

Effect of Aging Heat Treatment on the Mechanical Properties of SiC Reinforced 7075 Al-Alloy Composites Manufactured by Vortex Casting Method

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Abstract Nowadays, light part production by the strategies of performance improving known as 'Engine Downsizing' by decreasing the engine size is popular. Al-Zn-Mg alloyed composites reinforced by SiC particle are mostly produced by powder metallurgy. In fact, Liquid mixing casting technique alternatively developed against the powder metallurgy has more than advantageous when taking into the consideration of its production capacity, production cost and part production similar to the definitive form. In this study, the hardness variation of SiC particle reinforced composites manufactured by the method of affordable 'Vortex Casting' and in different amounts by weight and 7075 alloy after aging process in different times at 140°C and 230°C was reviewed and their microstructure analyses were made accordingly. After 16 hours aging of 7075 alloy and the composites reinforced by 5% SiC at 140°C and 12 hours aging in the composites reinforced by 3% SiC, at 230°C, after 9 hours aging in all materials, the maximum hardness value was measured. In higher aging temperature, due to the fact that max hardness was achieved in shorter period, in lower aging temperature, higher hardness was achieved.

Keywords Metal Matrix Composite, Precipitation Hardening, Hardness

1. Introduction

The requirements of producing more quality products and marketing such products with low costs oblige the development of new generation materials. Aluminum alloy is produced from the SiC particle reinforced composited with matrix and automotive parts where the hardness and wearing properties are very important, such as segments, brake pedal, pistons, cylinders and pulleys [1, 2]. The

average weight of the parts in a vehicle is about 10% of the total weight. Decreasing in each 1000 gr weight means the lower 0,6 liters of oil consumption. On the other hand, the lower oil consumption means lower exhaust emission and working cost. Due to the fact that aluminum and alloys have the properties such as low density, high corrosion resistance, easy workability making no concessions on security, comfort and safety, it has wide area in the automotive industry [2, 3].

MMC's reinforced by SiC up to 40%, manufactured by the casting has drawn the commercial attention thanks to its many properties. Some of these products are shown in Figure 1 [4].

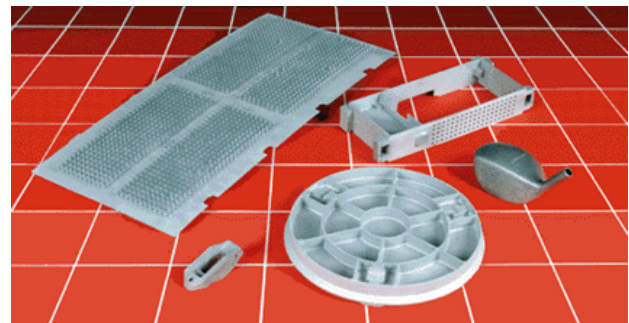


Figure 1. Some of the composite products with metal matrix [4]

Development of performance increasing strategies is important by decreasing the engine volume. Instead of forging aluminum alloys in the automotive piston groove, when using Al matrix composites reinforced by SiC particle, 50% increasing in the elastic module, 10% decreasing in the weight have been provided [5].

Application areas of MMK materials are not limited to the engine parts, NASA and American Air Forces have carried out many studies for this purpose [6]. Due to the fact that MMK reinforced by the particle has better mechanical, isotropic and physical properties than others

reinforced by fiber, development of their production and properties are important [2, 7].

Generally, SiC particle reinforced composites with Al-Zn-Mg alloyed matrix are manufactured by powder metallurgy and information about the composites manufactured by the techniques of solidification are limited [8].

Composites are the structures where metal and nonmetal materials are coexisting and they should reveal properties so that the components creating themselves could not have them alone. In order to obtain optimum properties in the composites, the homogenous distribution of a material should be provided in other material [1]. The composites are the materials composing two or more than two macro components in which their figures and/or chemical components are different and could not degraded within each other [9]. Modern engineering composites could be defined as “designed microstructures” by adding the dispersed phase having micron dimensions and reinforcing elements [10].

According to the shapes of the structural components, the composites could be combined into five groups such as composites reinforced by the particle, composites reinforced by the composites, plate shaped composites, laminated composites and filled composites. According to the current matrix material, composites are divided into three main groups such as polymer, ceramic and metal matrix composites [11].

The polymers are cheap and easy working materials. However, they have lower temperature of use, electrical and thermal conductivity [12]. Ceramic materials are very hard and brittle, they have low thermal shock resistance and toughness. For this reason, when they meet sudden damage in the terms of use, their using in some areas is dangerous [13]. Despite some disadvantageous, the most important reason of using the composites with metal matrix when considering the composites with ceramic matrix as high temperature material are is that the metal science and technology is beyond from the ceramics [14]. Due to the fact that MMC materials are continuously reinforced by the fiber, wicker or particles, the high strength could be achieved [15].

Many factor such as thermal expansion of matrix, machinability, hardness, thermal conductivity and electrical conductivity, procurement, area of utility are effective in the selection of the matrix material that create the composite. Graphical comparison of the temperature and density properties of different matrix materials has been already performed [16]. Matrix metal should have sufficient strength and ductility to transmit the strains on it to the reinforcing member. When the difference between the thermal expansion coefficients of matrix and reinforcing member is big, the permanent thermal stress at high temperatures could occur [17].

7xxx series aluminum alloys have been widely used as

the matrix material in the working conditions because of thermal stability at high temperatures and due to the fact that it has higher hardness and strengths than other Al alloys, their lower densities, high thermal and electrical conductivity and their cost efficiencies, these are preferred as the best matrix material [2].

Reinforcing member is as effective as matrix in the development of the properties of the composites. There are important factors in the selection of the ceramic reinforcing member. These are; elastic module, strength, hardness, density, melting temperature, thermal stability, thermal expansion coefficient, dimension and figure as well as harmony with the matrix and cost.

The properties to provide using the SiC as reinforcement are; its low density (3.2 g/cm^3), high hardness (SiC is the hardest material after diamond and boron carbide) and it has perfect resistance against chemicals. SiC has high strength and it protects its strength up to 1600°C . Its elastic module is 414 GPa. The oxidation resistance of SiC is good and in many places, it could be used easily up to 1500 and 1650°C . Its thermal conductivity is high and thermal expansion coefficient is low [18].

The production methods of MMC are divided into three as liquid phase, solid phase and reaction production method based on the temperature of the matrix during the production [6]. In spite of the fact that MMC production by reaction is a function of the liquid and solid production methods, many researchers divided production methods into two groups liquid phase and solid phase production methods [16]. By means of the casting and reaction developed as the alternative to the powder metallurgy, MMC production techniques are cheap and practical [5]. Liquid mixing casting technique from liquid techniques is ahead in terms of production capacity and cost efficiency in the engineering applications [19].

Powder metallurgy, extrusion, diffusion bonding etc. as the solid phase production methods could be taken into the consideration. Additionally, as the liquid phase production methods, liquid metal infiltration, pressure casting, reaction method and liquid tempering method could be considered. Liquid phase production methods are more advantageous than solid phase production methods. Solid phase production methods require longer time. Liquid phase production methods have been mostly preferred because of their production cost and part production similar to them. On the other hand, in the liquid phase production methods, although some problems could be met such as insufficient wetting, gas pocket, particle sedimentation, segregation, deposition in grain boundary, unhomogenous mixing, such problems could be minimized by checking the process parameters [20]. However, such problems could be minimized by checking the process variables. In the vortex method, in the controlled atmosphere, within the molten matrix metal, the composites are produced by adding the reinforced materials to the vortex by the help of

a mixer. Mixing process and additions should be made in the controlled atmosphere. If the process variables could not be checked well, the porosity ratio could be increased up to 30% [20]. The method is shown as schematic in Figure 2. The casting quality depends on the distribution of the particles. The factors that affect the particle distribution are; rate of cooling, fluidity of the liquid, specific weight of the particle and melt, the volume rate of the particles, the figure and dimension, composition of the crystalline phases, morphology and interaction with the particles, nucleation of the first phases in the ceramic, pushing or pulling the particles from solidification interface and the force coming from outside during the solidification [15]. The bonding force and porosity in the interface in the steps of this process affect the mechanical properties of the composite.

Power of mixer, speed of mixer, pre-heating temperature of the mold, particle addition speed and casting speed are important parameters in the production of successful composite [2].

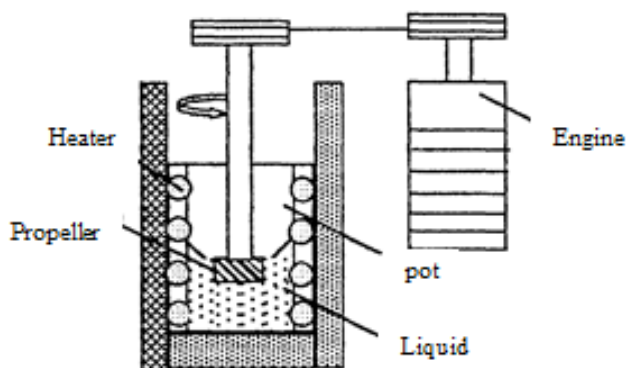


Figure 2. Schematic picture of the ceramic particle mixing method in the melted metal

Mixer speed, mixing pin and dimensions and the position of the mixing pin in the liquid are the other variables of this method. The casting method enables complicated figures and number of part production.

When reviewing the studies about the vortex method, in the composites that were produced by adding 18% SiC particles in volume and in the dimension of 40 μ m to 5024 aluminum alloy, it is stated that the fractures occurred in the areas where the intermetallic components and the homogenous distribution was obtained and when SiC volume rate are increased, the porosity are also increased [8]. In the composites by adding SiC particles to 6061 aluminum alloy at the rate of 10-20 % and in the dimension of 20 μ m, it was observed that SiC particles have been very much accumulated in the grain boundary. It was found that two stage mixing develops the wetting in the interface of Al-SiC [21]. In different SiC volume rates, the homogenous distributions of 64 μ m SiC particles were provided. When SiC volume rate increases, it was found that Vickers Hardness value increases [2].

Heat treatments that have been made to optimize the

properties of the aluminum alloys affect the microstructure and mechanical properties of the material. Aging is the progress of the physical and mechanical properties of the material as a result of the precipitation of a phase from supersaturated solid phase by the effect of time and temperature. By means of T6 heat treatment, the highest hardness values are achieved from 7075 aluminum alloys [2, 22-24].

In Al-5% Zn- 2 %Mg alloy, it was found that the highest strength achieved by the aging occurred at 20°C in 5 days and then 48 hours at 120°C by double aging is related to small but intensive GP areas [25]. In the composites of Al-Zn-Cu-Mg reinforced by SiC particle, it was said that the particles delay the aging. Lack of interaction between Zn and dislocations and due to the availability of MgO particles in the matrix Mg₂Si(β) and particle interfaces, it was anticipated that the consumption of the Mg atoms in the matrix retards the aging [26]. However, in other study, after the process of solution treated at 460 °C in 40 minutes, 12 and 40 hours aging at 140 °C was applied and due to the lack of interaction between Zn atoms and dislocation and the consumption of the Mg in the matrix, it was said that SiC particles in the composite of Al-Zn-Cu-Mg matrix accelerates the aging [27]. It was proven that after the aging and over aging the samples, in addition to the TEM images and coarse impurity on the grain boundaries, some more coarse impurity is available in the matrix and particle interfaces. Additionally, many researchers believe that aging process is encouraged by the reinforcements. However, the reinforcements could not change the aging order [28]. Some researchers keep dislocations in the forefront as the preferred area for the precipitation nucleation [29]. Differences between the studies show the complicated effect of the SiC particles in the aging process of the composites with Al metal matrix.

There are many microstructural changes that affect the mechanical properties. These are; aging conditions of the matrix materials, particle type, volume fraction and dimension [30].

The properties of 7075 Al matrix composites reinforced by SiC have been reviewed before aging, during aging and after over aging and in the reinforcement that was done by thicker particles, it was determined less yield as well as tensile strength and less ductility when comparing with others made by thinner particles. Solution treated for 1 hour at 465°C and then quenching was made. In the condition of pre-aging, aging for 1 hour at 135°C, 12 hour at 135°C in the condition of aging and 12 hour at 135°C in the condition of over aging was made accordingly. In the process of over aging, a second aging was made for 6 hours at 170°C. On the other hand, in the condition of aging, when the dimension of particle is increased from 13 μ m to 60 μ m, ductility has decreased however thickness has increased. This shows the importance of the gaps between the particles [30].

The reinforcement in Al alloys with 7xxx serial high strength could be reason for decreasing in yield and tensile strength [31]. In the metal matrix composites reinforced by the particle, the particles could be broken during the tensile testing [32].

By applying different heat treatments to the composites with Al-Zn-Mg alloy matrix reinforced by SiC particle produced by the solidification, the hardness and strength of the matrix were increased. The hardness was amplified rapidly in first five hours in each material. Even after 96 hours aging, due to the fact that hardness values remain stable, it was said that SiC particles have not affected the aging behavior. 18% composite has the lowest hardness. Full aging period for 16 hours is valid for alloy and composites. It was seen that the properties of the composites depend on the process technique and thermomechanical process that was consecutively applied. Lower hardness values could be based on the changes in the composition of the matrix because of interfacial reaction and in the higher volume fraction (18%) composites, lower hardness could show higher Mg loss [8].

In the vortex method, casting quality and mechanical properties depend on the distribution of the particles. For this reason mixing should be very good [15]. For homogenous mixing, in this study, a new casting furnace was designed, unlike previous work. At the same time the mixer mechanism, which can both rotating and up and down, moving has been added to furnace.

2. Materials and Method

2.1. Matrix and Reinforcement Material

As the matrix material, 7075 Al alloy from Al-Zn-Mg-Cu serial alloys having high strength values in the room temperature and showing superplastic properties was used. The chemical composition, physical properties and some mechanical properties of 7075 aluminum alloy are given in Table 1 and Table 2 respectively. Alloy was provided from Eskişehir Air Supply Maintenance Center. SiC particles in which density are 3.2 g/cm^3 , grain size is approximately $44\mu\text{m}$ were used.

Table 1. Chemical composition of 7075-Al alloy (amount of the components as % weight [33])

Zn	Mg	Cu	Cr	Mn	Si	Fe	Ti	Zr +Ti	Al
5.1-6.1	2.1-2.9	1.2-2	0.18-0.28	Max 0.3	Max 0.4	Max 0.5	Max 0.2	Max 0.25	90

Table 2. Some physical and mechanic properties of 7075-Al alloy [33]

Heat Treatment Condition	Melting Range °C	Thermal Conductivity W/m.K	Heat Capacity J/g.°C	Density gr/cm3	Hardness HV	Tensile Strength MPa	Yield Strength MPa	Elongation %
0	477-635	173	0.96	2.81	68	228	103	17
T6		130			175	572	503	11

2.2. Production of the Composites

Composites are produced by the vortex method that is among the liquid phase processes. Production was made in a resistance heating furnace that is bottom dump and its outer side is cast iron and inner side is MgO lined under the protective argon gas atmosphere by the vortex method that could be increased to 1200°C (Figure 3). First of all, melting pot was heated at 500°C and matrix material was put in the pot (Figure 4 a). After melting the matrix (700-750 °C), pre-heated SiC particles was added. 3% and 5% SiC particles was added gradually to the alloy by the mixer and it was well mixed. The mixing process was made as ~ 800 revolution per minute by a propeller from the casting material and an engine that turn the propeller. In order to have homogenous mixture, SiC particles were added from a near point of turning mile by a metal spoon (8 g/minutes). On the other hand, in order to have a homogenous mixture, a mechanism was added to enable the propeller turning and move up and down. After adding all SiC particles in the melt, it was mixed for 10 minutes. Adding the SiC particles and mixing process were made under the argon gas atmosphere. As a result of all these processes, the melted metal was casted to metal molds (Figure 4 b) produced from the steel by means of bottom casting technique. The bar-shaped samples at the dimension of 12x150 mm were obtained. SiC particles and steel mold was pre-heated as 2 hours in 750°C in the Heraeus KS-1251 furnace. In order to prevent cooling, the tank bottom was heated by flame.

2.3. Aging Heat Treatment

Samples was treated to 1hour solid solution at 460°C and then at 140°C in different times (3, 6, 9, 12, 16, 20 and 40 hours) aging process (Heraeus KS-1251 model furnace).

2.4. Hardness Measurement

Hardness measurement was made by the method of micro hardness measuring and 100 gr loading was applied by 20 seconds. For each sample, 5 measurements were made and the measurement was made distant from the particles and from the matrix of the composites.

2.5. Microstructure Analysis

The samples were prepared by Struers trademarked cutting, grinding and polishing machines. For microstructure analysis, Olympus PMG-3 metallography and Leco-2001 image analyzing machines were used. After

aging process, it was reviewed if the microstructure changes and SiC particle distribution in the composites are homogenous or not.

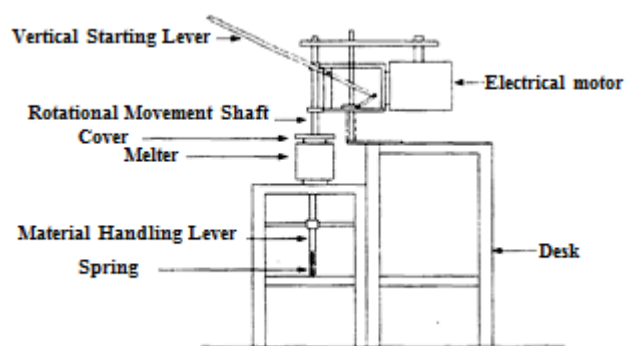


Figure 3. Schematic picture of the system used in the production [34]

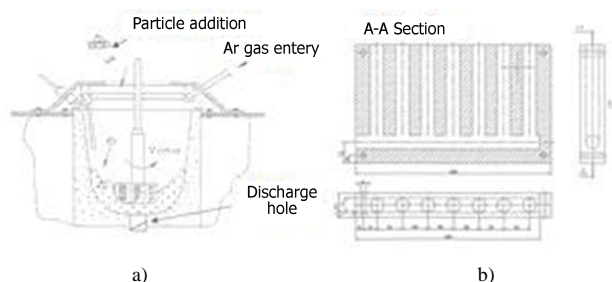


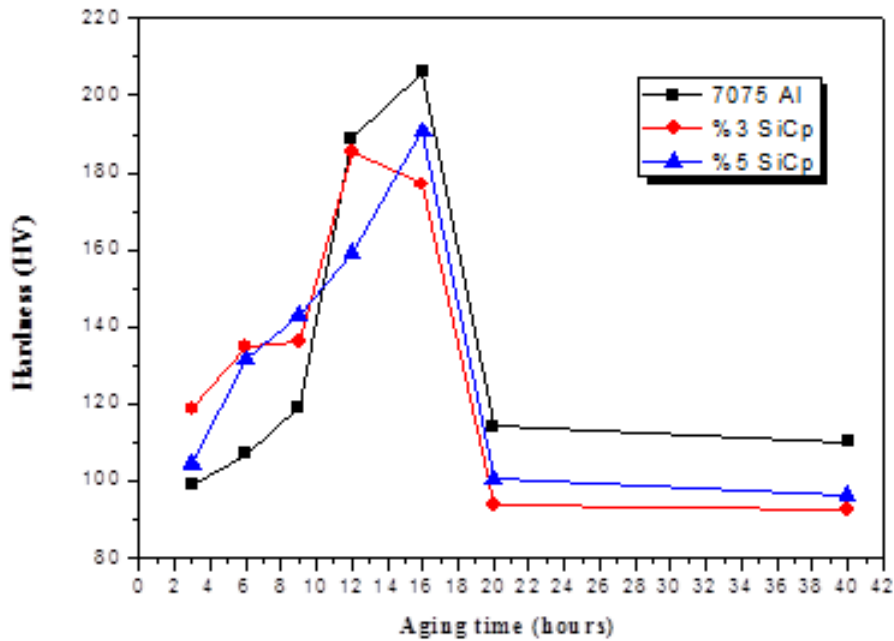
Figure 4. a) Schematic picture of the melting furnace, b) Sampling mold produced by 1040 steel [35]

3. Results and Discussion

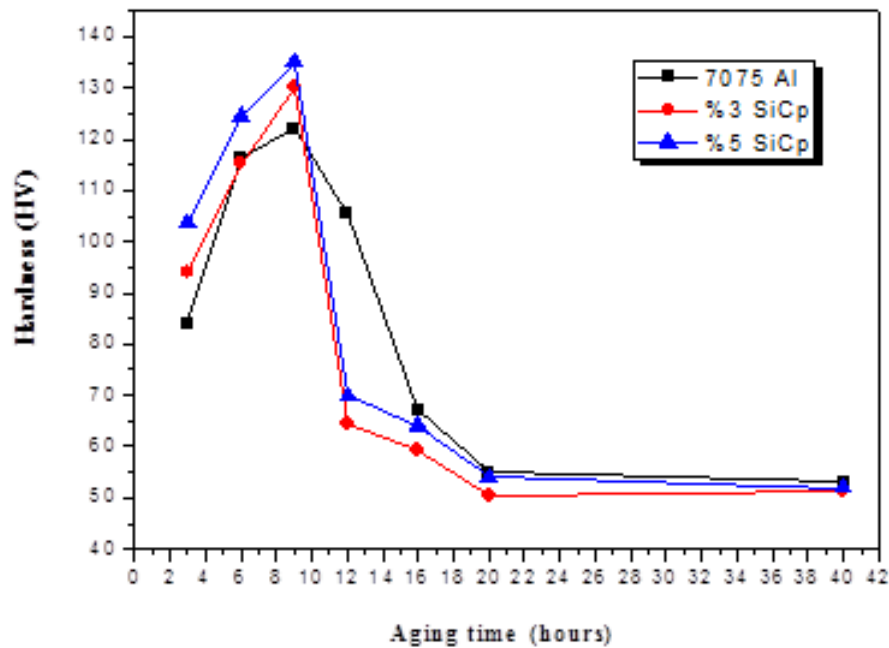
After casting of the composites reinforced by 3% and 5% particle with the matrix of 7075 alloy and 7075 Al alloy, their hardness before heat treatment are respectively 135 HV, 144 HV and 138,66 HV. The hardness values of each sample based on the aging time at 140°C and 230°C was shown in Table 3, aging time-hardness values graphics was given in Figure 5. In table 4, as a result of aging process at 140 and 230 °C, changes of the hardness values measured based on the aging temperature was given. In figure 6, depending on the aging period, aging temperature and hardness variation were shown respectively for each sample. The whole results in Figure 7 were given as graphical. Microstructure images of each sample that were aged at 140°C in Figure 8-10, at 230°C in Figure 11-13 were showed before full aging, during full aging and over aging (100X).

Table 3. Hardness values of the samples that were aged at 140 and 230 °C in different aging period.

Aging time (Hour)	140°C Hardness (HV)			230°C Hardness (HV)		
	7075	3% SiCp	5% SiCp	7075	3% SiCp	5% SiCp
3	99	118,66	104,33	84,06	94,1	103,56
6	107	135	131,5	116,325	115,33	124,5
9	119	136	143	122	130	135
12	189	185,33	159,33	105,33	64,53	69,9
16	206	177	190,66	67,1	59,4	64
20	114	93,66	100,33	55	50,288	54
40	110	92,42	96,4	53	51,33	52



a)

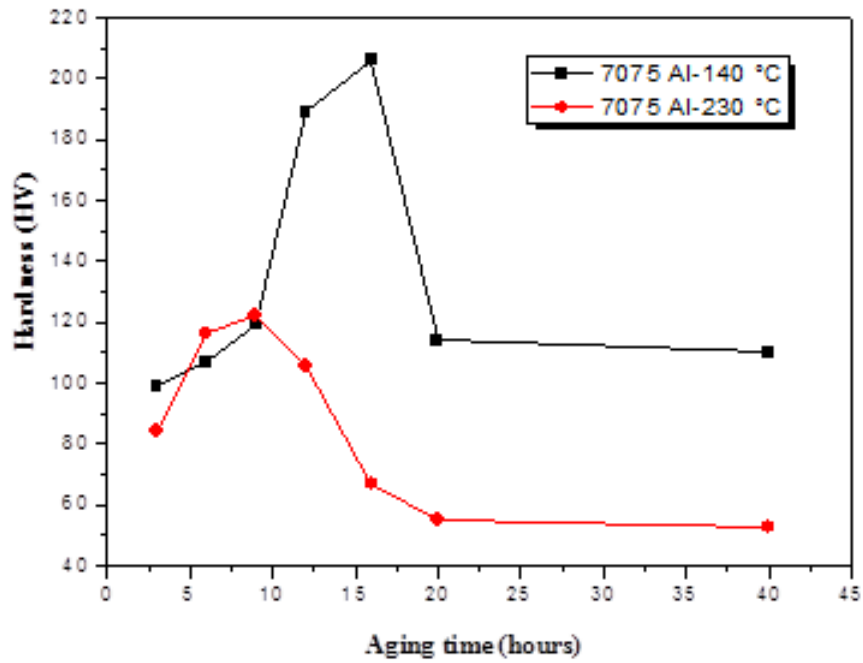


b)

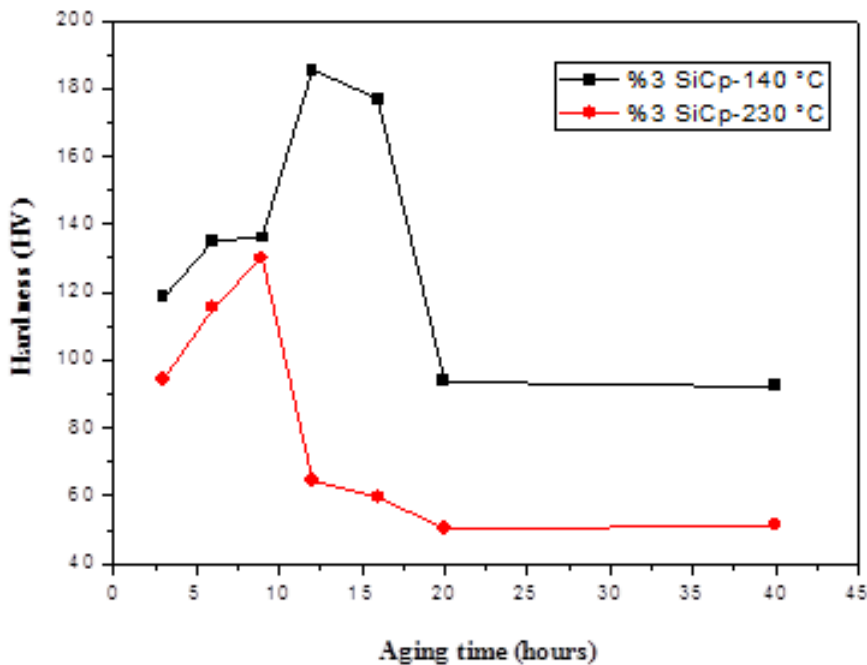
Figure 5. Aging time-Hardness graphics of the composites that were aged at a) 140°C, b) 230°C

Table 4. Hardness variables of the samples based on the aging temperature

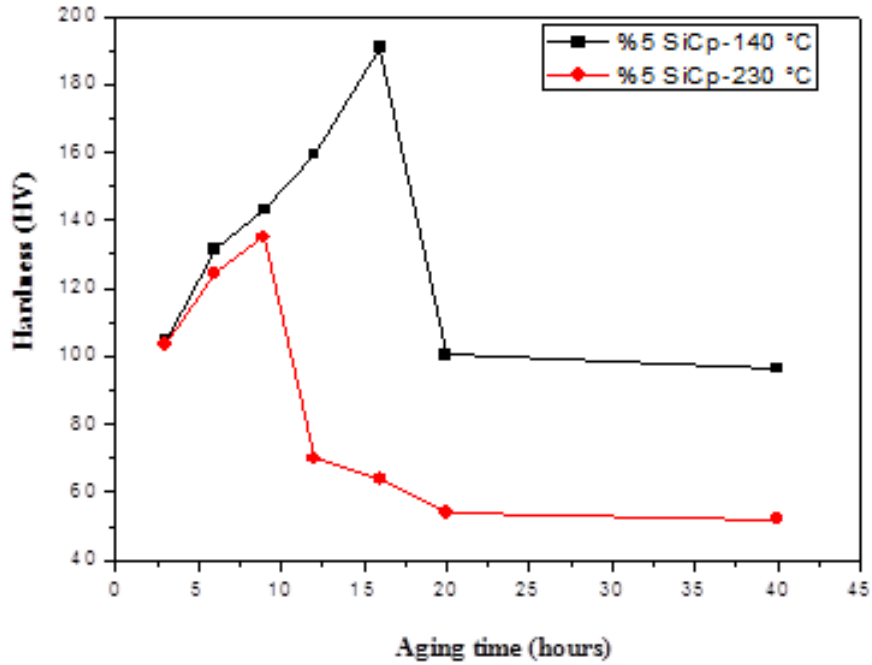
Aging time (hours)	7075-Al		3% SiCp		5% SiCp	
	140°C	230°C	140°C	230°C	140°C	230°C
3	99	84,06	118,66	94,1	104,33	103,56
6	107	116,325	135	115,33	131,5	124,5
9	119	122	136	130	143	135
12	189	105,33	185,33	64,53	159,33	69,9
16	206	67,1	177	59,4	190,66	64
20	114	55	93,66	50,288	100,33	54
40	110	53	92,42	51,33	96,4	52



a)



b)



c)

Figure 6. Hardness variation based on the aging time and temperature a) 7075 alloy b) composite reinforced by 3% SiC particle c) composite reinforced by 5% SiC particle

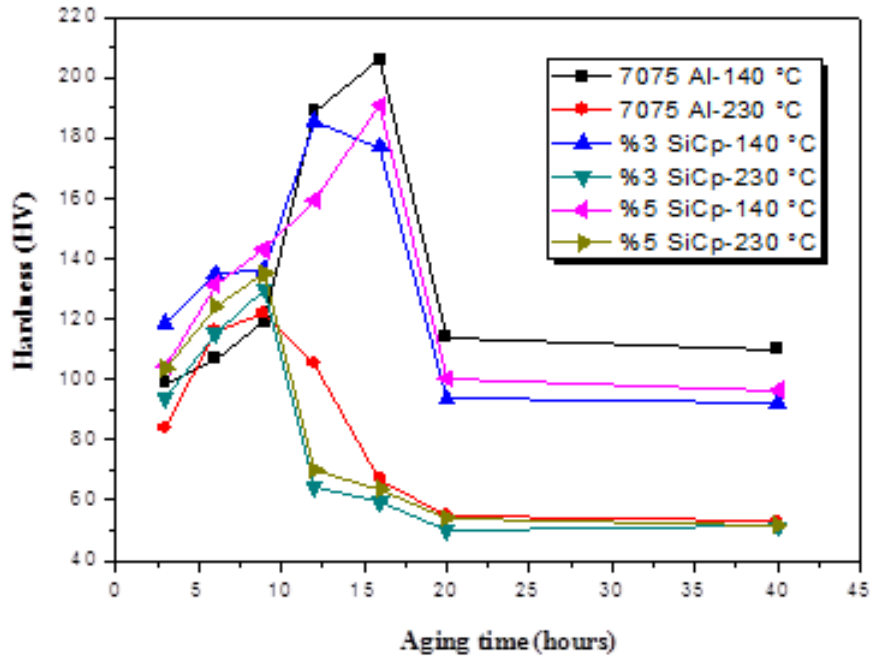


Figure 7. Hardness variation based on the aging temperature of each sample and aging time

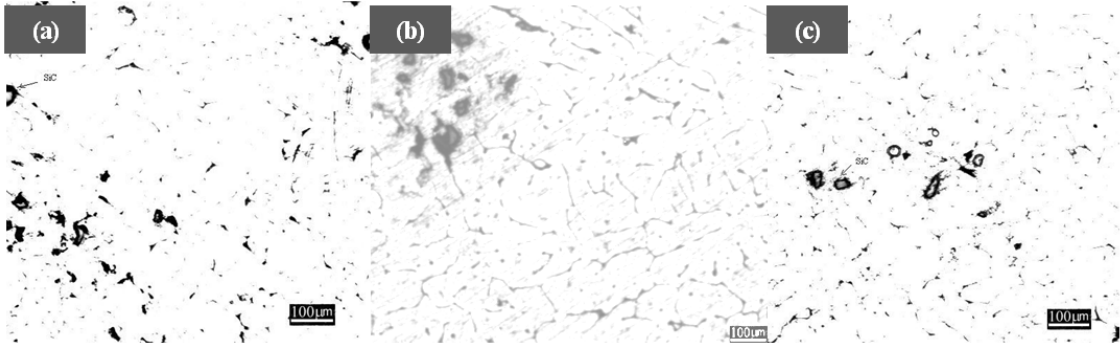


Figure 8. Microstructure images of the composite reinforced by 3% SiC particle at 140°C. a) before full aging; b) 12 hours full aging; c) after over aging for 40 hours (100x)

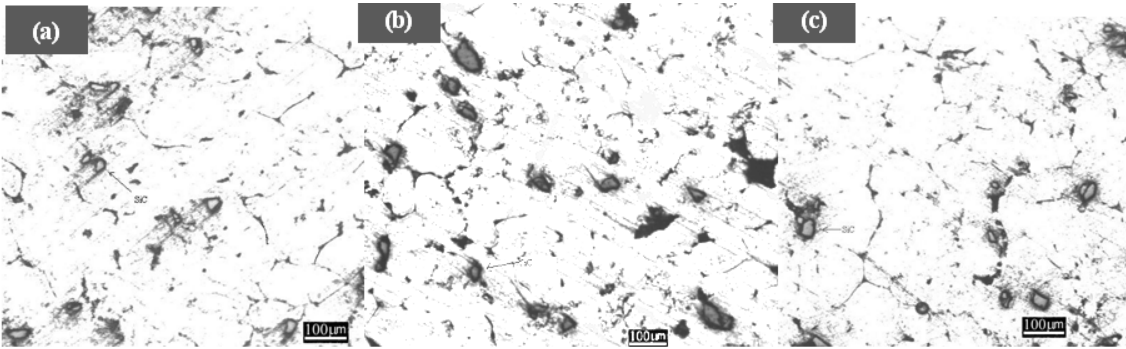


Figure 9. Microstructure images of the composite reinforced by 5% SiC particle at 140°C. a) before full aging; b) 12 hours full aging; c) after over aging for 40 hours (100x)

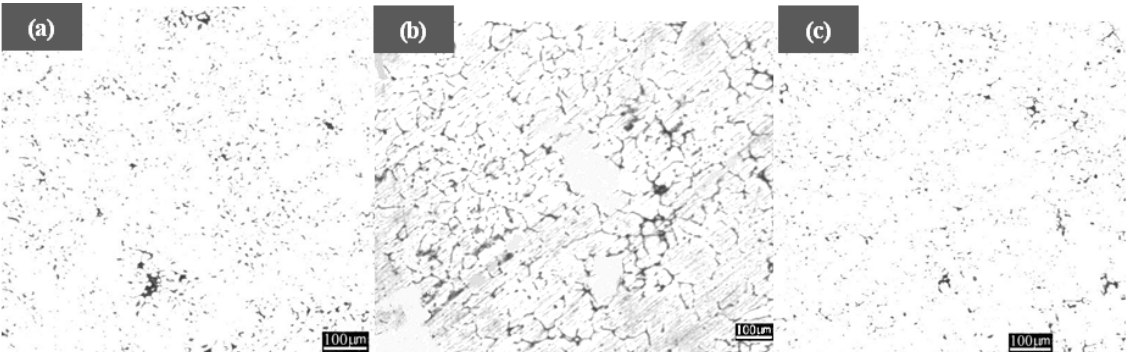


Figure 10. Microstructure images of 7075 Al alloy at 140°C. a) before full aging; b) 16 hours full aging; c) after over aging for 40 hours (100x)

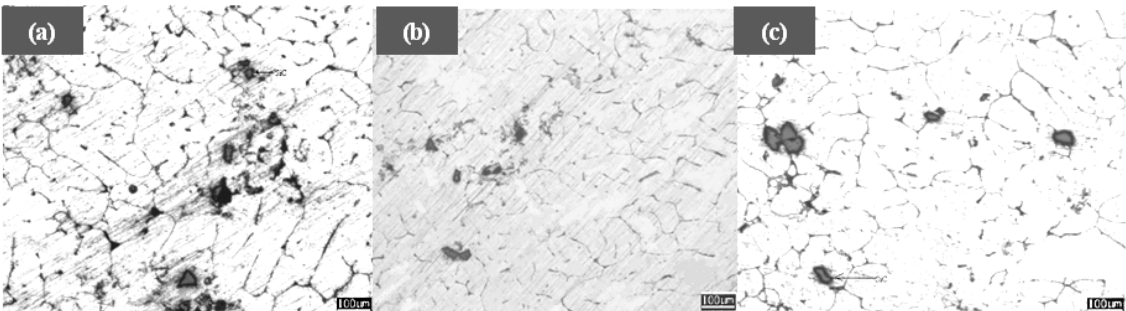


Figure 11. Microstructure images of the composite reinforced by 3% SiC particle at 230°C. a) before full aging; b) 9 hours full aging; c) after over aging for 40 hours (100x)

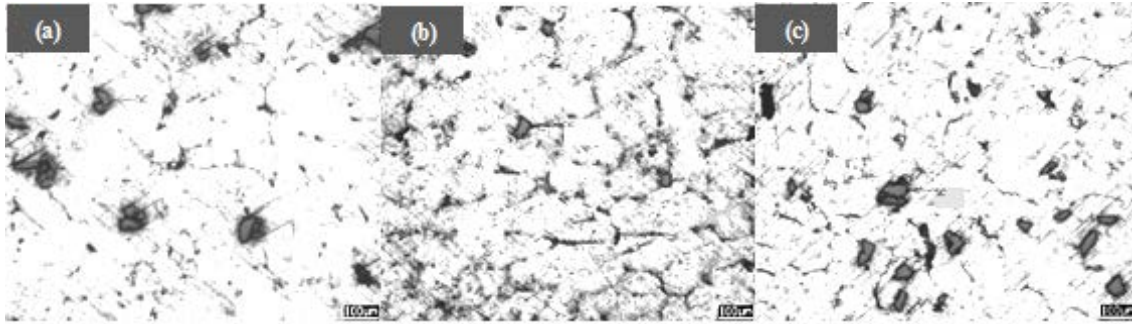


Figure 12. Microstructure images of the composite reinforced by 5% SiC particle at 230°C. a) before full aging; b) 9 hours full aging; c) after over aging for 40 hours (100x)

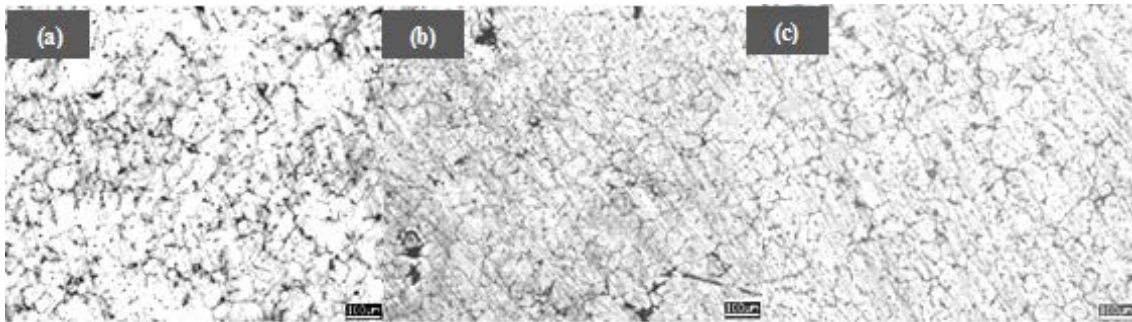


Figure 13. Microstructure images of 7075 alloy at 230°C. a) before full aging; b) 40 hours full aging; c) after over aging for 40 hours (100x)

4. Conclusions

By applying aging process at 40°C and 230°C for 3, 6, 9, 12, 16, 20 and 40 hours to the composites produced by Vortex method with 7075 alloy and 7075 Al alloy matrix reinforced by 3% and 5% SiC particle; their hardness variation was reviewed. As a result of aging at 140°C, it was seen that the maximum hardness was achieved in 7075 alloy (206 HV) and reinforced by 5% SiC composites at 16 hours (190.66 HV) and on the other hand, it was achieved at 12 hours in the composites reinforced by 3% SiC (185.33 HV) and lowest maximum hardness was occurred in this composite and maximum hardness was also occurred in 7075 alloy. In the conditions of full aging and over aging, for the composites reinforced by 3% and 5% particles, the hardness was lower than 7075 alloy. Before full aging, matrix hardness of the composites is more than 7075 alloy. 7075 alloy and composites that were not reinforced showed similar aging trend in accordance with the micro hardness data within the framework of experimental errors at 140°C. Under the conditions of full aging, the particle additions accelerate the aging but under the conditions of over aging, it is the reason for decreasing the hardness.

As a result of aging at 230°C, in each material, it was seen that maximum hardness was achieved at 9 hours. It means that SiC additions in the aging at 230°C have not affected full aging time. The maximum hardness value is 7075 alloy that is the lower one (122 HV). By the way, in the composite reinforced by 5% particle, the highest hardness value was observed (135 HV). In the composite

reinforced by 3% SiC particle, maximum hardness value is 130 HV. As a result of aging at 230°C, the hardness is higher than 7075 alloy for the composites before full aging and under the full aging. By taking into the consideration of these results, it could be considered that the precipitation amount occurred under the conditions before aging could increase in the level that prevents the movement of the dislocation. The alloy and composites that are not reinforced showed similar aging trend in accordance with the micro hardness value during the aging at 230°C. SiC addition does not affect full aging period. However, in the aging at 230°C, the hardness drop under the over aging condition is accelerated by the addition of the particle.

It was seen that higher aging temperature (230°C) is reason for max hardness value in the shortest period. However, higher hardness was achieved for each three materials under the lower aging temperature (140°C) despite the longer time.

According to each experimental result;

- It is seen that SiC particle addition has not affected aging behavior.
- SiC particle addition decreases hardness in over aging prominently.
- When decreasing aging temperature, full aging period and maximum hardness increases.

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