Advanced Ceramics Progress: Vol. ?, No. ?, (Season 202?) ??-??

Materials and Energy Research Center

MERC

Contents lists available at ACERP

Advanced Ceramics Progress

Journal Homepage: www.acerp.ir

Original Research Article

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

Ali Zeinali [a], Masoud Rajabi [b], Mohammad Reza Rahimipour [c], Mohsen Ostad Shabani [d]

Author Scientific Position/Academic Degree, Authors affiliation must be Italic Cambria 8, Division, Department Name, Faculty, University/Institution/Organization with Acronyms If Available, City, Province/State, Country, ORCiD Number

[a] *Ph.D. student, Department of Materials Engineering, Faculty of Engineering, Imam Khomeini International University (IKIU), Qazvin. Iran*

[b] *Associate Professor, Department of Materials Engineering, Faculty of Engineering, Imam Khomeini International University (IKIU), Qazvin, Iran*

[c] *Professor, Ceramic Department, Materials and Energy Research Center, Karaj, Iran*

[d] *Assistant Professor, Ceramic Department, Materials and Energy Research Center, Karaj, Iran*

* Corresponding Author Email: AliZeinali45582@gmail.com

URL: http://www.acerp.ir/article_90833.html

ARTICLE INFO

Article History:

Received? Month 202?
Received in revised form Month 202?
Accepted Month 202?

Keywords:
solidification
alloy
reinforcement
optimization
design Expert

ABSTRACT

This study aims to place Mg_2Si reinforcing particles in the inner wall of the aluminum matrix composite tube and to optimize the microstructure and hardness of the inner wall using temperature parameters. By using Al-Si alloy and creating in-situ Mg_2Si particles in this alloy system and producing the pipe by centrifugal casting method due to the low density of Mg_2Si particles, we will get the accumulation of these reinforcing particles would be obtained 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 and the interaction of variables were determined using Design Expert software to achieve the highest hardness. Also, the most effective variable among the mentioned variables was heat treatment temperature and the best temperature was about 535 degrees Celsius. Also, the best pouring temperature was found to be around 700 degrees Celsius and it was determined that a higher temperature is needed to preheat the mold to obtain reinforcement with uniform placement.

https://doi.org/10.30501/acp.2018.90833

1. INTRODUCTION

Please cite this article as: Zeinali, Ali., Rajabi, Masoud., Rahimipour, Mohammad Reza., "Investigating The Role Of Pouring Temperature, Heat Treatment And Mold Preheating Temperature On The Hardness And Microstructure Of The Inner Surface Of Al-15Mg2Si In Situ Composite Pipe Fabricated By Centrifugal Casting Method., ***Advanced Ceramics Progress***, Vol. ?, No. ?, (202?), ??-??. https://doi.org/10.30501/acp.2018.90833

Composite materials have important characteristics compared to ordinary alloys and unreinforced materials, and the use of these advanced materials in various industries is increasing significantly. In short, the main goals of developing composite materials are: reducing weight, increasing the strength-to-weight ratio, increasing elastic modulus, reducing thermal expansion coefficient, improving thermal shock resistance, increasing yield strength, increasing creep resistance at high temperatures, improving fatigue properties at high temperature and improving wear properties. Composites have a combination of properties that do not exist in metal, ceramic, and polymer materials alone, so composites give us design power and this feature makes them unique.

The in-situ process is one of the common methods of producing cast aluminum matrix composites, which is thermodynamically stable, and basically by germination and growth, the reinforcing phase is formed in situ from the matrix. Special attention is paid to these composites due 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 particles, and agglomeration of reinforcing particles, the in-situ method creates stable interfaces between particles and the ground, while its properties are mechanically suitable and the manufacturing method is also simple[1].

1.1. Introduction of Al-Mg_2Si composite

Aluminum alloys are the most widely used light materials for use in the automotive industry to lighten and increase efficiency in fuel consumption and reduce CO_2 gas. In the last 50 years, the percentage of using aluminum alloys and other light alloys in industries has increased. A lot of aluminum alloys in parts such as engine cylinders, body, chassis, manifold, wheels, and decor are used in the automotive industry. Due to the decrease in energy resources and the increase in the consumption of goods and energy in the world today, increasing the use of aluminum alloys due to their lightweight and easy production and shaping (compared to other metals such as steel) in industries seems more important than before. In general, increasing the efficiency of aluminum alloys is classified into two groups: 1- Increasing productivity by controlling the production process, and 2- Increasing productivity by improving 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 reinforcement. Al-Mg_2Si alloys with advantages such as uniform distribution of reinforcing phase, high wettability of particles, and low cost of production are a very suitable alternative for Al-Si alloys used in aerospace and automotive industries and other industries. Among the reinforcing materials that are used in the form of particles in metal-based composites, Mg_2Si has the lowest density, so 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 has a melting temperature of 1083°C, a density of 99.1*10^3 Kg m^{-3}, high hardness (4500 NMm^{-2}), low thermal expansion coefficient (7.5*10-6 k^{-1}), and relatively high elastic modulus. (120 GPa). It should be noted that in terms of properties and freezing behavior, there are many similarities between Mg_2Si and Si, as well as between Al-Mg_2Si and Al-Si systems [2].

1.2. Centrifugal casting

One of the new methods of shaping materials is centrifugal casting, which has been effectively used in various industries today, and is based on the use of centrifugal force. In this method, the mold is movable and rotating, and the melt is added to it during the rotation of the mold. The material of the mold is generally made of steel, graphite, and stainless steel, and this method is used to make parts such as All kinds of gas and water lines pipes, annular parts, pipe wall insulation, engine cylinders, pistons, train wheels, and other things are used. 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 causes the accumulation of heavier particles in the outer wall and the tendency of lighter particles to accumulate in the inner part of the final piece. Among the advantages of this method compared to the traditional casting method, the following can be mentioned:

1- High manufacturing speed [۳], 2- The quality of the final part in terms of dimensional accuracy, suitable final surface, and low porosity on the surface [۳], 3- Fast freezing with high metallurgical quality [۳] and 4- Simple method and low machining required [۳].

By using Al-Si alloy and creating in-situ Mg_2Si particles in this alloy system, and producing pipes by centrifugal casting method, due to the low density of Mg_2Si particles, we will get the accumulation of these reinforcing particles in the inner wall of the pipe has occurred. The tribological properties of the inner wall of the pipe could be improved with optimization of 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, including 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 could be manufactured by 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 and 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, and other things [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 are formed, which are: Ekman flow, Cote flow, and Taylor flow [7]. The solidification rate of the molten metal in centrifugal casting is very important because of its great effect 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 and areas with lower solidification speed have rougher grains [8].

Zhai et al. [۹] used 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.

By increasing the rotation speed of the mold, the shrinkage defect decreases and 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 hardness and mechanical properties of Al-15wt.%Mg_2Si alloy made by centrifugal casting method. By increasing the mold rotation speed, the thickness of the area containing the reinforcement decreased, but 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, scientific considerations limit the temperature range used. Increasing the pouring temperature causes an increase in grain size and dendritic arm distance (SDAS), particle separation, and an increase in 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.

Various factors in the separation of particles and their distribution in the part obtained from centrifugal casting, including The pouring temperature, mold temperature, and G number are effective ($G=\omega^2 R/g$ where R is the radius of the tube in meters, ω is the rotation speed of the mold in revolutions per second and g is the centrifugal force). At the pouring temperature of 720 degrees Celsius and the mold temperature of 90 degrees Celsius and G>60, reinforcement particles accumulate in the inner layer, while under the same conditions, with G<40, the reinforcement layer is not formed and the particles are spread on the ccross-section[۱۵].

Increasing the pouring temperature leads to improved tensile strength and reduced 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 the results, the most important parameters in this test are: Pouring temperature, pouring height, and mold preheating temperature. The results showed that increasing the temperature of the pouring and decreasing the height of the pouring play a big 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-5wt.%Mg_2Si semi-solid hypoeutectic composite. The results showed that lowering the pouring temperature improves the α-Al structure and the eutectic cell (α-Al+Mg_2Si) and reduces 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. When the freezing speed is high, the possibility of creating shrinkage porosity is higher, while when the freezing happens gradually, the possibility of creating shrinkage porosity decreases. For this purpose, it is recommended to preheat the centrifugal casting molds 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 and dissolve intermetallics such as Al_2Cu, Mg_2Zn, and Mg_2Si, and make the eutectic Si spherical [۱۹-۲۰]. In Al-Si-Mg alloys, Mg_2Si dissolves easily, which is caused by the high penetration rate of magnesium in aluminum, although the microstructure and amount of magnesium affect the dissolution process [۱۹,۲۱].

Zedi et al. [۲۲] performed dissolution operation at 520 C for 6 hours and aging operation at 200 C for 6 hours in Al-10%wt Mg_2Si alloy, and the results showed that the Mg_2Si phase form 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 does not change much with the increase of the heat treatment temperature, and since the penetration starts from these areas into the background, the sharp corners are rounded and the eutectic Mg_2Si network is partially broken.

After 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. Also, 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.

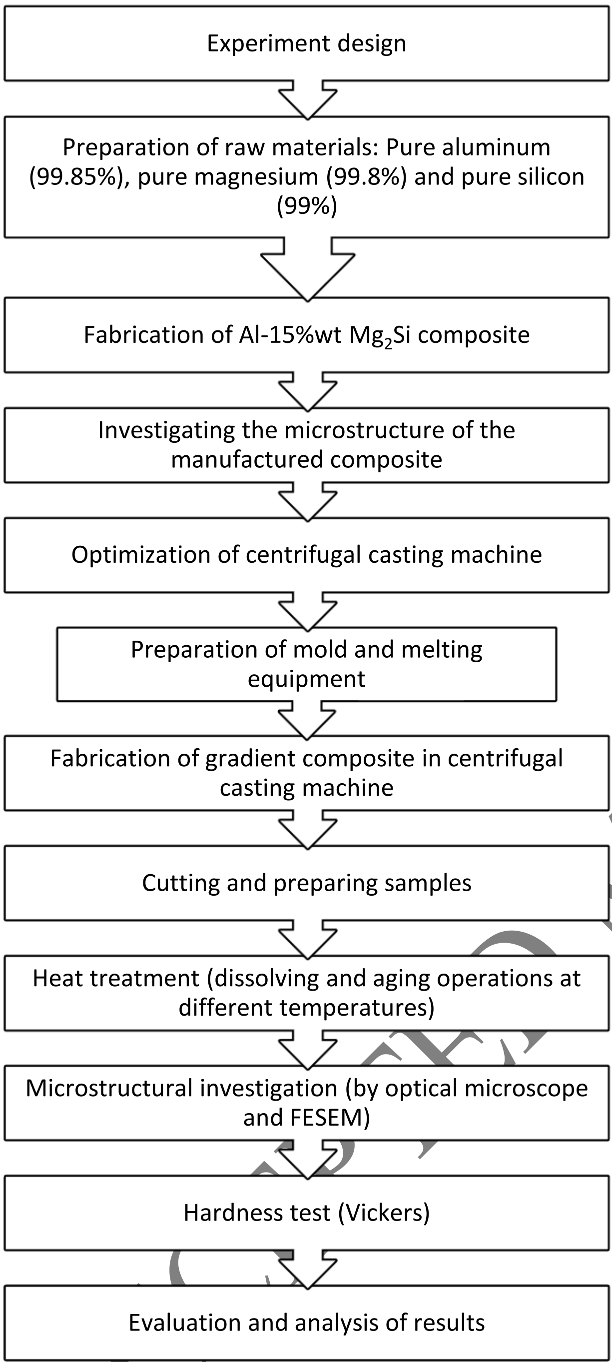


Figure 1. The flowchart of the path of this research.

2.1. Primitive material

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

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 degrees Celsius, then preheated silicon and magnesium pieces were added to it and kept at this temperature for 15 minutes. then It was molded and cooled at room temperature. To make 2 kg of this alloy, 1750 grams of aluminum, 200 grams of magnesium (including waste), and 115 grams of silicon were used. Due to the characteristic of creating a vortex in the casting in the induction furnace, there was no need to stir the resulting alloy. To check the microstructure of the resulting alloy and to ensure the proper formation of Mg_2Si and the absence of iron in the aluminum background, the obtained alloy was sampled, polished, and etched. 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 a rotation speed of 1500 rpm was used, and after preheating the mold (at two temperatures of 150 and 300 degrees Celsius), 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 as well as 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

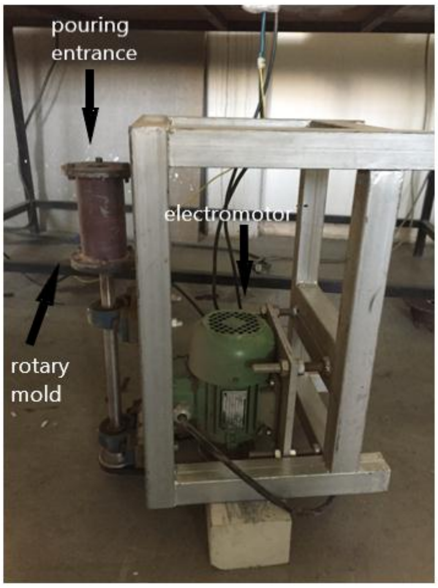
The mold of the device is made of cast iron with an inner diameter of 5 cm and a length of 12 cm. The end of the mold was blocked by a cap with a muscle. A 1 HP single-phase electric motor was used to create rotational movement in the mold. To control the rotation speed of the mold, changing the ratio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

$$N2 = \mathrm{N1} * \mathrm{D1}/\mathrm{D2} \quad (1)$$

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

Considering that the desired speed of rotation of the mold was considered fixed for this research and according to the nominal speed of the machine (900 rpm), two 6 and 10-cm pulleys were used to achieve a 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, 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, to observe the microstructure by optical microscope and scanning electron microscope (SEM), sanding papers from P-80 to P-1500 have been used. Polishing of samples was started by using coarse sandpaper under water flow and was continued until the softest sandpaper. After changing each sandpaper, the sample was rotated 90 degrees, and as the sandpaper became softer, the pressure applied to the samples on the polishing machine was 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 morphology of Mg_2Si particles and also the morphology of the Mg_2Si phase in the alloy according to the characteristics of the Al-15%wt Mg_2Si alloy and to observe the morphology 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

Considering the shape and size of the pieces cut from the pipe, performing the hardness test of the samples at ambient temperature makes the use of mounts inevitable. For this purpose, epoxy resin and hardener were used in a ratio of 2:1. After stirring (5 minutes), this mixture was poured into a mount mold and heated at 70°C for 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 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. Also, 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 to investigate the morphology of the reinforcement. 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 used 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 in the end, the 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 it is clear from the figure, the Al-15wt% Mg_2Si gradient composite was successfully fabricated by the centrifugal casting method, and the reinforcing particles are placed in the inner wall of the cylinder. According to the deep etching 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 and can be seen a in dark color, and we see the accumulation of the reinforcement in a dense manner in the inner wall.

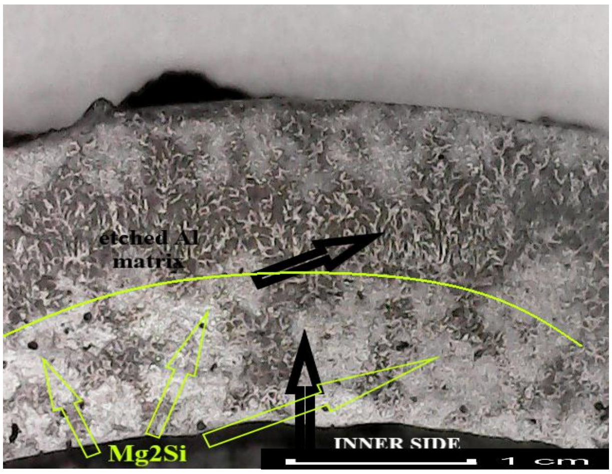


Figure 3. Image of a cross-section of the cylinder along the thickness of Al-15wt% Mg_2Si composite.

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

Table 1. Table of variables and levels of each variable

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

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

Table 2. Test design table and results

			Factor 1	Factor 2	Factor 3	Response
Std	Block	Run	B:melt T	D:heat treatment T	E:aging T	hardness
			deg C	deg C	deg C	HV
1	300 C (BLOCK 1)	1	650	500	210	101
2	300 C (BLOCK 1)	14	650	500	170	77
3	300 C (BLOCK 1)	9	750	500	170	132
4	300 C (BLOCK 1)	4	750	500	210	103
5	300 C (BLOCK 1)	18	650	500	170	78
6	300 C (BLOCK 1)	24	650	500	210	100
7	300 C (BLOCK 1)	15	750	500	210	106
8	300 C (BLOCK 1)	5	750	500	170	125
9	300 C (BLOCK 1)	13	650	570	170	120
10	300 C (BLOCK 1)	19	650	570	210	127
11	300 C (BLOCK 1)	21	750	570	210	96
12	300 C (BLOCK 1)	23	750	570	170	100
13	300 C (BLOCK 1)	16	650	570	210	128
14	300 C (BLOCK 1)	17	650	570	170	115
15	300 C (BLOCK 1)	7	750	570	170	105
16	300 C (BLOCK 1)	20	750	570	210	96
17	300 C (BLOCK 1)	22	700	535	190	104
18	300 C (BLOCK 1)	8	700	535	190	104
19	300 C (BLOCK 1)	11	700	535	190	108
20	300 C (BLOCK 1)	3	700	535	190	105
21	300 C (BLOCK 1)	10	700	535	190	104
22	300 C (BLOCK 1)	2	700	535	190	104
23	300 C (BLOCK 1)	6	700	535	190	103

24	300 C (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

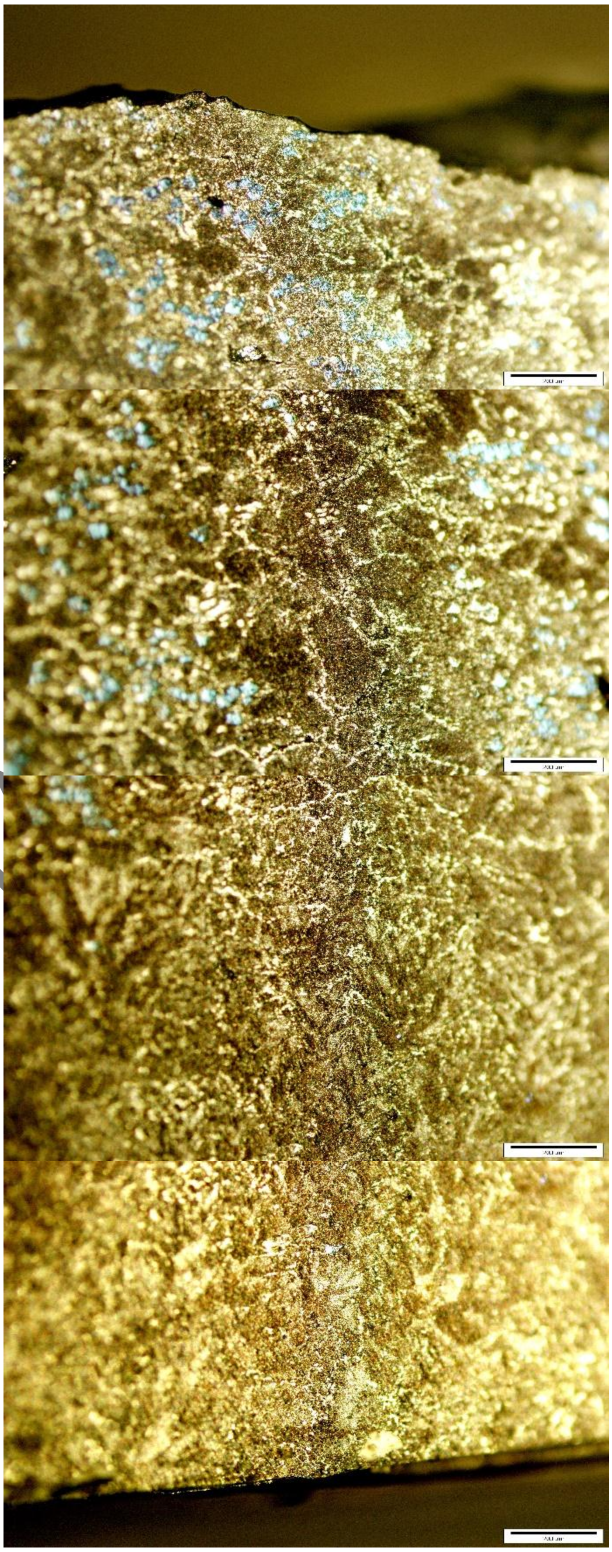
As can be seen from Table 2, 35 samples were made with different levels of variables and the hardness of each sample was measured, and the results can be seen. It should be noted that the accuracy and correctness of the results were checked using ANOVA, and the predicted results matched the experimental results by 89.9%. The final equation (equation 2) for predicting results for hardness is as follows:

Equation (2)

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

Figures 4 to 8 show the cross-sectional images of the samples along the thickness with different pouring temperatures. At 4 pouring temperatures (650, 700, 750 and 800 degrees Celsius), the samples were made with a mold preheat temperature of 300 degrees Celsius, and a series of samples were made according to the test design (pouring temperature 700 degrees Celsius) in a mold with a preheating temperature of 150 degrees Celsius. became. As it is clear from the figures (4-8) 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 can be caused by the recoil of the reinforcement particles due to 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. Also, the points close to the mold have the highest freezing speed, which limits 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 a pouring temperature of 650 degrees Celsius. 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 that 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 is 700 and 750 degrees Celsius, which, due to the higher fluidity and greater freezing range, provides more opportunity for the reinforcement to move in the melt and reach the inner wall during freezing. In Figure 8, it can be seen that with the increase of the pouring temperature to 800 degrees Celsius, the distribution of particles in the inner wall is not done well, which could be caused by the high fluidity of the melt, and the reduction of friction between the melt and the mold, This causes the speed of the melt does not reach the speed of the mold in a short time, and the centrifugal force does not play a role well during freezing, and as a result, the reinforcement is not placed well in the inner wall [۲۶]. Also, the clustering of reinforcing particles is evident, which originates from the high temperature of the pour. According to the amount and shape of reinforcement particles in the inner wall, the hardness of the samples is different. For example, at a temperature of 650 degrees Celsius, 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 studies conducted, the amount of wear resistance and in some cases, the amount of hardness has increased by performing heat treatment. In Al-Mg_2Si composites, there are three types of reinforcing phase: primary and secondary Mg_2Si and eutectic Mg_2Si, where the primary Mg_2Si phase appears as polygonal or rough blocks and the eutectic phase appears as feather or rods. Secondary Mg_2Si also 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 causes 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, turns into a fine fibrous phase or particles, which leads to improvement The toughness and consequently the wear properties will be improved. At higher pouring temperatures, the size of the primary Mg_2Si particles is larger and the distance between the eutectic compounds is greater. As the pouring temperature decreases, the size of the primary Mg_2Si particles decreases and the distance between eutectic arms decreases. This change in morphology will lead to an increase in hardness and brittleness and a decrease in ductility and toughness.



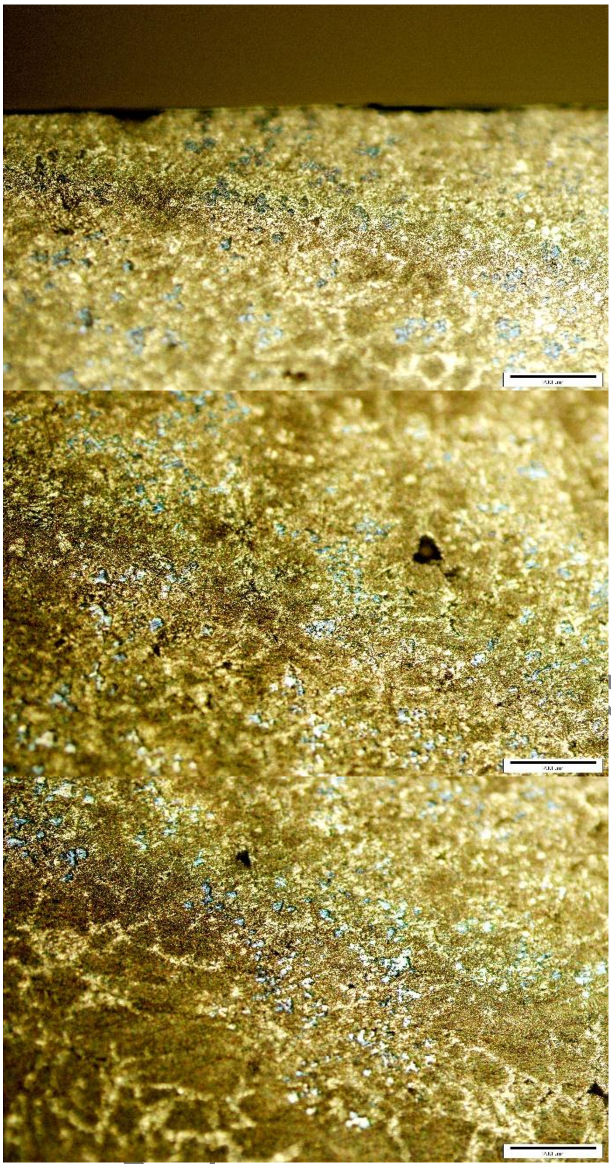


Figure 4. Distribution of reinforcing particles along the thickness from the outer wall to the inside (up to down) for the pouring temperature of 650 degrees Celsius (Scale bar is 200 µm)

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 degrees Celsius (Scale bar is 200 µm)

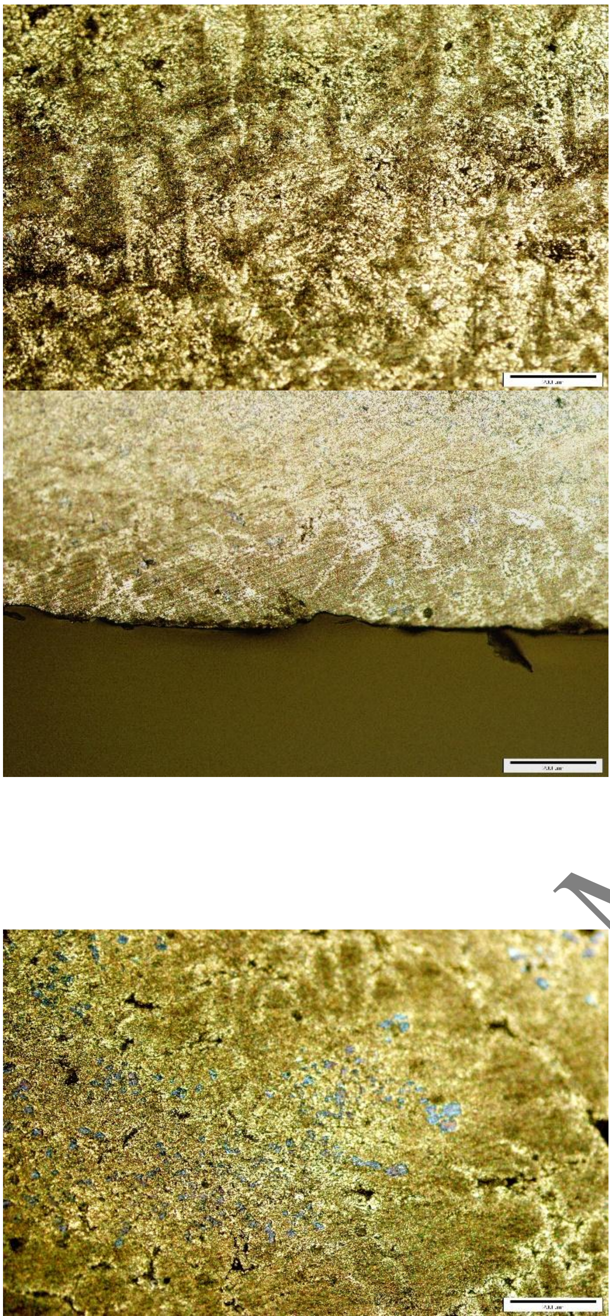


Figure 7. Distribution of reinforcing particles along the thickness from the outer wall to the inside (a to d) for the pouring temperature of 700 degrees Celsius and preheat 150 degrees (Scale bar is 200 µm)

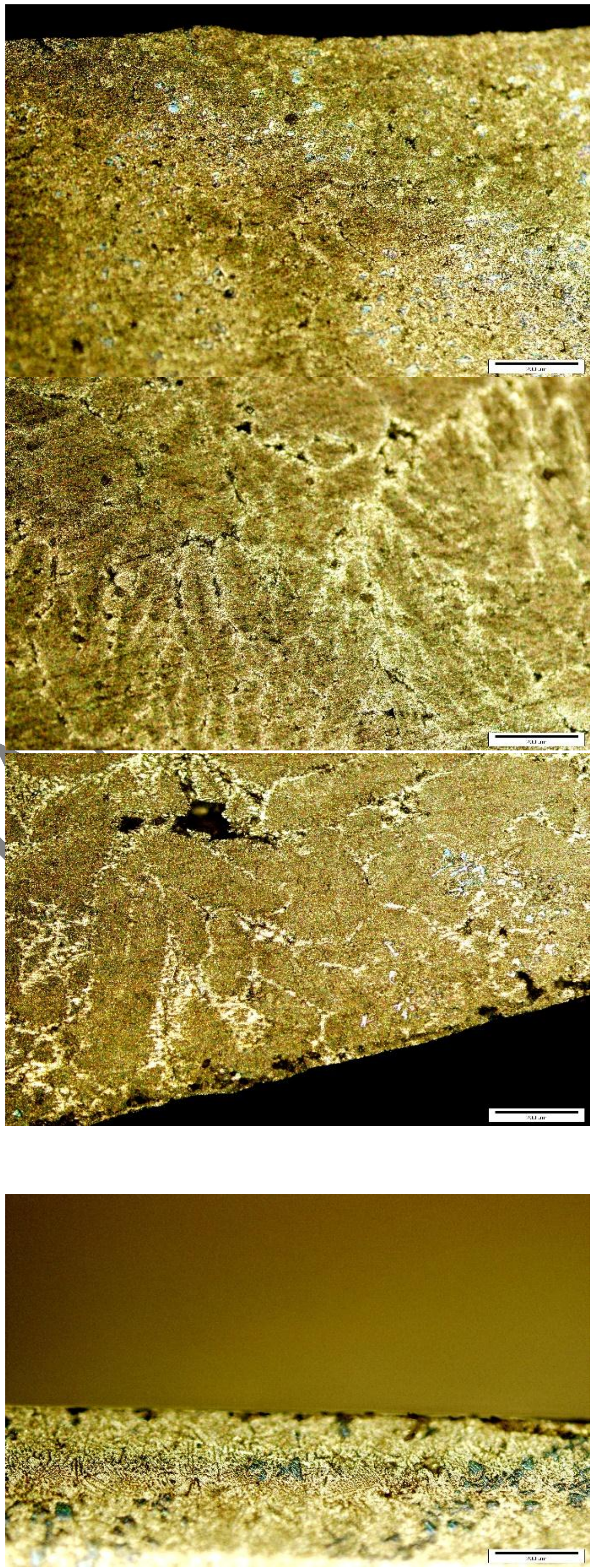


Figure 6. Distribution of reinforcing particles along the thickness from the outer wall to the inside (a to d) for the pouring temperature of 700 degrees Celsius and preheat 300 degrees (Scale bar is 200 µm)

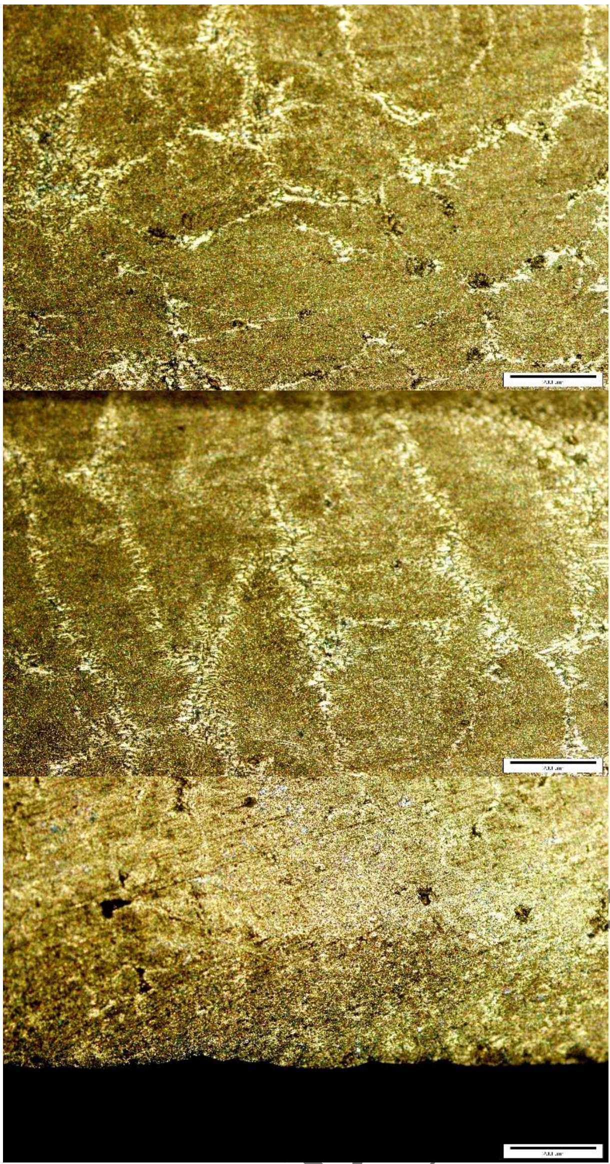
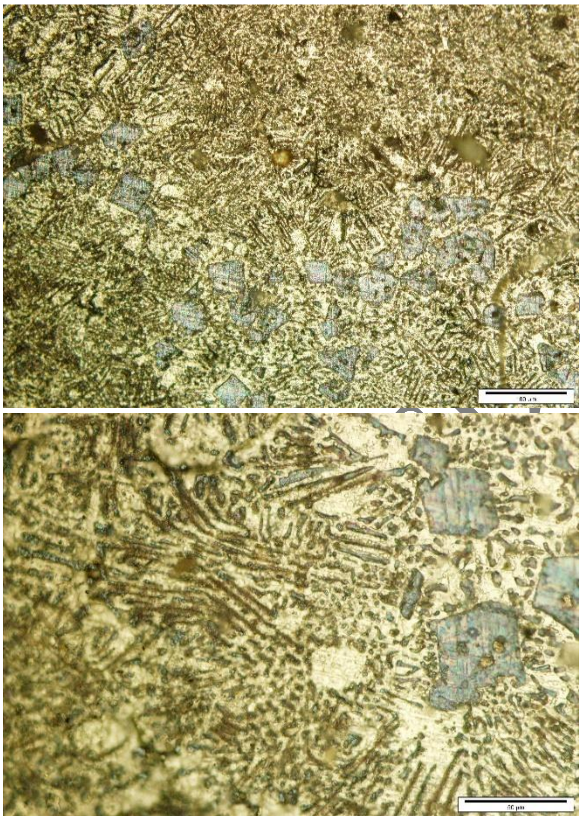


Figure 8. Distribution of reinforcing particles along the thickness from the outer wall to the inside (a to d) for the pouring temperature of 800 degrees Celsius (Scale bar is 200 µm)

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 degrees Celsius, a dissolution temperature of 500 degrees Celsius, and an aging temperature of 210 degrees Celsius. 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 9. Light microscope image of the inner surface of the sample with a pouring temperature of 650 degrees Celsius

a

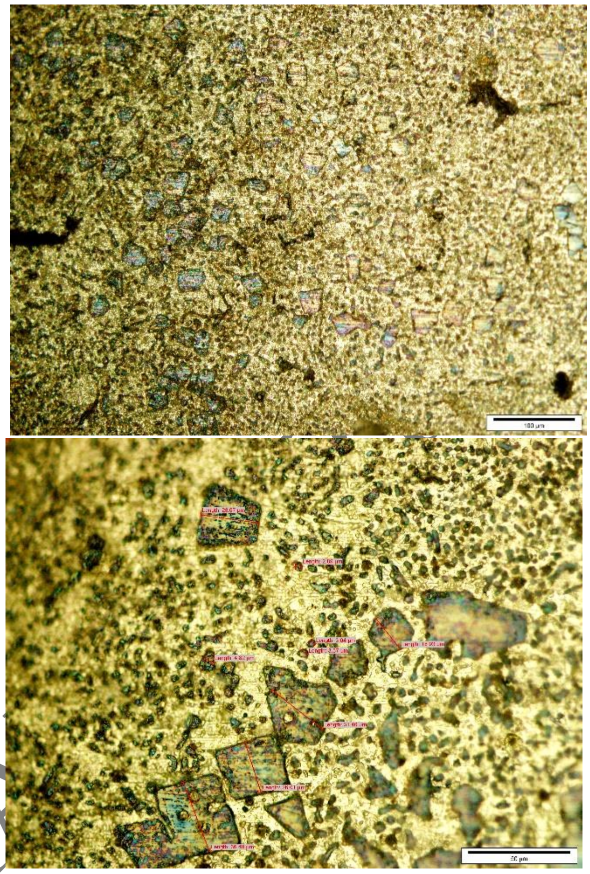


b

and a dissolution temperature of 500 degrees Celsius and an aging temperature of 210 degrees Celsius a) magnification 200x b) magnification 500x

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

a



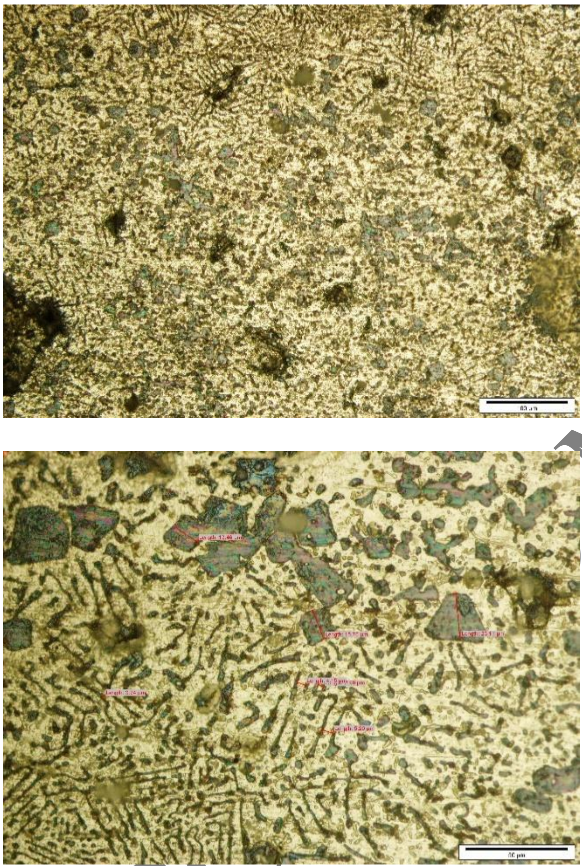
b

Figure ١٠ shows the light microscope images of the microstructure of the inner surface of the above composite with a pouring temperature of 650 degrees Celsius, a dissolution temperature of 570 degrees Celsius, and an aging temperature of 210 degrees Celsius. 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 11 shows the morphology of the reinforcement on the inner surfaces of two samples with a pouring temperature of 700 degrees Celsius and dissolution and aging temperatures of 535 and 190 degrees Celsius at two different preheat temperatures. According to the lower preheat temperature of the mold in sample B (150 degrees Celsius), 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 degrees Celsius (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.

a

b



c

d

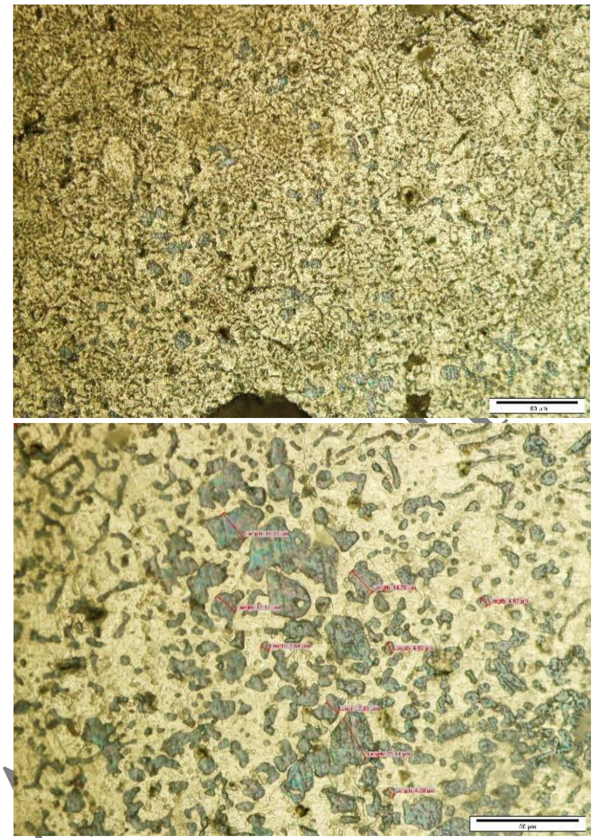


Figure 11. Light microscope image of the inner surface of the sample with a pouring temperature of 700 degrees Celsius, a dissolution temperature of 535 degrees Celsius, and an aging temperature of 190 degrees Celsius a and b)mold temperature 300 c c and d) mold temperature 150 c

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

a

b

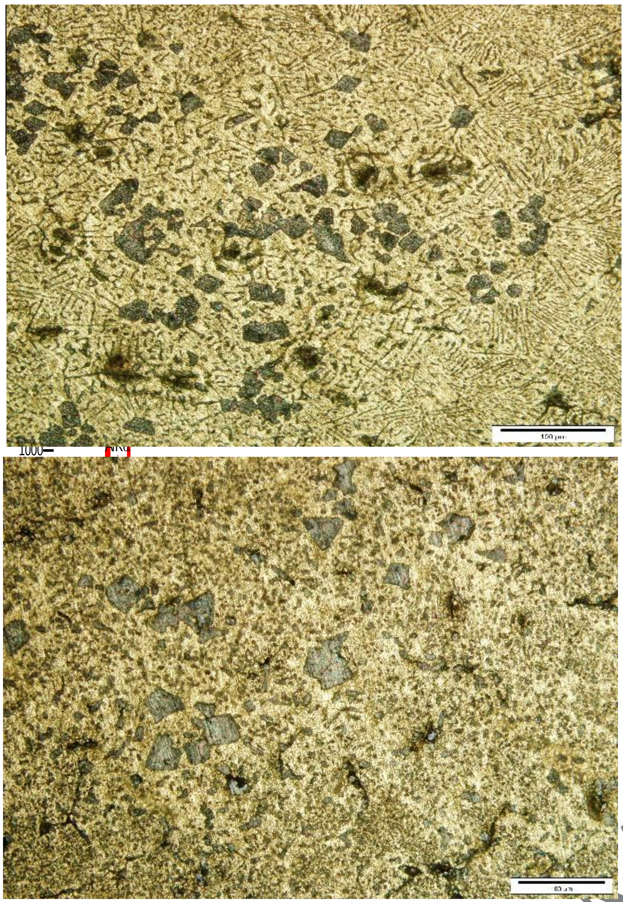


Figure 12. The microstructure of the internal surfaces of two samples at two pouring temperatures of 750 and 650 degrees Celsius with the same heat treatment process (dissolution temperature of 570 and aging temperature of 210 degrees Celsius) and the same mold preheat temperature a) 750 degrees Celsius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

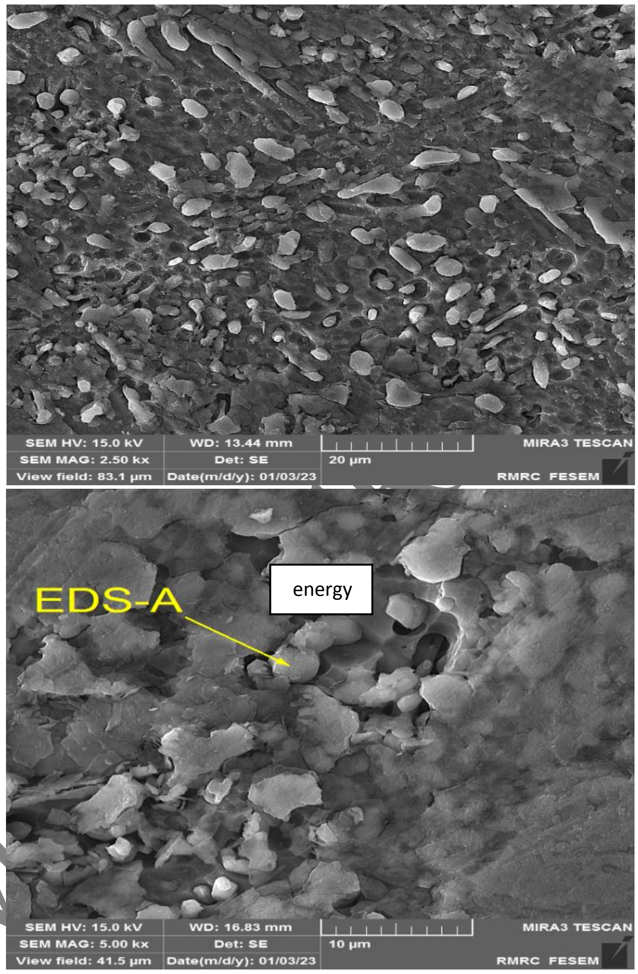


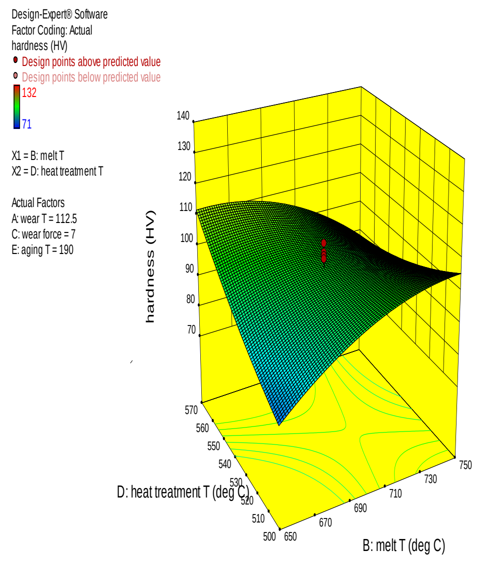
Figure 13. FESEM image of the reinforcement located on the inner surface of the sample poured at 750 °C and dissolution temperature of 570 °C

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

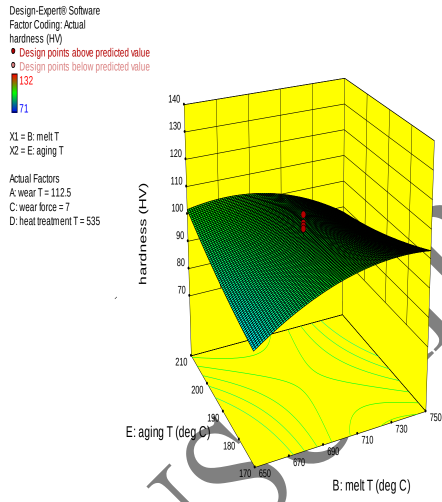
intensity

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

According to the microstructure images and hardness tests, we see the highest hardness in samples with heat treatment temperature in the range of 535 degrees Celsius and pouring temperature near 700 degrees Celsius, 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. 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 and the disappearance of the brittle corners of the reinforcement, and the improvement of the interface between the reinforcement and the ground. Also, 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, which leads to a decrease in hardness, and on the other hand, at low pouring temperature, due to the small freezing range and insufficient opportunity for the reinforcement to be placed in the wall. Internally, the hardness is low. Also, at high temperatures, with the increase in fluidity and decrease in melt viscosity, the friction between the mold and the melt is reduced, and the melt does not reach the speed of the mold in a short time, which affects the lack of effective placement of the reinforcement in the inner wall, which leads to a decrease



in hardness.

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

Figure 16 shows the simultaneous effect of aging temperature and pouring temperature on the hardness of the inner wall of different samples. As can be seen from the picture, the hardness improves with the increase of the pouring temperature up to 700 degrees Celsius and then it drops [٢٨]. Also, the change in aging temperature does not have much effect on the hardness, which seems normal considering the use of pure aluminum. Also, according to pictures 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).

Figure 16. The simultaneous effect of aging temperature and

pouring temperature on the hardness of the inner wall of Al-15wt%Mg_2Si gradient composite pip

According to Table 13 from Design Expert software, values with P-VALUE less than 0.05 have a significant effect, and values greater than 0.1 do not have a significant effect on the desired response (hardness). Also, to check the mutual effect of different variables, you can pay attention to the P-VALUE of those two variables. As can be seen from the ANOVA table, the pouring temperature and dissolution temperature variables have been identified as influencing factors on the response (hardness), and the effect of aging treatment is not known as significant which was discussed earlier. Regarding the mutual effects of variables, pouring temperature and heat treatment temperature have been introduced as factors that have significant mutual effects.

Table13. 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*			
Cor Total	6582.17	34				

4. Conclusion

1) The experimental results of this study were in good agreement with the results predicted by ANOVA (above 89%).
2) Among the variables introduced in this study, the temperature of heat treatment (dissolution) has the greatest effect on the hardness of the Al-15Mg_2Si composite, and the best result was obtained at a temperature of about 535 degrees Celsius.
3) The preheat temperature of the mold does not have much effect on the hardness of the final piece.
4) The pouring temperature of about 700 degrees Celsius showed th

References

[1] K.K. Chawla Composite Materials. 2nd ed., (1998), New York, Springer.

[2] A. Honarbakhsh, R. Khorshidi. (2012) 'Aluminum matrix composite processing methods'.

[3] Kaufman J. Aluminium Alloy Castings Properties, Processes, and Applications, (2004). ASM International. Materials Park, USA.

[4] Shailesh Rao A, P G Mukunda, "Influence of teeming temperature of molten metal of Tin during centrifugal casting", (2010), 51-54.

[5]Xiu, D., Yu, Q., Li, X., & An, G. Mold filling behavior of melts with different viscosity under centrifugal force field. (2002), J. Mater. Sci. Technol, 149.

[6] Zagórski, R., & Œleziona, J., Pouring mold during the centrifugal casting process. (2007), Archives of Materials Science, 442- 442.

[7] Das, A., and Fan, Z. Morphological development of solidification structures under forced fluid flow: experimental observation. (2003), Materials science and technology, 573-580.

[8]Kumar, S., Sarma, V. S., & Murty, B. S. Functionally Graded Al Alloy matrix in-situ composites. (2010), Metallurgical and Materials Transactions A, 242-254

[9]Yanbo, Zhai., and Ziuteng, Ma., and Zhen, Mei. "Centrifugal Forming Mechanism of Al Gradient Composites Reinforced with Complementary Primary Si and Mg_2Si Particles.", (2014), Rare

Metal Materials and Engineering 43(4): 0769-0774.
[10] Meiling Xin a ., Zhaodong Wang A., Bing Lu a ., Yong Li. “Effects of different process parameters on microstructure evolution and mechanical properties of 2060 AleLi alloy during vacuum centrifugal casting”. (2022), Journal of materials research and technology. 54-68.
[11]Xue Sheng., Xiaoming Qian., Longzhou Meng., Zhaodong Wang. “Numerical Simulation of Density Segregation of Al Alloy During Centrifugal Casting”. 2nd International Conference on Advanced Materials and Mechatronics (ICAMM 2022). doi:10.1088/1742-6596/2343/1/012012.
[12] M. Arefkhani, M. Razavi*, M.R. Rahimipour, A. Faeghinia. “The Effect of Rotation Speed on the Microstructure and Hardness of Synthesized Al-WC Nano-Composite by Centrifugal Casting”, (2016), Advanced Ceramics Progress, Vol. 2, No. 4, 1-6.
[13] Mohamad Nirumand, Yaser Vahidshad, Massoud Emamy , Karen Abrinia. “Design and manufacturing of Al-Mg2Si cylindrical functionally graded composites using in-situ centrifugal casting”, (2020), vol 8, No. 4, 1749-1757.
engineers. https://doi.org/10.1177/09544062221124064.
[14] S Senthil Murugan ., S Balu Mahandiran ., M Vigneshkumar ., P Ashoka Varthanan ., S Sakthivel ., V Vicknesh. “Microstructural Analysis of Al-Sic Composites Fabricated Through Centrifugal Casting Process”.(2022), International Conference on Advancements in Materials and Manufacturing Engineering.291-296.
[15]Subhash Chandra Ram., Kausik Chattopadhyay.,and Awani Bhushan. “A literature review on Al-Si alloy matrix based in situ Al-Mg_2Si FG-composites: Synthesis, microstructure features, and mechanical characteristics”.(2022), institution of mechanical engineers. https://doi.org/10.1177/09544062221124064.
[16] Verma, R.K., Parganiha, D. & Chopkar, M. 2021. “A review on fabrication and characteristics of functionally graded aluminum matrix composites fabricated by centrifugal casting method”. SN Applied Sciences. https://doi.org/10.1007/s42452-021-04200-8.
[17] Yunus Emre ASAN., Murat ÇOLAK. 2022. “Modeling the Effect of Pour Height, Casting and Mold Heating Conditions for the Analysis of Fluidity of Different Section Thicknesses in Die Mold Casting of Al12Si Alloys. Journal of Science and Technology. 14-27.
[18] Yi Si., Wanshan Di., Miao Liu., Yuexiang Zhao. “Effects of pouring temperature and electromagnetic stirring on the semi-solid microstructure of hypoeutectic Mg_2Si/Al composite”. (2020), IOP Conference Series: Earth and Environmental Science. 692.
[۱۹] Shivkumar, S., Ricci, S., Keller, C. & Apelian, D. Effect of solution treatment parameters on tensile properties of cast aluminum alloys. (1990), Journal of Heat Treating, 63-70.
[20] Ogris, E., Wahlen, A., Lüchinger, H. & Uggowitzer, P. J. On the silicon spheroidization in Al-Si alloys. , (2002), Journal of Light Metals, 263-269.
[21] Zhang, D. L., Zheng, L. H. & StJohn, D. H. Effect of a short solution treatment time on microstructure and mechanical properties of modified Al–7wt.%Si–0.3wt.%Mg alloy. (2002), Journal of Light Metals, 27-36.
[22] Li, Zedi., and Li, Chong., and Liu, Yongchang., and Yu, Liming., and Gou, qianying., and Li, Huijun. “ Effect of heat treatment on microstructure and mechanical property of Al-10%Mg_2Si alloy.”, (2016), Journal of Alloys and Compounds 663: 16-19.
[23] A. Oyewole., A.M. Sunday. 2011. “Design and fabrication of a centrifugal casting machine”. International journal of engineering science and technology. 8204-8210.
[۲۴] M. TEBIB., F. AJERSCH., A.M. SAMUEL., and X.-G. CHEN. “Solidification and Microstructural Evolution of Hypereutectic Al-15Si-4Cu-Mg Alloys with High Magnesium Contents”, (2013), The Minerals, Metals & Materials Society and ASM International. 4282-4295.
[۲۵] M. R. Akbarpour , F. S. Torknik. “Modelling and Optimization of Densification and Hardness of Cu/SiC Nanocomposites based on Response Surface Methodology (RSM)”, (2022), Advanced Ceramics Progress, vol 7, No.4, 28-35.
[۲۶] Prasad, K. K., Murali, M. S., & Mukunda, P. G. (2010). Analysis of fluid flow in centrifugal casting. Frontiers of Materials Science in China, 103-110.
[۲۷]C. Rajaravi., B. Gobalakrishnan., and P. R. Lakshminarayanan. “Effect of pouring temperature on cast Al/SiCp and Al/TiB2 metal matrix composites”, (2019), Journal of the Mechanical Behavior of Materials. 162-168.
[۲۸] D.M. Wankhede., B.E. Narkhede., S.K. Mahajan., C.M. Choudhari. 2018. “Influence of pouring temperature and external chills on mechanical properties of aluminum silicon alloy castings”. Materials Today: Proceedings. 17627-17635.