mold did not have much effect on the hardness of the final piece. The best distribution of reinforcing particles was obtained in the temperature range of 700 to 750 °C.

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