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The Effect of Zr on LM6 Aluminum Alloy

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Abstract

In this study, the effect of Zr amount on LM6 alloys which were produced by conventional casting method and contained different amounts of Zr (0.05% and 0.15) on the microstructure and mechanical properties of the alloys was investigated. In addition, produced alloys were modified with 200-250 ppm Strontium (Sr). optic microscope (OM) and scanning electron microscopy (SEM / EDS analysis) were used for microstructure analysis. The hardness and tensile tests of the alloys which were modified by Sr and alloyed with different amounts of zirconium were performed. As a result of the studies that were done, it was determined in the images of optical microscope (OM) and scanning electron microscope (SEM) that the morphology of Al-Si-Fe phase changed depending on the addition of Zr, and that Al-Si-Fe intermetalics having different amounts of Zr composed. While the highest level of percent elongation was obtained from the Al12Si alloy, the highest level of hardness and maximum tensile strength were obtained from the LM6 alloy modified by strontium. The highest level of yield strength was obtained from LM6 alloy which was alloyed with 0.05 Zr. It was found that the amount of added Zr did not show a significant difference at the maximum tensile strength level of Al12Si alloy.

Keywords: Al-Si alloys, modification, alloyed, microstructure, mechanical properties.

LM6 Alüminyum Alaşımlarında Zr'nin Etkisi

Öz

Bu çalışmada, konvansiyonel döküm yöntemiyle üretilen ve alaşımların mikroyapı ve mekanik özellikleri üzerine farklı miktarlarda Zr (% 0,05 ve 0,15) içeren LM6 alaşımları üzerindeki Zr miktarının etkisi incelenmiştir. Ek olarak, üretilen alaşımlar 200-250 ppm Strontium (Sr) ile modifiye edilmiştir. Mikroyapı analizlerinde optik mikroskop (OM) ve taramalı elektron mikroskobu (SEM / EDS analizi) kullanılmıştır. Farklı miktarlarda zirkonyum ilave edilen ve Sr ile modifiye edilmiş alaşımların sertlik ve gerilme testleri yapılmıştır. Yapılan çalışmalar sonucunda, optik mikroskop (OM) ve taramalı elektron mikroskobu (SEM) görüntülerinde, Al-Si-Fe fazının morfolojisinin Zr ilavesine bağlı olarak değişmiştir. En yüksek yüzde uzama Al12Si alaşımından elde edilirken, stronsiyum tarafından modifiye edilen LM6 alaşımından en yüksek sertlik ve maksimum gerilme dayanımı elde edilmiştir. En yüksek akma dayanımı 0.05 Zr ile alaşımlı olan LM6 alaşımından elde edilmiştir.. Eklenen Zr miktarının, Al12Si alaşımının maksimum çekme dayanımında önemli bir fark göstermediği bulunmuştur.

Anahtar Kelimeler: Al-Si alaşımları, modikasyon, alaşımlama, mikroyapı, mekanik özellikler.

1. Introduction

Aluminum casting alloys are generally divided into two groups as heat treatable and non-heat treatable alloys. Casting aluminum alloys are industrially classified in accordance with the amount of Si that alloys contain. While the Si existing in the chemical composition of the alloys enhances the fluidity of the liquid metal it increases the problem of hot tearing during the solidification of the casting part (depending on the geometry of part). On the purpose of improving the mechanical and chemical properties of Al alloys, alloying process are conducted with different elements such as Cu, Mn, Mg, Zn and, notably Si. Moreover, the elements such as Cr, Fe, Mo, Ni, Ti, V, Zr and so on, may also counted in addition to these alloys [1]. Al-Si alloys have an industrially widespread usage area, notably in the automotive sector, due to their low density, economy and high casting characteristics [2-5]. In addition to this, since the casting Al-Si alloys have high corrosion resistance and low melting temperature they have been preferred in the production of many parts used in maritime sector and defense industry in recent years [3-5]. Mechanical performance of Al-Si alloys is closely related to microstructure morphology.

Since the grain structure and morphology of these alloys are effective on mechanical properties, modification and grain refining operations (alloying etc.) are carried out [6]. It was aimed that Al-Si eutectic in the form of plates or lamellar morphology in the micro-structure of Al-Si alloy was distributed in a more spherical and homogeneous way between aluminum dendrites (in eutectic). That the Si particles in Al-Si eutectics have sharp corners cause generation of extra stresses in sharp-shaped end zones during the use of these alloys under stress. Modification processes are conducted to eliminate these extra stresses in the eutectic structure. Si particles in Al-Si eutectics are prevented from exhibiting notch effect under stress with the modification process applied to alloys [7 and 8]. It is stated in a study done by Haque that Silicon in acicular morphology between Al dendrites in both molds (0.1% Sr) with strontium modification was more spherical-ovalized after modification in Al-Si alloys produced by pouring into both sand and permanent mould. Additionally, it is emphasized that the maximum tensile strength and percent elongation of the modified Al-Si alloys increased at the end of the tensile tests [9]. It is known that Zr which is added to A356 alloys, forms AlZr3 intermetalics in the structure of cast alloys, and accordingly provides the grain refinement effect. This intermetallic phase formed in the structure is seen to be formed as smaller in size depending on the temperature and time of solution taken in the age hardening process of the alloys. These small-sized intermetallic phases formed in the structure are thought to play an active role in the formation of α-Al dendrites [10]. In a previous study, grain refinement was applied to A356 alloy by Gd and Zr, and the Al5Si2Zr intermetalics were detected together with Al3Zr intermetallic in XRD analyzes. According to the results of tensile test, it is stated that these phases improve the strength and ductility of the A356 alloy [11]. Nevertheless, the cleaning the liquid metal with ceramic filters and removing inclusions are necessary to improve the mechanical properties of the casting material. Removal of oxide type intermetalics by filtration significantly improves mechanical properties [12].

In this study, the LM6 alloy was first modified by Al10Sr and then alloyed with Al10Zr master alloy. The effect of Zr quantity on the AlSiFe intermetallic formed in microstructure and on the mechanical properties was aimed to be determined in alloys to which different amounts of (0.05% and 0.15%) Zr was added.

2. Materials and Methods

The chemical compositions of the master alloys used for the modification and grain refining process together with the LM6 alloy are given in Table 1 in this study.

Table 1. Chemical composition of LM6, Al10Sr and Al10Zr master alloy used in the study (wt%).

	Si	Mg	Fe	Cu	Mn	Ti	Zr	Sr	Al
LM6	12.32	0.46	0.57	0.04	0.07	0.01	---	---	Balance
Al10Sr	0.04	---	0.12	----	---	---	---	10	Balance
Al10Zr	0.30	---	0.45	---	---	0.10	10	---	Balance

The melting process of LM6 alloy was made in stainless steel crucible by 4kW electric-resistance furnace. After keeping the alloy for 5 minutes by adding Al10Sr (0.025 Sr% wt.), master alloy Al10Zr (0.05 and 0.15 Zr% wt.) was added to the alloy. The liquid metal was poured into the molds (with the help of the pouring basins) prepared at about 720-740 ° C. In casting processes, pouring basin with stopper was used to reduce oxidation along sprue and contact of the liquid metal with the atmosphere. In addition, 20 ppi ceramic foam filters (25x25x15 mm) were used to prevent inclusions from entering the mould cavity on the horizontal runner system. Sand moulds for casting were prepared by mixing the 60-70 AFS silica sand with the resin and serter. The images of prepared sand moulds (a) and images of the parts produced after casting (b) are given in Figure 1.

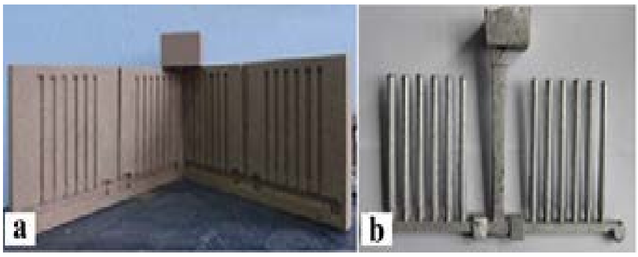

Figure 1. The image of sand molds (a) and image of casting parts (b)

The artificial aging (T6) heat treatment was applied to LM6 alloys to which modification and grain refining processes had been applied. The alloys, in the T6 heat treatment, were cooled rapidly after taking to solution at 540 ° C for 10 hours. After this process, the alloys were artificially aged for 12 hours at 160 C. Samples were prepared in accordance with ASTM E03-11 standard for metallographic examinations. Samples prepared by metallographic processes were cauterized by Keller's solution (2 ml HF (48%) + 3 ml HCl + 5 ml HNO_3 + 190 ml H_2O) for 30-45 s. Optical microscope analyses were performed with MEIJI branded optical microscope and MSQ PLUS 6.5 image analysis program. Scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS) analyses were performed by Carl Zeiss Ultra Plus Gem (FEG) branded scanning electron microscope. 12 tensile samples were prepared in accordance with ASTM B557M-10 standard in all alloy groups in order to determine the mechanical properties. Tensile tests were made with a speed of 1 mm/min by SHIMADZU AG-IS model tensile device with 50 kN capacity. The hardness measurements of the alloys were performed by SHIMADZU branded micro hardness measurement device under 2 N-load. Hardness measurement results were determined by the mean of 5 measurements taken from each sample.

3. Results and Discussion

3.1. Microstructure Analyses

After casting processes, the chemical compositions of LM6 alloys which were modified and alloyed by different amounts of Zr are given in Table 2.

Table 2. After casting processes, chemical compositions of LM6 alloys which were modified, and alloyed with different amounts of Zr.

Alloys	Elements (Wt.%)							
	Si	Mg	Fe	Cu	Mn	Ti	Zr	Al
LM6	12.13	0.51	0.60	0.04	0.08	0.01	-	Balance
LM6+Sr	12.32	0.51	0.57	0.04	0.07		-	
LM6+Sr+5Zr	11.87	0.52	0.64	0.04	0.08		0.05	
LM6+Sr+15Zr	11.13	0.48	0.59	0.04	0.08		0.15	

(Note: %0.023 Sr in LM6+Sr alloys, %0.026 Sr in LM6+Sr+5Zr alloys and %0.024 Sr in LM6+Sr+15Zr alloys)

The images of optical microscope (OM) and scanning electron microscope (SEM) of LM6 alloys to which modification and grain refinement were applied are given in Figure 2. In the initial LM6 alloy which were not undergone any treatment. The microstructure consists of the α-Al dendrites (white zones), the plate-shaped Si-eutectic (gray zones) between dendrites, and the needle-shaped AlSiFe intermetalics (black zones). Fe-based intermetalics in the structures of Al-Si alloys are known to form depending on the amount of Si or Fe + Si. It was seen in LM6 alloy that the eutectic Si formed in the structure by modification with Sr, was homogeneously dispersed between Al-dendrites and refined. In addition, there are Fe-based intermetalics in the structure. The determining factor in the formation of these intermetalics is the amount of Fe. Nonetheless, the cooling rate also has a significant effect on the formation and stability of Fe-based intermetallic phases. Fe-based intermetallic phases in Al and its alloys compose of the β-AlFeSi and chinese script α-AlFeSi, which usually have needle morphology. The low level of cooling rate and high level of silicon content in Al alloys increase the formation of β-AlFeSi intermetallic [13]. When Mg and Mn are added to Al-7% Si alloy, it increases the intermetallic formation of α-AlFeSi instead of β-AlFeSi intermetallic in microstructure. Furthermore, Sr modification hinders the growth of β-AlFeSi intermetallic in the structure as well [9 and 14]. Cao and Campbell state that the most suitable zones for the nucleation of α-AlFeSi and β-AlFeSi intermetalics in Al-Si alloys are around of the bi-films or oxides formed during the preparation or transfer of liquid metal [15]. On the other hand, Cameron et al point out that the β-AlFeSi intermetalics formed in Al-Si alloys having high amount of iron are complex and have polygonal structure. Additionally, it is emphasized in the same study that α-AlFeSi intermetalics grow more branched than block or polyhedral β-AlFeSi intermetalics. The formation of α-AlFeSi intermetalics becomes difficult by increase in the cooling rate and decrease in the amount of Mn [16]. Elhadari et al stated in their study that addition of Ti, Zr and V to Al-7% Si-1%Cu-0.5%Mg alloys produced α-Al dendrites and Al-Si eutectic containing Mg/Cu/FeAl-Si and surrounding these dendrites [17]. In addition to this, it is stated that nano-sized trialuminide precipitates formed in the structure depending on the alloy element added. By addition of Zr to LM6 alloy, it was determined that some of the Fe-based intermetalics which are known to affect the mechanical properties in the structure shortened, and some of them formed in morphology having more complex than plaque-form morphologically.

However, it is seen that they are in plaque-shaped in many zones. It is seen in the microstructure that the porosities formed on the interfaces of the Al-dendrites or on the interfaces of the different phases. There are two arguments in the way that these porosities form due to the tensile of the closed liquid ponds between the dendrites or due to the amount of oxide films.

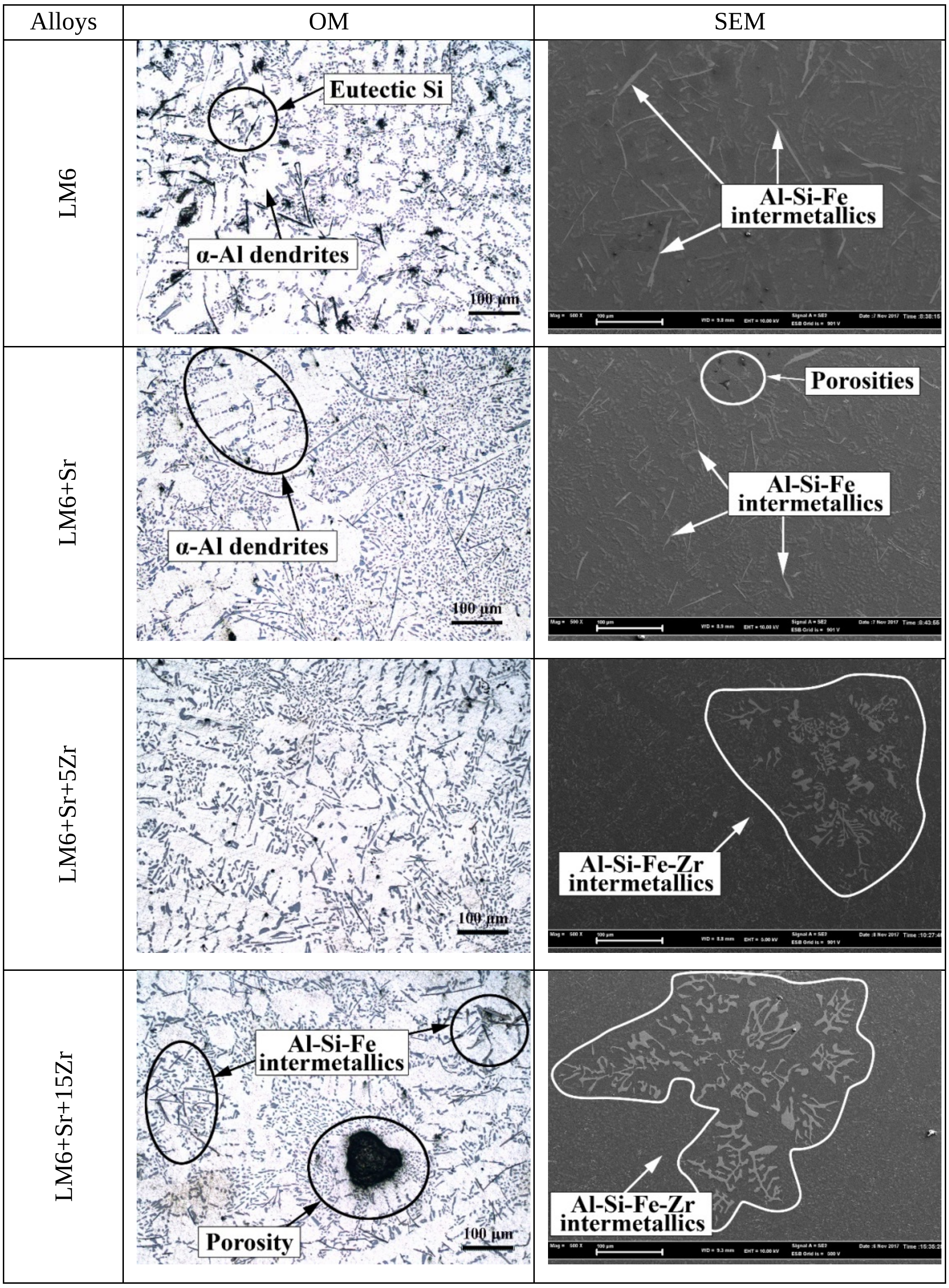

Figure 2. The images of optical microscope (OM) and scanning electron microscopy (SEM) of LM6 alloys which were modified and alloyed with Zr.

While the scanning electron microscope images of LM6 alloys which were modified and alloyed by different amounts of (0.05 and 0.15% wt.) Zr is given in Figure 3 their EDS analysis results are given in Table 3. It is also understood from the SEM images given in Figure 2 that the distribution and morphology of the AlSiFe intermetallic in the structure changed depending on the amount of Zr added to the Al12Si alloy. It was seen In the OM microscope images given in Figure 2 that the AlSiFe intermetalics, and AlSiZr intermetallic phases whose grayscale were different on Al-matrix interfaces were formed. It was determined that AlSiZr intermetalics having approximately 6% Zr were formed in especially Al12Si alloy to which 0.15% Zr was added (light gray zone in Figure 3.b).

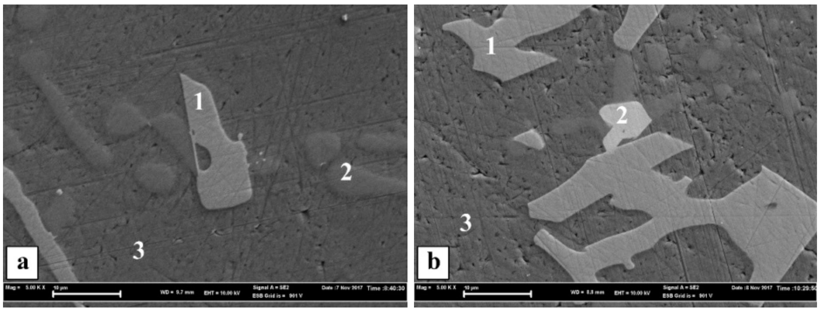

Figure 3. SEM images of LM6 alloys which were alloyed by 0.05% Zr (a) and 0.15% Zr.

Table 3. EDS analysis results of LM6 alloy which were alloyed by 0.05% Zr (a) and 0.15% Zr.

Locations		Elements (wt.%)				
		Al	Si	Fe	Cu	Zr
3.a	1	54.77	19.03	25.67	0.52	-
	2	2.17	97.37	-	0.45	-
	3	98.04	1.35	-	0.47	0.13
3.b	1	65.73	13.88	19.89	0.34	0.15
	2	38.06	55.24	-	-	6.69
	3	98.21	1.11	0.49	-	0.19

3.2. Mechanical Properties

The micro hardness and tensile test results of modified and alloyed LM6 alloys obtained in this study are given in Table 4. Micro-hardness measurements were calculated by the average of 5 measurements taken from each of three different samples. The mean of ultimate tensile strength (UTS), yield tensile strength (YTS) and percent elongation (% e) values obtained from 12 tensile test samples were taken.

Table 4. Micro hardness and tensile test results of modified and alloyed LM6 alloys.

Alloys	Micro hardness (HV2)	Tensile Test		
		UTS (MPa)	E(%)	YTS (MPa)
LM6	99	198	1.93	89
LM6+Sr	131	236	1.10	64
LM6+Sr+5Zr	117	220	1.42	83
LM6+Sr+15Zr	115	217	1.43	59

The results of the micro hardness measurements which were obtained after modification process done by adding Al10Sr to the LM6 alloy and after the alloying process done by adding Al10Zr master alloy are given in Table 4. It is understood that addition of Sr to the alloy for the purpose of modification caused a certain increase in micro hardness. In contrast, it can be seen that the alloying process done with Zr adversely affected micro hardness. It was thought to be stemmed from the addition of Zr alloying element which deformed chemical composition and morphology of Fe-based intermetalics formed depending on amount of Fe found in the structure. Sepehrband et al state that the increase in hardness value with the addition of a small amount of Zr to A319 alloys leads to Al_3Zr dispersoids depending on the temperature of inclusion to solution [18]. The results of SDAS measurement of LM6 alloys to which modification and alloying process applied are given in Figure 4.

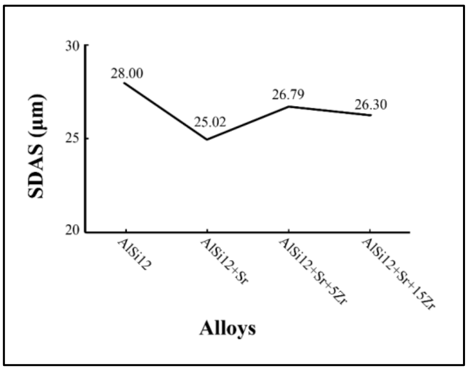

Figure 4. SDAS results of LM6 alloys with modification and alloying processes applied

According to the SDAS measurement results, while there was a reduction of about 10% in the SDAS results of the LM6 alloy modified with Sr, this reduction increased by the addition of Zr alloy. It is seen that the alloying process done with Zr influenced the morphology and chemical composition of AlSiFe intermetalics which is formed in the structure rather than the SDAS results. It was determined that there was not any change depending on the amount of Zr in LM6 alloy. Kasprzak et al point out that the Zr-V elements added to the A356 alloys in small quantities may not be potentially suitable for grain refinement. However, they noted that they were effective in additions of 0.20% or higher [19]. It was determined that β-Al5FeSi intermetalics formed in the structure depending on the amount of Fe added to the A356 alloy turned into αAl8Fe2Si intermetallic and that its negative effect decreased [20].

4. Conclusions

The micro hardness and mechanical properties of Al-Si-Fe alloys produced by applying modification process with LM6 alloyed Sr and alloying process with Zr (0.05%, 0.15), are investigated and the results are given below.

- When the casting LM6 (Al-Si-Fe) alloy modified with strontium, it was determined that the eutectic Al-Si phase was taken part in the structure in the shape of spherical morphology and homogeneous. The modification with Sr showed a very high performance on the eutectic phase. It was determined that disperse of eutectic silica phase improved the structure, hardness and maximum tensile strength. On the contrary, the yield tensile strength and the percent elongation were affected negatively. It is thought that this was derived from the concentration of AlSiFe phases formed in the structure.
- When the Sr modification and the alloying process with Zr applied to the casting LM6 alloys, hardness value of AlSiFe intermetallics formed around eutectic Al-Si phase decreased owing to deformation by Zr addition.
- According to the tensile test results, while the ultimate tensile strength of the alloy decreased with Zr alloying process, the values of yield tensile strength and percent elongation increased. The reason is that was the change in the morphology of the AlSiFe intermetallics formed in the structure and was the formation of AlSiZr containing intermetallics forming around it (light gray colored phase, Table 3 and Figure 3. (b) in SEM image).
- When SDAS measurements and mechanical test results (hardness and tensile test) were evaluated together, it was seen that SDAS decreased with Sr modification. However, no significant change was observed in the alloying process with Zr. The ultimate yield strength was obtained with the addition of 0.05% Zr.

5. References

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Genişletilmiş Özet

Giriş

Alüminyum döküm alaşımları genellikle ısıl işlem gören ve ısıl işlem görmeyen alaşımlar olarak iki gruba ayrılır. Döküm alüminyum alaşımları endüstriyel olarak alaşımların içerdiği Si miktarına göre sınıflandırılır. Alaşımların kimyasal bileşiminde bulunan Si, sıvı metalin akışkanlığını arttırırken, döküm parçasının katılaşması sırasında (parçanın geometrisine bağlı olarak) sıcak yırtılma problemini arttırır. Al alaşımlarının mekanik ve kimyasal özelliklerinin geliştirilmesi amacıyla, alaşımlama işlemi Cu, Mn, Mg, Zn ve özellikle Si gibi farklı elementlerle gerçekleştirilir. Ayrıca, Cr, Fe, Mo, Ni, Ti, V, Zr vb. gibi elementler de bu alaşımlara ek olarak sayılabilir. Bu alaşımların tane yapısı ve morfolojisi mekanik özellikler üzerinde etkili olduğu için modifikasyon ve tane artırma işlemleri (alaşım vb.) gerçekleştirilmektedir. Al-Si alaşımının mikro yapısındaki plaka veya lamel morfolojisi şeklindeki Al-ötektik'in, alüminyum dendritler (ötektik) arasında daha küresel ve homojen bir şekilde dağıtılması hedeflenmiştir. Al-Si ötektiklerindeki Si parçacıklarının keskin köşelere sahip olmalarının, bu alaşımların gerilim altında kullanımı sırasında keskin şekilli uç bölgelerde ekstra gerilmelerin oluşmasına neden olmasıdır. Ötektik yapıdaki bu fazla gerilmeleri gidermek için modifikasyon işlemleri yapılır. Al-Si ötektiklerindeki Si parçacıklarının, alaşımlara uygulanan modifikasyon işlemi ile stres altında çentik etkisi göstermesi önlenir. A356 alaşımlarına eklenen Zr'nin, dökme alaşımların yapısında AlZr3 intermetalikleri oluşturduğu ve buna göre, tahıl inceltme etkisi sağladığı bilinmektedir.
Bu çalışmada, konvansiyonel döküm yöntemiyle üretilen ve alaşımların mikroyapı ve mekanik özellikleri üzerine farklı miktarlarda Zr (% 0,05 ve 0,15) içeren LM6 alaşımları üzerindeki Zr miktarının etkisi incelenmiştir. Ek olarak, üretilen alaşımlar 200-250 ppm Strontium (Sr) ile modifiye edilmiştir. Mikroyapı analizlerinde optik mikroskop (OM) ve taramalı elektron mikroskobu (SEM / EDS analizi) kullanılmıştır. Sr ile modifiye edilmiş ve farklı miktarlarda zirkonyum ilave edilen alaşımların sertlik ve gerilme testleri yapılmıştır.

Metot

Bu çalışmada, LM6 alaşımı ilk önce Al10Sr tarafından modifiye edilmiş ve daha sonra Al10Zr master alaşım ile alaşımlanmıştır. LM6 alaşımı, yaklaşık 150-200 ppm Sr ile modifikasyon işlemi uygulandıktan sonra kum kalıbı döküm yöntemi ile üretildi ve % 0.05 ve% 0.15 Zr (Al10Zr master alaşımları) ile alaşımlama işlemi yapıldı.

Sonuçlar ve Tartışma

Sonuç olarak, LM6 alaşımlı Sr ile modifikasyon işlemi uygulanarak üretilen Al-Si-Fe alaşımlarına ilave edilen Zr miktarının (% 0,05, 0,15) mikro sertlik ve mekanik özellikler üzerine etkisi incelenmiş ve sonuçlar verilmiştir. Stronsiyum ile modifiye edilmiş LM6 (Al-Si-Fe) alaşımı, ötektik Al-Si fazının yapıda küresel morfoloji ve homojen formda yer aldığı tespit edilmiştir. Sr ile yapılan değişiklik, ötektik aşamada çok yüksek bir performans göstermiştir. Ötektik silika fazının dağılmasının yapıyı, sertliği ve maksimum gerilme kuvvetini arttırdığı tespit edilmiştir. Aksine, akma dayanımı ve uzama yüzdesi olumsuz yönde etkilenmiştir. Bunun, yapıda oluşan AlSiFe fazlarının konsantrasyonundan kaynaklandığı düşünülmektedir. Sr modifikasyonu ve Zr ilave edilen döküm LM6 alaşımlarının sertlik değeri Zr ilavesi nedeniyle azalmıştır. Çekme testi sonuçlarına göre, alaşımın çekme dayanımı Zr alaşımlama işlemi ile azalırken, çekme dayanımı ve yüzde uzama değerleri artmıştır. Bunun nedeni, yapıda oluşan AlSiFe intermetalliklerinin morfolojisindeki değişiklik ve onun etrafında oluşan intermetallik içeren AlSiZr oluşumudur. SDAS ölçümleri ve mekanik test sonuçları (sertlik ve çekme testi) birlikte değerlendirilmiş, SDAS'ın Sr modifikasyonuyla azaldığı görülmüştür. Bununla birlikte, Zr ile alaşım işleminde önemli bir değişiklik gözlenmemiştir. En yüksek akma dayanımı % 0.05 Zr ilavesiyle elde edilmiştir.