
**POLİTEKNİK DERGİSİ**

***JOURNAL of POLYTECHNIC***

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)
URL: http://dergipark.org.tr/politeknik


# Effects of stirring duration and casting temperature in ultrasonic assisted stir casting of Al A356 matrix composites

## *Al A356 matris kompozitlerin ultrasonik destekli karıştırmalı döküm ile üretiminde karıştırma süresi ve döküm sıcaklığının etkileri*

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**Bu makaleye şu şekilde atıfta bulunabilirsiniz(To cite to this article)**: Yuksel T., Aybarc U. and Ertugrul O., "Effects of stirring duration and casting temperature in ultrasonic assisted stir casting of Al A356 matrix composites", ***Politeknik Dergisi***, 23(4): 1265-1275, (2020).

**Erişim linki (To link to this article):** http://dergipark.org.tr/politeknik/archive

**DOI:** **10.2339/politeknik.629473**

# Effects of Stirring Duration and Casting Temperature in Ultrasonic Assisted Stir Casting of Al A356 Matrix Composites

## *Highlights*

- *Aluminum matrix composites*
- *Ultrasonic vibration*
- *Mechanical stirring*
- *Casting temperature*
- *SiC particle*

## *Graphical Abstract*

*In the present study, two casting parameters as stirring duration and casting temperature were taken into consideration in order to determine the effect of stirring process on mechanical properties of aluminum matrix composites.*

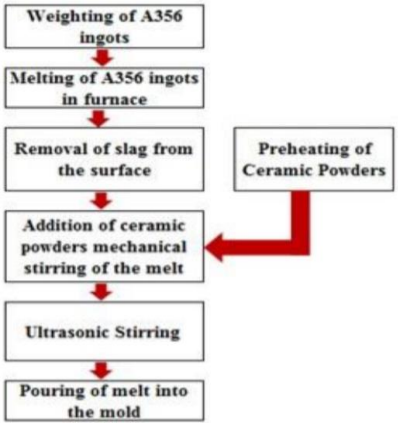


**Figure.** Casting process

## *Aim*

*The aim of the present study is to determine the appropriate stirring process parameters and casting temperature for producing aluminum matrix composites with SiC particle reinforcement.*

## *Design & Methodology*

*Experimental process was taken into consideration in two groups as to determine the appropriate stirring process and to determine the appropriate casting temperature. At first step, to determine the optimum stirring parameters, composite samples were produced with different stirring conditions that included both mechanical stirring and ultrasonic vibration (with different durations as 3-1, 2-2 and 1-3 minutes, respectively). At the second step, to determine the optimum casting temperature, composite samples were produced with different casting temperatures as 700°C, 720°C and 740°C by applying the optimized stirring condition at first step.*

## *Originality*

*The novelty of this study is the need for optimization of the stirring process and the molten metal temperature in ultrasonic assisted stir casting of micron-sized SiC reinforced aluminum matrix composites.*

## *Findings*

*By the addition of SiC particles, the dendrite lengths have decreased. SiC particles showed the best modification effect with 1 minute mechanically and 3 minute ultrasonic vibration casting. It has been observed that the SiC particles act as nucleation sites in the molten metal and accelerate the nucleation rate of the dendrites. Additionally the casting temperature at 720°C is appropriate to obtain the highest quality index.*

## *Conclusion*

*As a conclusion, in order to produce advanced SiC particle reinforced aluminum metal matrix composites using ultrasonic assisted stir casting technique, 1 minute mechanical stirring and 3 minutes ultrasonic vibration and casting temperature at 720°C should be used.*

## *Declaration of Ethical Standards*

*The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.*

# Effects of Stirring Duration and Casting Temperature in Ultrasonic Assisted Stir Casting of Al A356 Matrix Composites

*Araştırma Makalesi / Research Article*

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(Geliş/Received : 04.10.2019 ; Kabul/Accepted : 05.01.2020)

**ABSTRACT**

In the present study, two main parameters as stirring duration and casting temperature were taken into consideration in order to determine the effect of stirring process on mechanical properties of aluminum matrix composites. AlSi7Mg0.3 aluminum alloy and silicon carbide (SiC) particles were used as matrix and reinforcement materials to produce composite samples. Firstly, stirring processes were applied as the combination of mechanical stirring and ultrasonic vibration for the various time as 3-1, 2-2 and 1-3 minutes, respectively. To determine the effect of stirring process, tensile tests were applied to whole samples and Quality Indexes (QI) were calculated by using the results of tensile tests. According to the values of QI, the produced samples with the combination of 1 minute mechanical stirring and 3 minutes ultrasonic vibration showed the maximum mechanical properties. Afterwards, the determined stirring combination was chosen to specify the appropriate molten metal temperature. Three different casting temperatures were addressed as 700˚C, 720˚C and 740˚C. According to mechanical tests results and calculations of QI and metallographic analysis, the maximum mechanical properties were obtained with aluminum composite reinforced with 1 wt. % SiC at 720˚C molten metal temperature by applying 1 minute mechanical stirring and 3 minutes ultrasonic vibration.

**Keywords: Aluminum matrix composites, ultrasonic vibration, mechanical stirring, casting temperature.**

# Al A356 Matris Kompozitlerin Ultrasonik Destekli Karıştırmalı Döküm ile Üretiminde Karıştırma Süresi ve Döküm Sıcaklığının Etkileri

**ÖZ**

Bu çalışmada, karıştırma işleminin kompozit malzemelerin mekanik özellikleri üzerindeki etkisinin belirlenmesi için karıştırma süresi ve erimiş metal sıcaklığı gibi iki temel parametre göz önünde bulundurulmuştur. Kompozit numune üretiminde, AlSi7Mg0.3 alüminyum alaşımı matris malzemesi olarak silisyum karbür (SiC) parçacıkları ise takviye malzemesi olarak kullanılmıştır. İlk aşamada, mekanik karıştırma ve ultrasonik titreşimli karıştırma işlemleri çeşitli süreler için faklı kombinasyonlarda 3-1, 2-2 ve 1-3 dakika olarak uygulanmıştır. Karıştırma işleminin etkisini belirlemek için tüm numunelere çekme testleri uygulanmış ve çekme testi sonuçları kullanılarak Kalite İndeksleri (Kİ) hesaplanmıştır. Kalite İndeksi sonuçlarına göre, 1 dakikalık mekanik karıştırma ve 3 dakikalık ultrasonik titreşim kombinasyonu ile üretilen örnekler maksimum mekanik özellikleri göstermiştir. Daha sonra, tespit edilen karıştırma kombinasyonu uygun erimiş metal sıcaklığını belirtmek için seçildi. Üç farklı döküm sıcaklığı 700˚C, 720˚C ve 740˚C olarak ele alınmıştır. Mekanik testler ve Kİ hesaplamaları ve metalografik inceleme sonuçlarına göre, maksimum mekanik özellikler 1 dakika mekanik karıştırma ve 3 dakika ultrasonik titreşim uygulanan 720˚C döküm sıcaklığında ağırlıkça %1 SiC katkılı alüminyum kompozit ile elde edilmiştir.

**Anahtar kelimeler: Aluminyum matrisli kompozitler, ultrasonik titreşim, mekanik karıştırma, döküm sıcaklığı**.

## 1. INTRODUCTION

Aluminum alloys are one of the most important material group used in the automotive industry due to their lightness, high corrosion resistance, easy formability, recyclability and high specific strength [1-3].

Particularly, in recent years, work has begun on decreasing vehicle weights, especially due to new regulations aimed at reducing environmental pollution, and studies on products such as aluminum have gained momentum. Thus, engineers have begun to look for alternative materials such as metal matrix composites (MMCs) since they perform improved mechanical properties for instance high elastic modulus, improved strength, hardness, wear resistance and fatigue resistance, lower thermal expansion coefficient. In addition, MMCs have high shear and compression strength at elevated temperatures by the help of having metallic and ceramic material properties [4-6].

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Particle reinforcement is the most common and inexpensive reinforcement type. At this point, the problem of the homogeneity of a composite material is encountered. The particle distribution in a matrix is a crucial for the performance of metal matrix composite (MMC) [7]. Several production methods such as Powder Metallurgy, Squeeze Casting, Spray Casting, Stir Casting, and Liquid Metal Infiltration have been used for many years [8, 9]. The most preferred method is liquid state due to economically, suitability and simplify processing, easy to work and handily applicable. Stir casting production method is the most common type that is mechanically mixing of molten metal matrix. The production method is simplest and low fabrication cost. Some conditions become crucial during the stir casting are; achieving of homogenously dispensation reinforcement material, wetting between reinforcement and matrix material, chemically bond between materials, porosity of metal matrix composite and reaction of atmospheric condition between metal matrix composite components [10]. In last years new production technologies have been improved to fabrication of particle reinforced MMCs such as stir casting assisted with ultrasonic vibration [11, 12]. Later many modifications have been done by the researchers in various liquid state metallurgical methods and introduced the ultrasonic-assisted stir casting method for better wettability and dispersion of hard nanoparticles in the aluminum alloy matrix. On the other hand, there can be segregation thence gravity or density differences between matrix and reinforcement material, especially when there is nano-sized ceramic particles. Not only a uniform distribution of nano-size ceramic particles in metal matrix composites is obtained during the ultrasonic assisted casting process, but also molten metal purifies and grain refinement occurs [13,14,15].

Studies are investigated which is used ultrasonic stirring technique so ultrasonic stirring have lots of advantages such as; SiC, eutectic and intermetallic phases are properly modified [16], ultrasonic stirring is positively affected, mechanical properties (yield strength, tensile strength, SDAS, elongation) are increased [17]. M. Rahman et al. are applied stir casting for different percentages of SiC (0, 5, 10 and 20 wt. %) reinforcement material in aluminum metal matrix composites. Results of the study show that hardness, tensile test value and wear resistance increase with increasing SiC content. Also, nonhomogeneous dispersion and clustering are observed. The microstructural analysis showed that porosity decreases with increasing SiC content [18]. Sozhamannan and coworkers examined process conditions on reinforcement dispersion and mechanical properties. Aluminum metal matrix composites with reinforcement SiC were fabricated by stir casting process with different pouring temperature (at 700°C, 750°C, 800°C, 850°C, 900°C) and different holding time (10, 20, 30 min). The results observed are reinforcement particles are distributed uniformly in the matrix at 750°C and 800°C. Ultimate strength of MMC reduced with increasing holding time. Effect of holding time is viscosity of liquid metal and reinforcement distribution [19]. S. Jia and L. Nastac are examined the effect of ultrasonic stirring on the mechanical properties and microstructure of A356 Alloy. It is observed reduction of SDAS (15-20%) via ultrasonic stirring so structure become modified. Besides mechanical properties are also increased. Another result is that degassing process is more effective than standard degassing process [16]. Based on these studies it can be well overcame homogenous distribution of micron and nano sized ceramic particles in melted matrix via mechanical stirring method combining of ultrasonic stir. Also wettability can increase between reinforcement and matrix.

As aforementioned, composite material, especially aluminum metal matrix composites, are taken great attention for last ten years. But it is not evidently that the producing parameters such as the stirring and casting temperature. Because of this, the aim and novelty of this research project is mainly the optimization of the casting parameters such as stirring process and the molten metal temperature for the producing of aluminum metal matrix composites with reinforced micron-sized SiC. Experimental process was taken into consideration in two groups as to determine the appropriate stirring process and to determine the appropriate casting temperature. At first step, to determine the optimum stirring parameters, composite samples were produced with different stirring conditions that included both mechanical stirring and ultrasonic vibration (with different duration times as 3-1, 2-2 and 1-3 minutes, respectively) were applied at 740°C. According to the results of first step, the optimum stirring process was determined as 1 minute mechanical stirring and 3 minutes ultrasonic vibration with the help of QI values. At the second step, to determine the optimum temperature, composite samples were produced with different casting temperature as 700°C, 720°C and 740°C by applying the determined stirring condition at first step. By using mechanical test results and calculation of QI value, the maximum result was obtained at 720°C. Conclusion of the present study, it could be said that to produce aluminum metal matrix composite with SiC particle reinforcement, 1 minute mechanical stirring and 3 minutes ultrasonic vibration and casting temperature at 720°C should be used.

## 2. MATERIAL and METHOD

### 2.1 Sample production

The hypoeutectic A356 alloy (Al7Si0.3Mg) was used as matrix material having the chemical composition given in Table 1. The ceramic reinforcement material was silicon carbide (SiC) in particulate form. The average particle size (APS) of the SiC powder is approximately 53 μm.

**Table 1.** Chemical composition of A356 alloy.

| **Element** | Al | Cu | Fe | Mg | Mn | Si | Ti | Zn |
|---|---|---|---|---|---|---|---|---|
| **wt. %** | Rest | 0.1 | 0.1 | 0.3 | 0.05 | 7.3 | 0.1 | 0.05 |

In the first experimental group; casting process including three different stirring times (2 mins mechanical stirring + 2 mins ultrasonic stirring; 3 mins mechanical stirring + 1 min ultrasonic stirring; 1 min mechanical stirring and 3 mins ultrasonic stirring) were done at 740°C casting temperature. In the second experimental group; two additional casting temperatures (700°C, 720°C, 740°C) were applied by using the casting process duration which was determined in the first experimental group in order to compare with 740°C casting temperature.

The casting process used to produce the composite samples was "ultrasonic assisted stir casting", and the procedure is shown as a flow chart in Figure 1. A356 ingot of 4 kg was melted at 740˚C in a graphite crucible in an electrical resistance furnace. Reinforcement powders were weighted as the amount would be 1 wt. %. In order to improve the wettability, SiC powders were preheated to 800˚C for 2 h before the addition. Five cell melting mould was preheated to 320°C in another furnace. One crucible was taken out from the furnace then, slag on the surface was removed.

After vortex occurred with the help of mechanical stirring, preheated SiC powders (1 wt.%) were added into the melt. Mechanical stirring and ultrasonic vibration were applied by 2-2, 3-1 and 1-3 minutes, respectively, for each crucible. Mechanical stirring was applied by Optimum B20400 V model stirrer at 600 rpm which is shown in Fig. 2a, and the ultrasonic stirring was applied by Rtul model vibration machine which is capable of 3 kW of electric energy at a constant resonant frequency of 19.8 kHz as shown in Fig. 2b.

After stirring was finished, the molten metal was casted into the preheated mold, which is applicable for simulate the wheel geometry, and shown in the Figure 3. This step was repeated for each stirring process parameters. To compare the effects of SiC reinforcement, a reference A356 sample was also cast under the same conditions without any addition of reinforcement. Two casting process were carried (totally 5 + 5 = 10 samples) in order to have reproducible results.

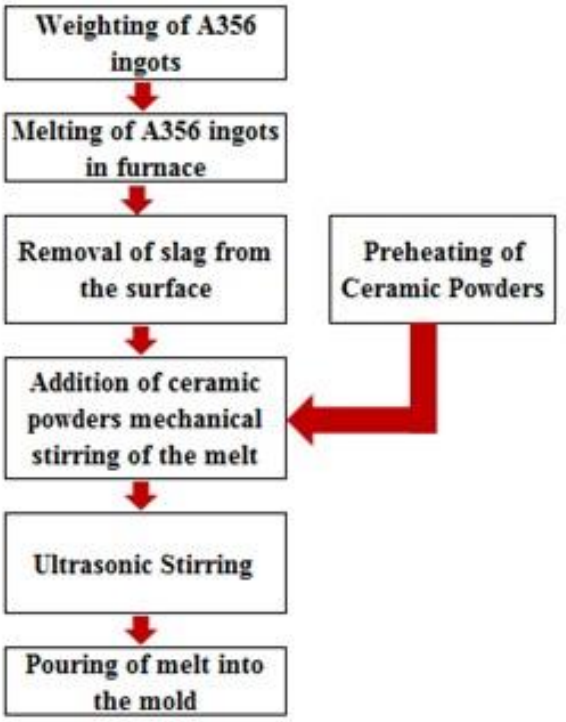



**Figure 1.** Casting process

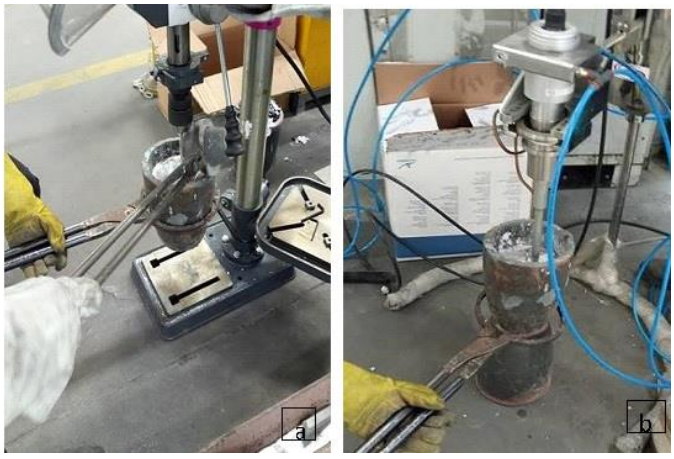
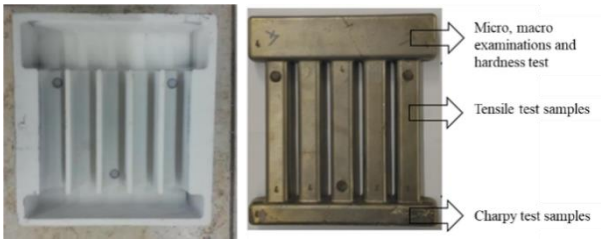



**Figure 2.** (a) Mechanical stirring, (b) ultrasonic vibration




(a) (b)

**Figure 3.** a) Preheated mold, b) test samples

### 2.2 Mechanical and metallographic analysis

Tensile test samples were prepared according to the DIN EN ISO 6892-1 standard, and tensile tests were applied using Zwick brand Z100 model tensile test machine in order to evaluate the mechanical properties. Quality Index (QI) values of the samples are calculated using the Equation 1 by the help of the tensile test results [24-26].

$$QI = UTS + K * \log(\%elongation) \quad (1)$$

In this equation

QI ; quality index(MPa)

UTS ; ultimate tensile strength (MPa)

K ; constant (for A356 alloy is equivalent to 150 MPa)

Elongation ; (%)

Brinell hardness tests and Charpy Impact tests were applied to the samples using Innovates Nemesis 9000 and Instron Ceast 9050 model machines, respectively. For metallographic study, samples were firstly grinded, and polished with diamond solution, then etched by 3% HF solution for macro and by $FeCl_3$ solution for microstructure examinations, respectively. Nikon Epiphot 200 optical microscope and Clemex S2.0C software were used for microstructure analysis. Additionally, SEM studies were done with Jeol JSM-6060 scanning electron microscope equipped with EDX (Energy dispersive X-Ray Spectroscopy).

## 3. RESULTS AND DISCUSSION

Experimental section consists of two group as follows;

a First group; to determine the stirring parameters,
b Second group; to determine the appropriate casting temperature

After first experimental group was concluded, second experimental group was carried out with the help of results of first experimental group. They are listed in Table 2. Additionally, Table 3 shows the chemical composition of all samples.

**Table 2** Given codes and explanations of the composite samples a) first b) second experimental groups

| Sam. group no. | Sample code | Stirring type* | Casting temperature | Heat treatment condition | SiC content (wt. %) |
|---|---|---|---|---|---|
| 1 | 2M2U-74-T6 | 2M + 2U | 740°C | with ht. | 1 % |
| 2 | 2M2U-74 | 2M + 2U | 740°C | without ht | 1 % |
| 3 | 3M1U-74-T6 | 3M + 1U | 740°C | with ht. | 1 % |
| 4 | 3M1U-74 | 3M + 1U | 740°C | without ht | 1 % |
| 5 | 1M3U-74-T6 | 1M + 3U | 740°C | with ht. | 1 % |
| 6 | 1M3U-74 | 1M + 3U | 740°C | without ht | 1 % |

(a)

| Sam. group no. | Sample code | Stirring type* | Casting temperature | Heat treatment condition | SiC content (wt. %) |
|---|---|---|---|---|---|
| 7 | 1M3U-70-T6 | 1M + 3U | 700°C | with ht. | 1 % |
| 8 | 1M3U-70 | 1M + 3U | 700°C | without ht | 1 % |
| 9 | 1M3U-72-T6 | 1M + 3U | 720°C | with ht. | 1 % |
| 10 | 1M3U-72 | 1M + 3U | 720°C | without ht | 1 % |
| 11 | 1M3U-74-T6 | 1M + 3U | 720°C | with ht. | 1 % |
| 12 | 1M3U-74 | 1M + 3U | 720°C | without ht | 1 % |
| 13 | 1M3U-Ref-T6 | 1M + 3U | 740°C | with ht. | 0 % (Ref.) |
| 14 | 1M3U-Ref | 1M + 3U | 740°C | without ht | 0 % (Ref.) |

(b)

*(M: mechanical stirring, U: ultrasonic stirring)

**Table 3** Chemical composition of all samples

| Sam. Code | Heat Treat. | Si | Fe | Mg | Ti | Sr | Al% |
|---|---|---|---|---|---|---|---|
| 2M2U-74-T6 | with | 6,57 | 0,89 | 0,26 | 0,11 | 0,004 | rest |
| 2M2U-74 | without | 6,61 | 0,87 | 0,26 | 0,11 | 0,004 | rest |
| 3M1U-74-T6 | with | 6,51 | 1,34 | 0,21 | 0,11 | 0,004 | rest |
| 3M1U-74 | without | 6,16 | 1,44 | 0,23 | 0,13 | 0,004 | rest |
| 1M3U-74-T6 | with | 6,76 | 0,62 | 0,26 | 0,12 | 0,003 | rest |
| 1M3U-74 | without | 6,44 | 0,79 | 0,28 | 0,13 | 0,003 | rest |
| 1M3U-70-T6 | with | 6,54 | 0,36 | 0,30 | 0,10 | 0,002 | rest |
| 1M3U-70 | without | 6,95 | 0,34 | 0,29 | 0,10 | 0,002 | rest |
| 1M3U-72-T6 | with | 6,67 | 0,41 | 0,29 | 0,11 | 0,003 | rest |
| 1M3U-72 | without | 6,46 | 0,40 | 0,29 | 0,11 | 0,003 | rest |
| 1M3U-74-T6 | with | 6,69 | 0,57 | 0,30 | 0,10 | 0,002 | rest |
| 1M3U-74 | without | 6,38 | 0,49 | 0,30 | 0,11 | 0,002 | rest |
| 1M3U-Ref-T6 | with | 6,48 | 0,59 | 0,29 | 0,11 | 0,003 | rest |
| 1M3U-Ref | without | 6,57 | 0,59 | 0,29 | 0,11 | 0,003 | rest |

### 3.1 Mechanical test results

#### 3.1.1 Effect of stirring duration

Tensile test was carried out to evaluate the effects of both heat treatment and each stirring duration and the results are listed in Table 4.

Yield strength, ultimate tensile strength, elongation and hardness values of the composite samples with different stirring methods are shown in Figures 4-7, respectively. According to Figure 4, the sample encoded as 3M1U-74 shows the highest yield strength value among the others in without heat treatment state. Paralelly, the sample encoded as 3M1U-74-T6 shows the highest yield strength in with heat treatment state. Ultimate tensile strength values of the samples encoded as 2M2U-74 and 1M3U-74 are close each other in without heat treatment

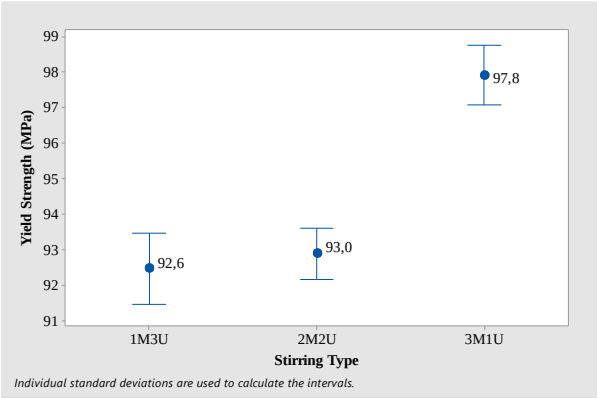
state as seen in Figure 5. The sample that is 3 minutes mechanical stirred and 1 minute ultrasonic stirred has the lowest ultimate tensile strength value in without heat treatment. However, ultimate tensile strength values of samples 2M2U-74 and 3M1U-74 are close each other in with heat treatment state which is higher than 1M3U-74 state.

**Table 4** Mechanical properties of A356 with different stirring durations

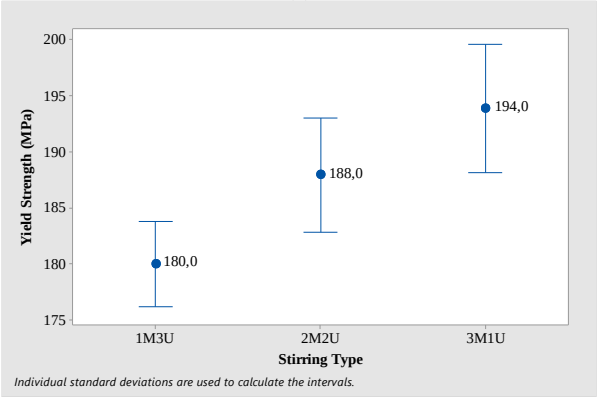
| Sam. code | YS* (MPa) | UTS** (MPa) | Elong. (%) | Impact Energy (J) | QI (MPa) | Hardness (HB) |
|---|---|---|---|---|---|---|
| 2M2 U-74-T6 | 188±3.7 | 232±2.8 | 1.2±0.1 | 10.3 | 242,2 | 93,7 |
| 2M2 U-74 | 93±0.5 | 173±5.2 | 3.0±0.5 | 11.7 | 244,8 | 63,8 |
| 3M1 U-74-T6 | 194±1.9 | 231±4.9 | 0.7±0.1 | 12.7 | 203,9 | 99,5 |
| 3M1 U-74 | 98±0.3 | 163±2.5 | 1.3±0.1 | 12.3 | 179,6 | 71,2 |
| 1M3 U-74-T6 | 180±2.7 | 223±1.9 | 1.6±0.3 | 13 | 252,0 | 92,4 |
| 1M3 U-74 | 92±0.7 | 171±4.2 | 3.7±0.6 | 13 | 255,3 | 63,5 |

*Yield Strength

**Ultimate Tensile Strength

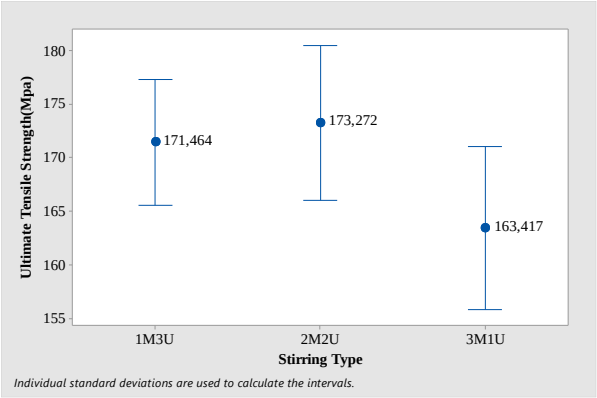



(a)

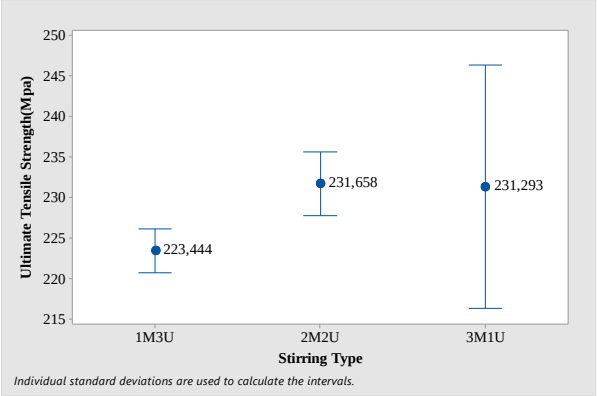



(b)

**Figure 4.** The yield strength values of A356/ 1% SiC composites with different stirring methods, (a) without heat treatment, (b) with heat treatment




(a)




(b)

**Figure 5.** The ultimate tensile strength values of A356/1% SiC composites with different stirring methods, (a) without heat treatment, (b) with heat treatment

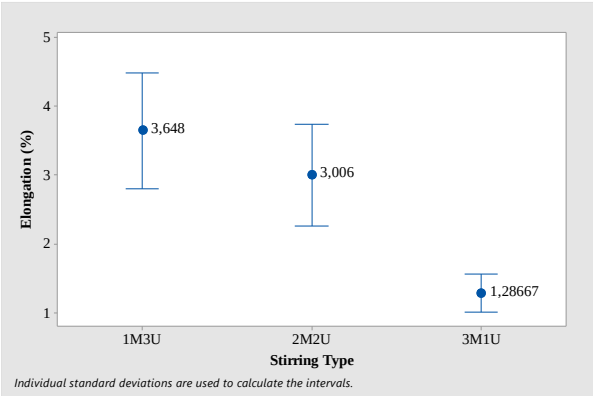
According to the Figure 6, the sample 1M3U-74 has the highest elongation value in without heat treatment state. The sample 3M1U-74 has the lowest elongation value with heat treatment state. Parallelly, the sample 1M3U-74 has the highest elongation values in both ways of heat treatment which is in contrast to yield and tensile strength values of these samples. The charpy impact test was applied for the samples of different stirring duration. Charpy impact results give the information about toughness properties of samples. According to Table 3, the sample encoded as 1M3U has the highest impact value in both ways of heat treatment with 13 J. But also, 3M1U samples have the impact energy of close value as 12.7 J.

The hardness values are clearly seen from Figure 7 that the sample 3M1U-74 has the highest hardness value among of others at different stirring duration parameters in both non heat-treated and heat-treated state.

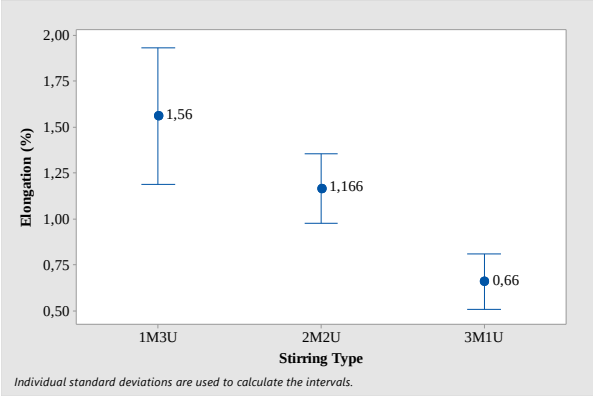
Silicon carbide particulates are ceramic materials that are harder than the aluminum matrix alloy. They block the dislocation motion and therefore an increase in strain hardening achieved.

The aluminum matrix composites were solution heat treated according to T6 heat treatment requirements. Heat treatment also has effects on the hardness values of aluminum matrix composites. By precipitation heat treatment rise in hardness values compared the reference

sample was obtained. It was seen that appropriate heat treatment increases the hardness values.




(a)




(b)

**Figure 6.** Elongation values of A356/1% SiC composites with different stirring methods, (a) without heat treatment, (b) with heat treatment

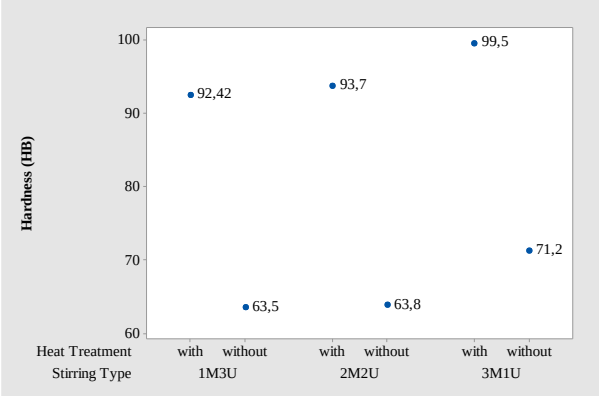



**Figure 7.** Hardness test results of A356/1% SiC composites with different stirring methods

### 3.1.2 Effect of casting temperature

According to first experimental results, 1 minute mechanically and 3 minute ultrasonic stirred material gives the highest quality index (QI) probably because of its highest elongation and toughness value. Therefore, 1M3U sample was chosen for this study. In this section, tensile test was carried out to evaluate the effects of both heat treatment and different casting temperature and the results are listed in Table 5.

**Table 5** Mechanical Properties of A356 Different Casting Temperature

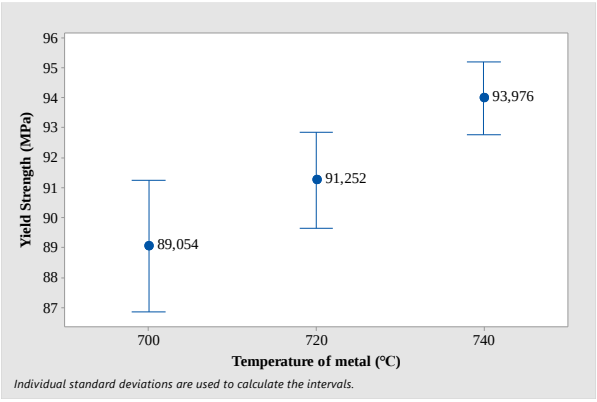
| Sample code | YS* (MPa) | UTS** (MPa) | Elong (%) | IM*** (J) | QI (MPa) | Hardness (HB) |
|---|---|---|---|---|---|---|
| 1M3U - 70-T6 | 191±1.9 | 228±11.5 | 1.18±0.6 | 13.1 | 238, 8 | 94 |
| 1M3U - 70 | 89±1.6 | 151±11.4 | 2.25±0.7 | 14 | 203,8 | 63.1 |
| 1M3U - 72-T6 | 191±2.0 | 241±6.2 | 1.95±0.5 | 12.6 | 284,5 | 93.4 |
| 1M3U - 72 | 91±1.2 | 174±4.1 | 4.27±0.6 | 12.8 | 268,6 | 64.3 |
| 1M3U - 74-T6 | 196±2.3 | 238±6.1 | 1.52±0.5 | 11.7 | 265,3 | 97.3 |
| 1M3U - 74 | 95±1.8 | 172±3.0 | 3.87±0.5 | 6.3 | 260,2 | 62.1 |
| 1M3U-Ref-T6 | 194±0.4 | 232±2.9 | 1.27±0.3 | 3 | 247,6 | 93.9 |
| 1M3U-Ref | 93±0.9 | 163±13.1 | 3.03±1.0 | 4.4 | 235,2 | 64.3 |

*Yield Strength

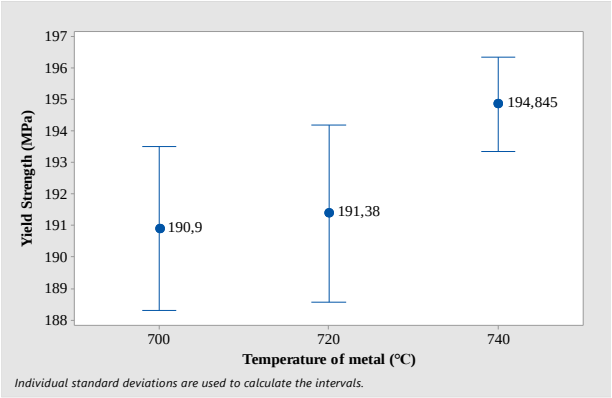
**Ultimate Tensile Strength

*** Impact Energy

Yield strength, ultimate tensile strength, elongation and hardness values of the composite samples with different casting temperatures are shown in Figures 8-11, respectively. According to Figure 8, the sample casted at 740°C shows the highest yield strength value among others in without heat treatment state. Paralelly, the sample casted at 740°C shows the highest yield strength value in with heat treatment state. According to Figure 9, the sample casted at 720°C shows the highest ultimate tensile strength value (240 MPa) in without heat-treated state which is very close to the value (238 MPa) belong to 740oC. Also the sample casted at 720°C shows the highest ultimate tensile strength value in with heat-treated state. Again, the sample casted at 720°C and 740°C are very close to each other in heat-treated state.

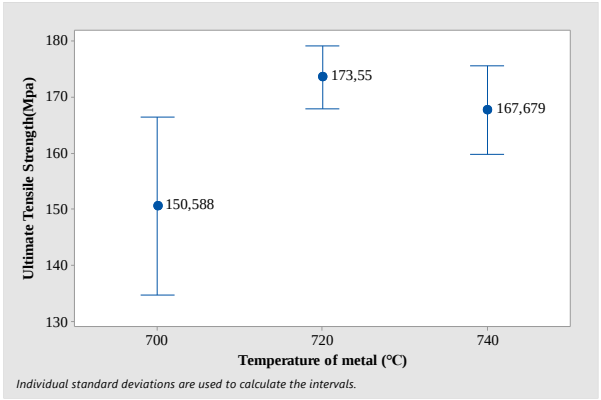



(a)

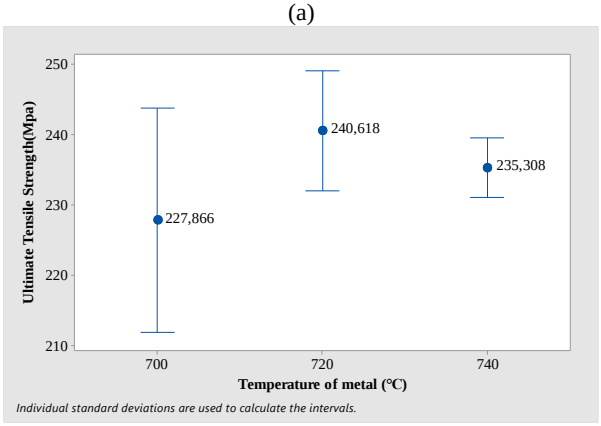



(b)

**Figure 8.** The Yield Strength values of A356/ 1% SiC composites and reference sample with different casting temperature, (a) without heat treatment, (b) with heat treatment



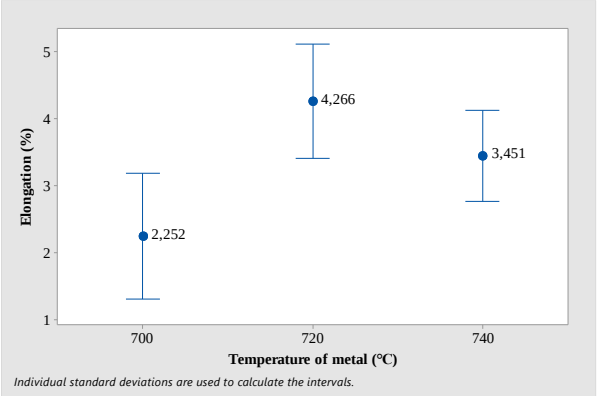

(a)



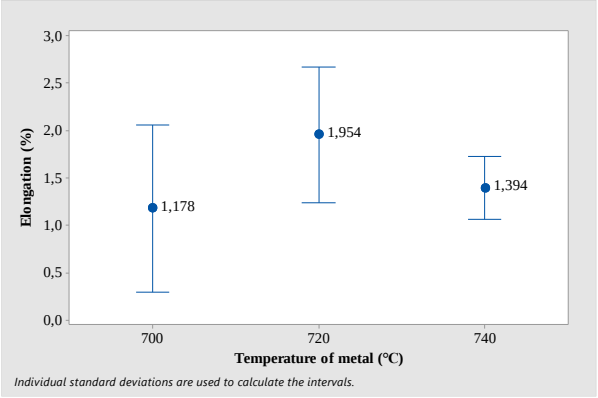

(b)

**Figure 9.** The ultimate tensile strength of A356/1% SiC composites and reference sample with different casting temperature, (a) without heat treatment, (b) with heat treatment

According to Figure 10, the sample casted at 720°C shows the highest elongation value in both with and without heat treatment state. It was observed that when the casting temperature decreases below 720°C the composite shows the lowest elongation value. The charpy impact test was applied for the samples of different casting temperature. According to Table 5, the sample casted at 700°C has the highest impact value in without heat treatment with 14 J. In parallel, the sample casted at 700°C has the highest impact value in with heat treatment with 13.1 J. On the other hand, this value is close to the value belong to 720°C casting temperature (12.6 J). It was also observed that impact energy values increased with silicon carbide addition. According to Table 4, the material casted at 720°C gives the highest quality index (QI) probably because of its highest tensile strength, elongation and toughness value. Therefore, it can be said that 720°C is the optimum casting temperature.




(a)




(b)

**Figure 10.** Elongation values of A356/1% SiC composites and reference sample with different casting temperature, (a) without heat treatment, (b) with heat treatment

The hardness values are clearly seen from Figure 11. Regarding to Figure 11, the sample casted at 740°C shows the highest hardness value (97.3 HB) among of others at different casting temperature parameters as heat-treated state. This value is also higher than the reference sample value (93.9 HB) which means hardness increases with SiC addition. Besides, hardness values are close in all samples in non-heat-treated state.

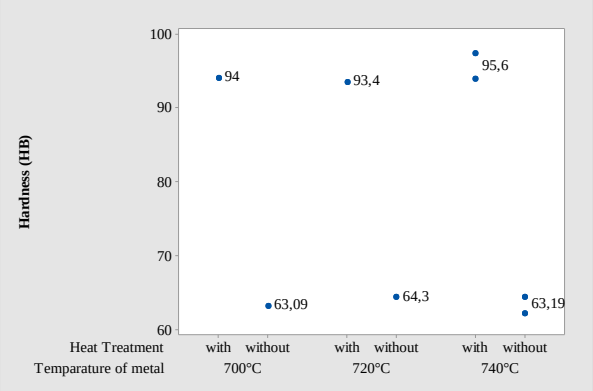



**Figure 11.** Hardness test results of SiC reinforced AMCs and reference sample with different casting temperature parameters

## 3.2 Microstructural study

### 3.2.1 Metallographic examinations

Metallographic examination was applied to the A356/ 1% SiC composites and reference sample with different stirring parameters and molten metal temperatures in heat-treated state. Figure 12 shows to effect of different durations on as-cast A356 heat treated samples. In these views dendritic arm spacing (DAS) is decreased with effect of heat treatment. Also intermetallic phases are decreased after heat treatment.

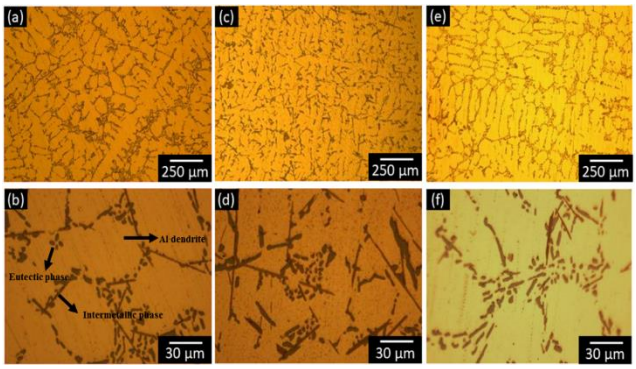



**Figure 12.** (a,b) 2minute mechanic 2 minutes ultrasonic stirred, (c,d) 3 minute mechanic 1 minute ultrasonic stirred, and (e,f) 1 minute mechanic 3 minute ultrasonic stirred at 740°C A356/ 1% SiC alloy with heat treatment.

Different molten metal temperature samples with constant stirring parameters according to the determined in the first experimental group were also investigated by using optical microscope. The images are given below:

Figure 13 belongs to the SiC reinforced AMMCs casted at different temperatures. The particles are not shown clearly in the microstructures. In the second work package, the microstructure images taken as a result of experiments carried out with constant stirring parameters. As the temperature increases, the decrease in surface energy between the additive and the liquid metal results in a more homogeneous mixture. In addition, as the temperature increases, the distance between the dendrite arms decreases, and less intermetallic phases are found in the heat treated samples. Based on the as-casted sample, the best microstructure is in the Figure 13(c) and (d).

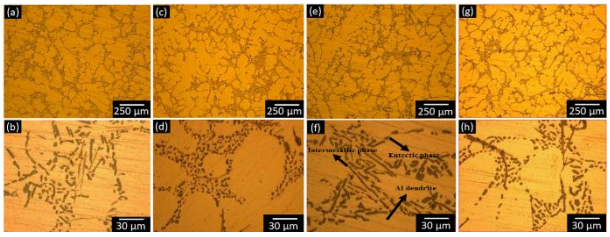



**Figure 13.** 1minute mechanic 3 minutes ultrasonic stirred at (a,b) 700°C, (c,d) 720°C, (e,f) 740°C A356/ 1% SiC alloy, and (g,h) reference sample with heat treatment.

### 3.2.2 Scanning electron microscopy (SEM) study

SEM examinations are done to the heat-treated composite samples in addition to the reference sample which was non additive A356 alloy. The SEM images of the composite samples casted at different duration are given in Figure 14. The secondary phases that are in needle like structure and porosities is observed in heat-treated samples. When we compare the samples, there is no big difference in microstructure between SiC additive and reference sample.

Especially, the coherence of interface of matrix and reinforcement material and the shape and size of the secondary phases in the matrix were important for this study. Not only smaller dendrites thought to be result in an increase in strength value, but also the interface also has an important role in this point.

According to SEM analyses, images were taken with secondary electrons provide information about surface morphology. When these images were examined, where the SiC additive were not homogeneously dispersed for images that taken at 150x and 500x. On the other hand, the distance between the aluminum dendrite arms increased linearly as the temperature increased. EDX analysis of the areas in the sample 2 minute mechanically stirred and 2 minute ultrasonic vibration are given in Figure 15. In the analyses from different regions, it is predicted that phases which are in the form of intermetallic phase and which are needle-shaped geometries are AlFeSi phases. Furthermore, it is predicted that these particles are SiC contribution as a result of analysis from the images of spherical particles according to the literature.

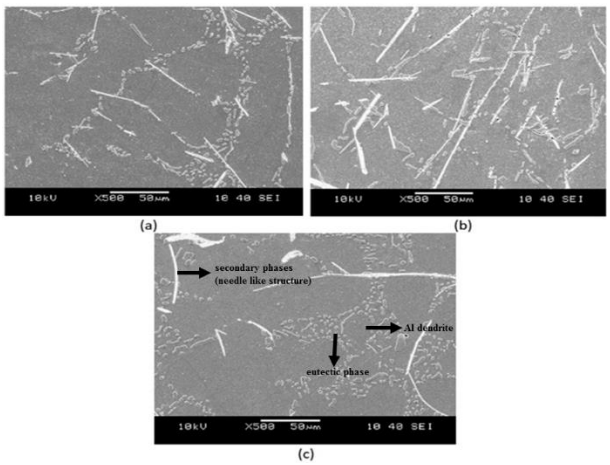
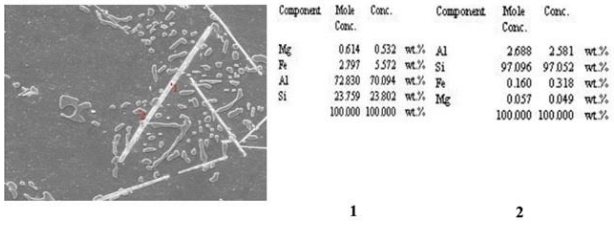


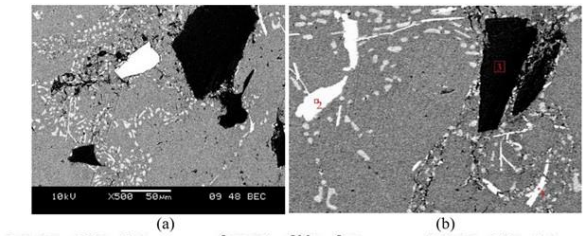

**Figure 14.** SEM images of (a) 2M2U-74-T6, (b) 2M2U-74-T6, and (c) 1M3Y-74-T6 samples.



| Component | Mole Conc. | Conc. | | Component | Mole Conc. | Conc. | |
|---|---|---|---|---|---|---|---|
| Mg | 0.614 | 0.532 | wt.% | Al | 2.688 | 2.581 | wt.% |
| Fe | 2.797 | 5.572 | wt.% | Si | 97.096 | 97.052 | wt.% |
| Al | 72.830 | 70.094 | wt.% | Fe | 0.160 | 0.318 | wt.% |
| Si | 23.759 | 23.802 | wt.% | Mg | 0.057 | 0.049 | wt.% |
| | 100.000 | 100.000 | wt.% | | 100.000 | 100.000 | wt.% |
| | 1 | | | | 2 | | |

**Figure 15.** EDX image of sample 2M2U-74-T6 and composition analyzes of points 1 and 2.

The SEM images of the composite samples casted at different duration are given in Figure 16(a), and EDX analysis of the areas in the sample 2 minute mechanically stirred and 2 minute ultrasonic stirred are given in Figure 16(b).




| Component | Mole Conc. | Conc. | | Component | Mole Conc. | Conc. | | Component | Mole Conc. | Conc. | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Si | 18.892 | 19.094 | wt.% | Si | 40.868 | 40.390 | wt.% | Si | 42.481 | 63.330 | wt.% |
| Fe | 2.119 | 4.259 | wt.% | Fe | 3.433 | 6.746 | wt.% | C | 57.519 | 36.670 | wt.% |
| Mg | 0.489 | 0.427 | wt.% | Mg | 0.228 | 0.195 | wt.% | | 100.000 | 100.000 | wt.% |
| Al | 78.500 | 76.219 | wt.% | Al | 55.471 | 52.668 | wt.% | | | | |
| | 100.000 | 100.000 | wt.% | | 100.000 | 100.000 | wt.% | | | | |
| | 1 | | | | 2 | | | | 3 | | |

**Figure 16.** (a) SEM images of 1 minute mechanic 3 minutes ultrasonic stirred at 700°C A356/SiC alloy with heat treatment, (b) EDS image of the sample casted at 720°C and chemical composition analyses 1, 2 and 3 areas

## 4. CONCLUSIONS

As aforementioned before, mechanic stirring and ultrasonic vibration were used to produce aluminum metal matrix composite with 1 wt% SiC reinforcement to determine the optimum stirring process parameter in the first experimental group. After determined the stirring process parameter, optimum casting temperature was determined in the second experimental group. Obtained results in present study are given briefly as follows;

- The mechanical strength of A356 considerably increased by a combination of T6 heat treatment and adding micro SiC particles. The increase in strength was in expense of ductility.
- QI values were calculated with the help of tensile test results to determine the appropriate stirring process parameters. The maximum QI result was obtained by applying 1 minute mechanical stirring and 3 minutes ultrasonic vibration as 252 MPa and 255,3 MPa with and without heat treatment, respectively. UTS value increased and elongation decreased because of occurring of $Mg_2Si$ phase during the heat treatment process.
- By the addition of SiC particles, the dendrite lengths have decreased. SiC particles showed the best modification effect with 1 minute mechanically and 3 minute ultrasonic vibration casting. It has been observed that the SiC particles act as nucleation sites in the molten metal and accelerate the nucleation rate of the dendrites.
- In the second experimental group, as the temperature increases, the decrease in surface energy between the additive and the liquid metal results in a more homogeneous mixture. In addition, as the temperature increases, the space between the dendrite arms decreases, and less intermetallic phases are found in the heat treated samples.
- The best results on mechanical strength was obtained from the optimization of molten metal temperature; At 740°C has the best yield strength value. At 720°C has the best ultimate tensile strength value. At 720°C has the best impact value and QI. At 740°C has the best hardness value.
- According to SEM analyses, images were taken with secondary electrons provide information about surface morphology. When these images were examined, where the SiC additive were not homogeneously dispersed for images that taken at 150x and

500x. On the other hand, the distance between the aluminium dendrite arms increased linearly as the temperature increased. EDS analysis was performed with backscattered electron mode images, where elements with larger molecular weights are displayed brighter. In the analyses from different regions, it is predicted that phases which are in the form of intermetallic phase and which are needle-shaped geometries are AlFeSi phases. Furthermore, it is predicted that these particles are SiC contribution as a result of analysis from the images of spherical particles.

– The effect of heat treatment on references samples with and without SiC reinforcement addition; hardness increased by 3.49%, YS value increased by 1.02%, UTS by 2.59%, elongation value increased by 16.45%, impact energy value increased by 74.36%.

## ACKNOWLEDGEMENT

The authors thank Caner Kalender for technical support. The authors acknowledge the financial support provided by 2209-B Programme of the TUBITAK (The Scientific and Technological Research Council of Turkey).

## DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

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