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The effect of Ni addition on microstructure and mechanical properties of cast A356 alloy modified with Sr

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Abstract

In this study, casting A356 alloy was pre-alloyed with Ni, and the modification process with Sr was applied by the casting method. The role of Ni on the microstructural and mechanical properties of the produced A356-Ni alloys was investigated. The produced alloys were naturally aged at room temperature for 24 h and artificially aged at 170 °C for 10 h. Optical microscopy (OM), scanning electron microscopy (SEM), and X-ray diffractometer were used in microstructure studies of the A356-Ni alloys. Tensile tests and hardness measurements were carried out to determine mechanical properties. Statistical analysis of Weibull distribution on the tensile test results revealed that the characteristic ultimate tensile strength increased due to increasing the amount of alloying elements, while the characteristic percentage elongation is decreased. This was because Al-Si-Fe intermetallic decomposition and Al-Si-Fe-Ni intermetallics were formed, primarily, 0.5 and 1.0 % Ni addition. It was also determined that the Al-Si-Fe-Ni intermetallics with a morphology non-sharp corners formed more homogeneous in the microstructure. But in the A356 alloys with the addition of 1.5 % Ni, Al-Si-Fe-Ni intermetallics are formed in coarser morphology. In A356 alloys, aluminium dendrites, Al-Si eutectic between dendrites, Mg2Si precipitates are formed in the structure by ageing. Depending on the amount of Ni added to the A356 alloy, the tensile strength of the alloys containing 0.5 and 1.0 % Ni is increased.

Key words: A356 alloy, nickel, microstructure, T6 heat treatment, mechanical properties

1. Introduction

Al-Si-Mg cast alloys are widely used in the automotive industry due to their good castability, high strength/weight ratio, and corrosion resistance [1–3]. The microstructure and mechanical properties of these alloys depend on many parameters such as chemical composition, melting, casting, and solidification conditions [4–6]. Addition elements such as Ni, Cu, Mg to these alloys increase the strength with various strengthening mechanisms. Among these elements, Ni activates the strengthening mechanisms by forming intermetallic phases connected to each other. This effect is more important as the amount of intermetallic phases increases [2, 5–7]. It aims to eliminate and/or reduce the negative effects of intermetallic with brittle and angular morphology such as β-Al5FeSi formed during the casting process by adding different alloying elements to Al-Si-Mg alloys produced by the casting process. However, Ni-containing alloy does not contribute significantly to the mechanical properties because it shows brittle properties in new phases such as Al_9FeNi formed in the system [2]. Since nickel is an expensive alloying element, it is essential to determine the amount of Ni added to the alloy for good performance [3, 8]. One way to improve the mechanical properties of Al-Si-Mg alloys at room temperature is ageing (T6) heat treatment. Magnesium and silicon are precipitated as Mg_2Si in aluminium dendrites with ageing heat treatment, which increases the strength of the alloy [9]. One of the factors affecting the mechanical properties of these alloys is the morphology of

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T a b l e 1. The chemical compositions of the A356 alloy and Al10Sr master alloy (wt.%)

Designation alloy	Si	Mg	Fe	Ti	Zn	Mn	Ni	Sr	Others	Al
A356	7.61	0.41	0.13	0.10	0.005	0.001	–	–	–	Balance
Ni	–	–	–	–	–	–	99.99	–	0.01	–
Al10Sr	–	–	–	–	–	–	–	10.95	–	Balance

T a b l e 2. The chemical compositions of cast A356/Ni alloys (wt.%)

Designation alloy	Elements (wt.%)						
	Si	Mg	Fe	Ni	Ti	Sr	Al
A356	7.19	0.39	0.166	0.001	0.117	–	Balance
A356 + 0.5Ni	7.20	0.35	0.313	0.51	0.113	0.022	
A356 + 1.0Ni	7.18	0.33	0.59	1.05	0.110	0.020	
A356 + 1.5Ni	7.27	0.37	1.14	1.46	0.114	0.019	

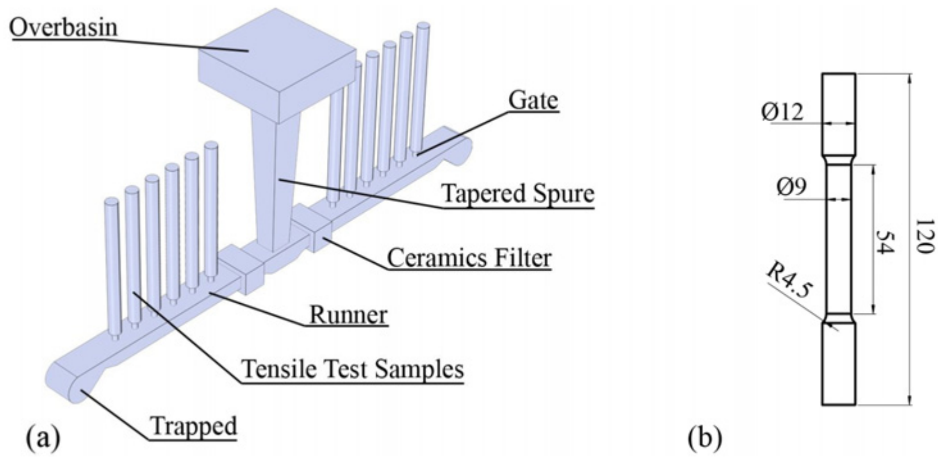


Fig. 1. 3D view of the casting and runner system (a) and tensile test sample dimensions (b) used in the study.

the Si particles. With the modification process, the mechanical strength of the alloy is increased by providing a finer (fibre-like) and regular distribution of Si particles in the eutectic than the lamella structure. During the modification process, a minimal amount of elements such as Na, Sb, Sr are added to the liquid metal (0.01–0.02 %) [10]. It is easier to control and add Sr element to liquid aluminium as a master alloy. For this reason, the use of Sr for modification is preferred by foundries over Na element. Rao et al. [11] reported that the mechanical properties of Al-Si alloys improved with 0.002 % Sr modification. Garcia-Hinojosa et al. [12] studied the effect of Ni additions (0.5 and 1 % by weight) on mechanical properties of Sr-modified and un-modified cast A356 alloys at room temperature. They stated that strength, elongation, and hardness decreased due to the brittle Al_3Ni particles formed in the structure. Therefore, this study aimed to determine the contribution of the Ni addition in different amounts and the modification with Sr to the microstructure and mechanical properties of the A356 alloy that is an Al-Si-Mg alloy.

2. Experimental procedure

The chemical composition of the A356 ingot, Ni element, and Al10Sr master alloy used in the experimental study is given in Table 1.

Initially, the A356 alloy was melted in a 10 kW stainless steel ladle (BN-coated) electric furnace and pre-alloyed with Ni element by holding at 780 ℃ for 30 min. Then, pre-alloyed A356/Ni alloys were modified with Al10Sr master alloy. Al10Sr master alloy (rod shape) was bathed by ladle with bell shape in liquid metal. The A356/Ni alloys' chemical composition was analysed using Foundry Master Compact Spectrometer. The chemical composition of the cast A356/Ni alloys produced is provided in Table 2.

A three-dimensional (3D) image of the casting and gating system used in the tensile test and microstructure studies is given in Fig. 1a. The cast specimens have a diameter of 15 mm and a length of 150 mm. Tensile test sample dimensions are given in Fig. 1b. Sand moulds were prepared using 60–70 AFS silica, Alphaset resin, and hardener.

To ensure homogeneous mixing during the secondary melting phase, the liquid metal was waiting in the furnace at 750 ℃ for 10 min and then poured out. Ceramic foam filters were placed on the horizontal runner (20 ppi) to remove the oxides formed during the preparation of the liquid metal and transfer them from the runner system to the mould cavity. Liquid metal is cast at 730–740 ℃ to the sand moulds. The A356/Ni alloys produced by the casting method are artificially aged (T6). As-cast alloys were quenched by keeping in water. After solution treatment at 540 ℃ for 8 h and ageing at room temperature for 24 h, as-cast alloys were artificially aged at 170 ℃ for 10 h. Metallographic samples (according to ASTM E03.11 standard) and tensile testing samples (according to ASTM B557M-10 standard) were prepared from aged A356 alloys containing different amounts of Ni. The prepared metallographic samples were etched for 30–45 s with Keller solution (2 ml HF (48 %) + 3 ml HCl + 5 ml HNO_3+ 190 ml H_2O). NIKON optical microscope (OM) and CLEMEX image analysis program and Carl Zeiss Ultra Plus Gemini (FEG) scanning electron microscopy (SEM/EDS) analysis were used to determine the microstructure of Ni added A356 alloy. In addition, Rigaku D-MAX RINT-2200 type X-ray diffractometer (XRD) was used to determine the phases formed in the microstructure. In the XRD analysis, copper (Cu) Kα radiation, 40 kV voltage, and 45 mA currents, 1°/102 s measurement speed and 10°–90° range were used. Tensile tests were carried out at a speed of 1 mm min^{-1} on a SHIMADZU AG-IS with 50 kN capacity. For each alloy group, between 8 and 12 tensile samples have been tested. The hardness tests were conducted in accordance with ASTM Standard E 10 using a Brinell hardness tester (AFFRI VRSD 251) with a ball indenter of 2.5 mm diameter and a load of 31.25 kg. The obtained tensile test results (ultimate tensile strength, percentage elongation, and yield strength) were evaluated by two-dimensional Weibull statistical analysis.

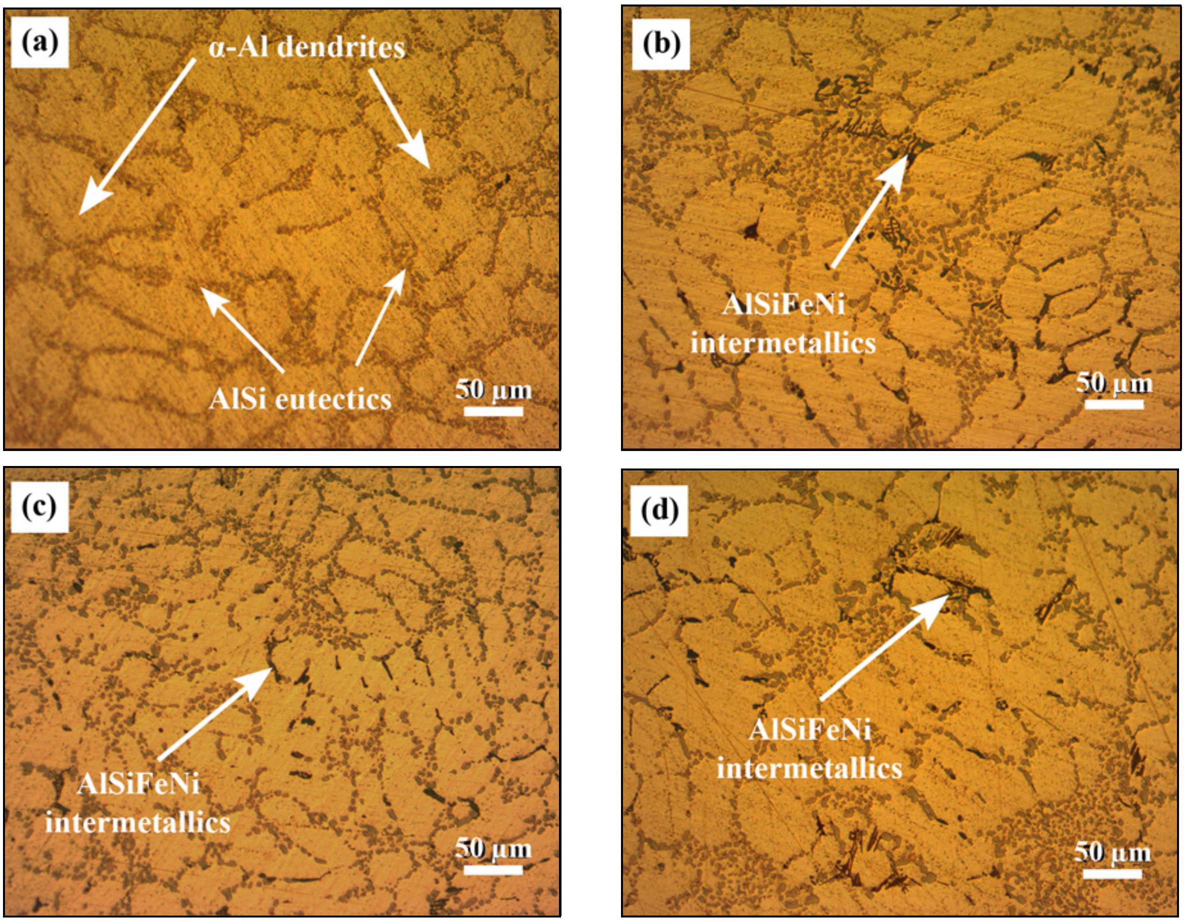
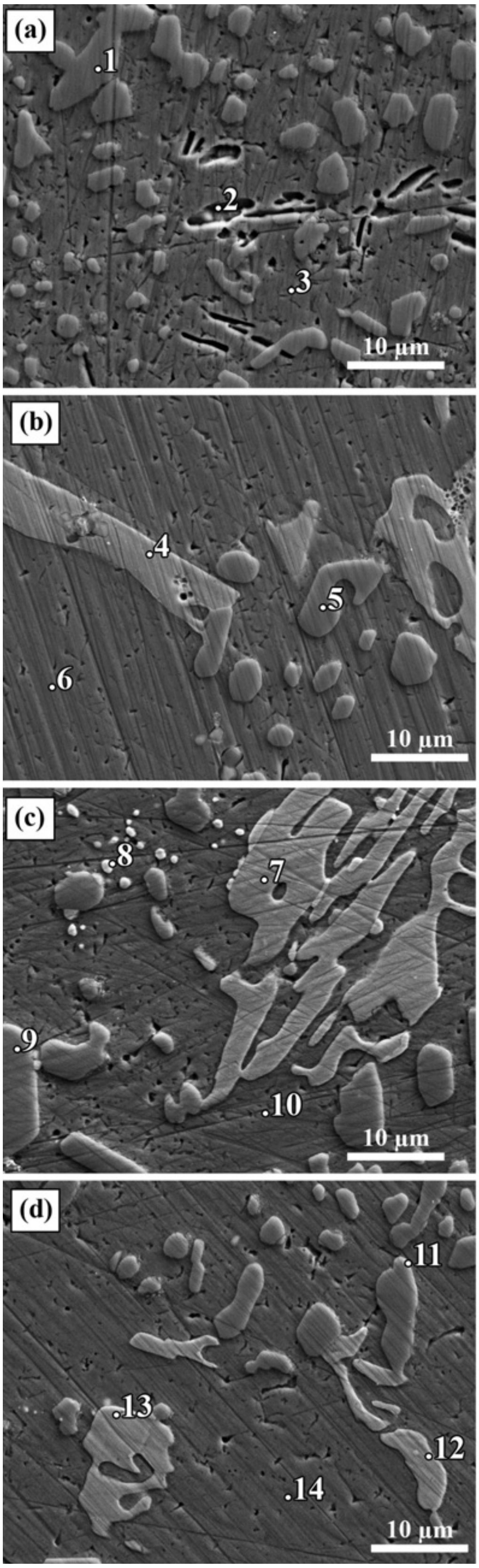


Fig. 2. OM images of A356/Ni alloy groups after T6 heat treatment: A356 (a), A356 + 0.5Ni (b), A356 + 1.0Ni (c), and A356 + 1.5Ni (d).



Element	Al	Si	Mg	Fe	O	Ni
1	11.26	87.36	0.24	0.31	0.84	-
2	64.82	11.39	0.59	20.58	2.62	-
3	97.00	0.91	0.93	0.00	1.16	-

Element	Al	Si	Mg	Fe	O	Ni
4	55.28	2.81	0.35	11.34	6.55	23.67
5	2.04	96.53	0.21	0.00	0.80	0.42
6	96.22	1.14	0.87	0.37	0.84	0.54

Element	Al	Si	Mg	Fe	O	Ni
7	59.78	0.86	0.36	6.07	5.56	27.37
8	59.61	0.88	0.40	4.99	5.43	28.69
9	5.21	91.99	0.22	0.09	0.88	1.61
10	96.90	0.86	0.87	0.00	0.92	0.45

Element	Al	Si	Mg	Fe	O	Ni
11	1.99	95.8	0.21	0.38	0.99	0.61
12	57.26	2.06	0.29	8.96	5.56	25.8
13	60.12	1.34	0.34	4.10	5.70	28.3
14	96.35	1.10	0.96	0.00	1.02	0.58

Fig. 3. SEM images and EDS analysis results (wt.%) of A356/Ni alloy groups after T6 heat treatment: A356 (a), A356 + 0.5Ni (b), A356 + 1.0Ni (c), and A356 + 1.5Ni (d).

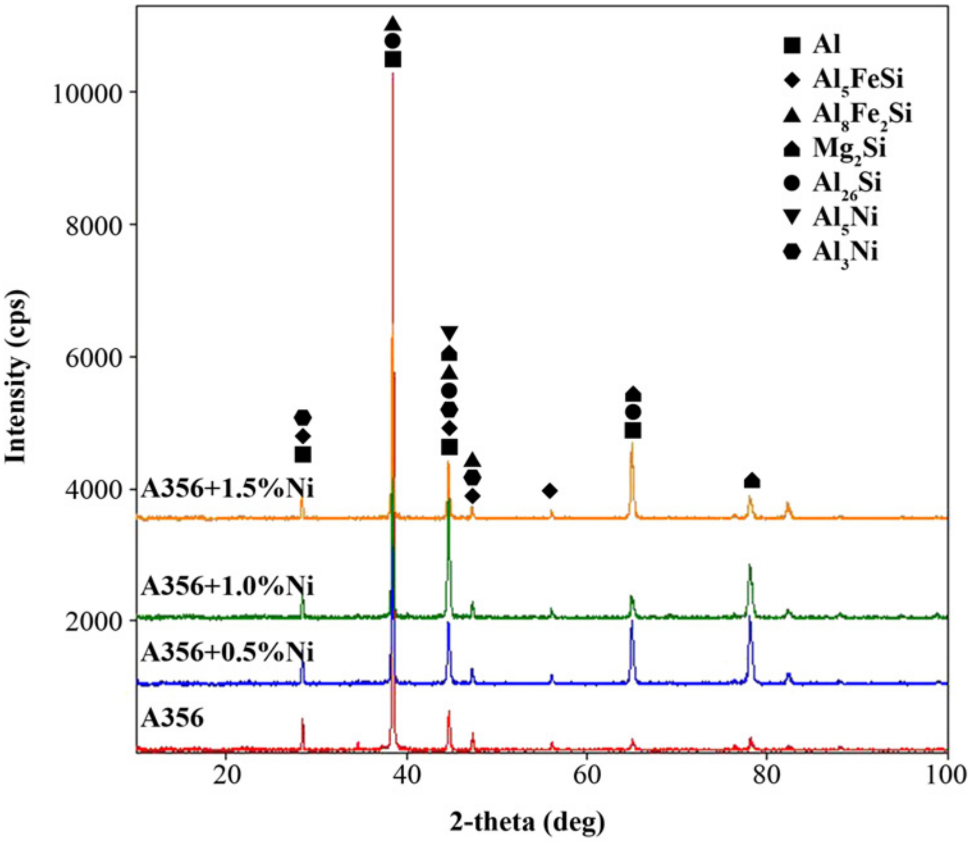


Fig. 4. XRD results of A356/Ni alloys after T6 heat treatment.

3. Results and discussion

Figure 2 gives the OM images of the microstructure of A356/Ni alloys. Focusing on the A356 alloy, Al dendrites, Al-Si eutectic between dendrites, and Mg_2Si precipitates can be observed. The Mg_2Si phase that precipitates in the matrix after the (T6) ageing process, which is carried out to reach the desired strength values in Al-Si-Mg alloys, contributes significantly to the strength of the alloy. According to the tensile and hardness test results, it is understood that Mg_2Si precipitates are formed in the alloy system, but it is complicated to view these precipitates [7, 13]. However, Al-Si-Fe intermetallics are nucleated around the Al-Si eutectic or oxide bifilms depending on the amount of Fe contained in the alloy. OM images in Fig. 2 show plate-shaped AlSiFeNi intermetallic around the Al-Si eutectic, Al dendrites, and Al-Si eutectic around dendrites. Si particulates are seen spherically due to modification with Al10Sr, which are added into A356 Al alloy. Ogris et al. [14] stated in their study that the dendritic Si in the A356 alloy with Sr added decomposes under surface tension if thermally activated, and the Si particles turn into a series of interconnected spherical particles at equal intervals. In Fig. 2, it is seen that depending on Ni content, AlSiFeNi and Chinese script intermetallics are formed. Depending on Ni content, these intermetallics formations are increased among Al dendrites in Fig. 2.

Alloys were investigated by scanning electron microscopy (SEM) to determine the effect of the amount of Ni on the microstructure in the modified A356 alloy. SEM and EDS analysis of Al-matrix (points 3, 6, 10, and 14), Al-Si (points 1, 5, 9, and 11), AlFeSi (point 2), AlSiFeNi (points 4 and 12), and AlFeNi (points 7, 8, and 13) intermetallics of A356 alloy are given in Fig. 3. In EDS analysis, it was seen Ni-rich AlSiFeNi and Al_8Fe_2Si phases formed among dendrites (which are shown in Fig. 2). XRD results support this situation. With the addition of 0.5 and 1.0 % Ni to the A356 alloy, the morphology of the Al-Si eutectic appears to have a relatively homogeneous distribution, but this distribution is clustering among the dendrites depending on the increased Ni content. Many researchers have reported that thermally stable Al_3Ni and Al_9FeNi intermetallic compounds are formed by adding Ni to Al-Si alloys [15, 16].

The results of XRD analysis for detecting Ni-based intermetallics formed in A356/Ni alloys are given in Fig. 4. Besides the base elements of A356 Al alloys such as Al, Al_5FeSi, and Al_8Fe_2Si intermetallics, Mg_2Si, Al_5Ni, Al_3Ni phases were formed in the structure. AlNi, Al_3Ni, $AlNi_3$, and Al_3Ni_5 are intermetallic compounds usually formed in the Al-Ni alloy sys-

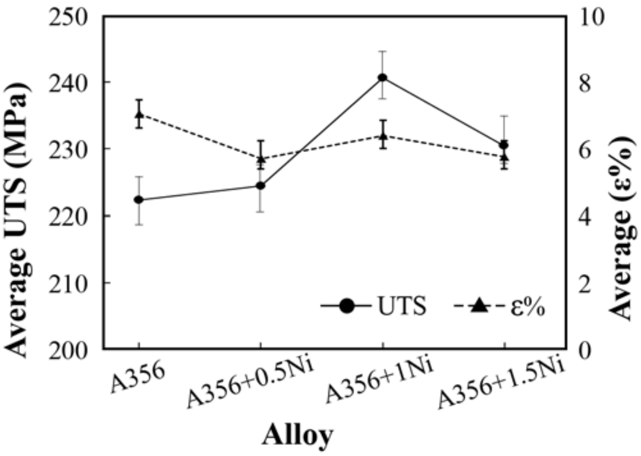


Fig. 5. Average tensile strengths and average elongations of A356/Ni alloys after T6 heat treatment.

tem [17–19]. In addition, Hanafee et al. [18] reported that Ni-added aluminium alloys (containing 10–16 % Si) increase the hardness of the alloy due to nickel aluminates formed in the structure (at about 315 ℃). Méndez et al. [19] reported improvement in the mechanical properties and the increase of Al_3Ni-based intermetallics in the structure due to the increasing amount of Ni in the aluminium matrix in Al-Ni alloys produced by powder metallurgy technique.

Hardness and tensile tests were carried out to determine the effect of the Ni element added to the A356 alloy. The data obtained in tensile tests were evaluated by Weibull statistical analysis. The average tensile strength and elongation values obtained using Weibull statistical analysis after the tensile test are given in Fig. 5. The ultimate tensile strength and percentage elongation values are given in Fig. 6. In Figs. 5 and 6a, the evaluation of Weibull analysis of ultimate tensile tests shows that the ultimate tensile strength is 229 MPa, the characteristic tensile strength is 231 MPa with modification and 0.5 % Ni addition, the tensile strength of the alloy with modification and 1.0 % Ni addition is 245 MPa, the tensile strength of the alloy with modification and 1.5 % Ni addition is 248 MPa. In Figs. 5 and 6b, the percentage elongation of the A356 alloy modified with strontium is 7.4 %, and the percentage elongation values with 0.5, 1.0, and 1.5 % Ni addition are 6, 6.71, and 6.2 %, respectively.

Hardness variation of A356/Ni alloys is given in Fig. 7. Depending on the amount of Ni added to the A356 alloy, it is increased in alloys containing 0.5 and 1.0 % Ni. Hardness values and UTS Weibull modules are increased by formed around Al-Ni spherical precipitation in A356 + 1.0Ni alloy (Figs. 3, 6, 7). This increase is due to prevent dislocation movements which formed spherical intermetallics. As can be seen in the OM pictures given in Fig. 2, it is seen that

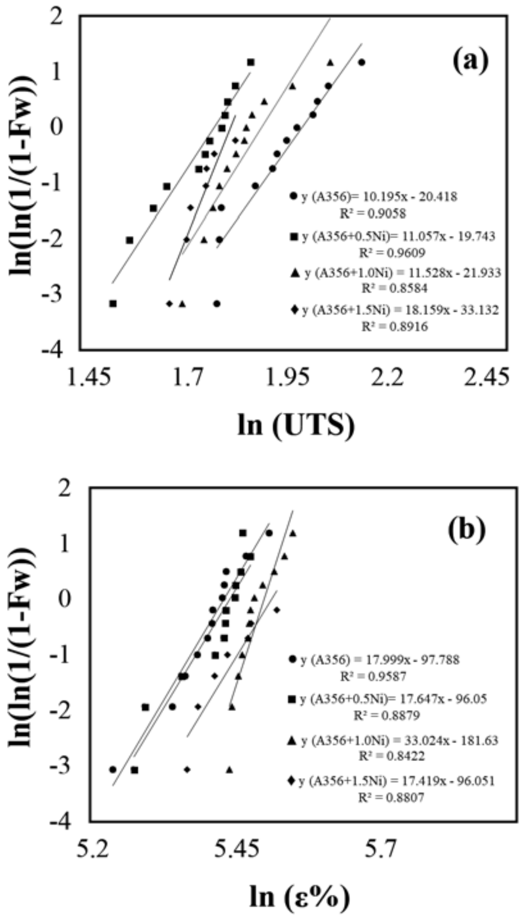


Fig. 6. Weibull distribution of ultimate tensile strength (a), percentage elongation Weibull distribution (b) of A356/Ni alloy groups after T6 heat treatment.

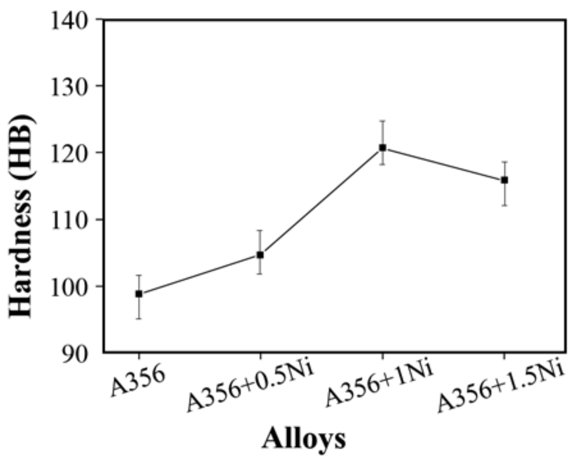


Fig. 7. Changes in hardness after T6 heat treatment of alloys containing different amounts of Ni.

the Ni-based intermetallic phases formed with the increase of Ni content are more clustered at the grain boundaries. The clustering of these intermetallics at

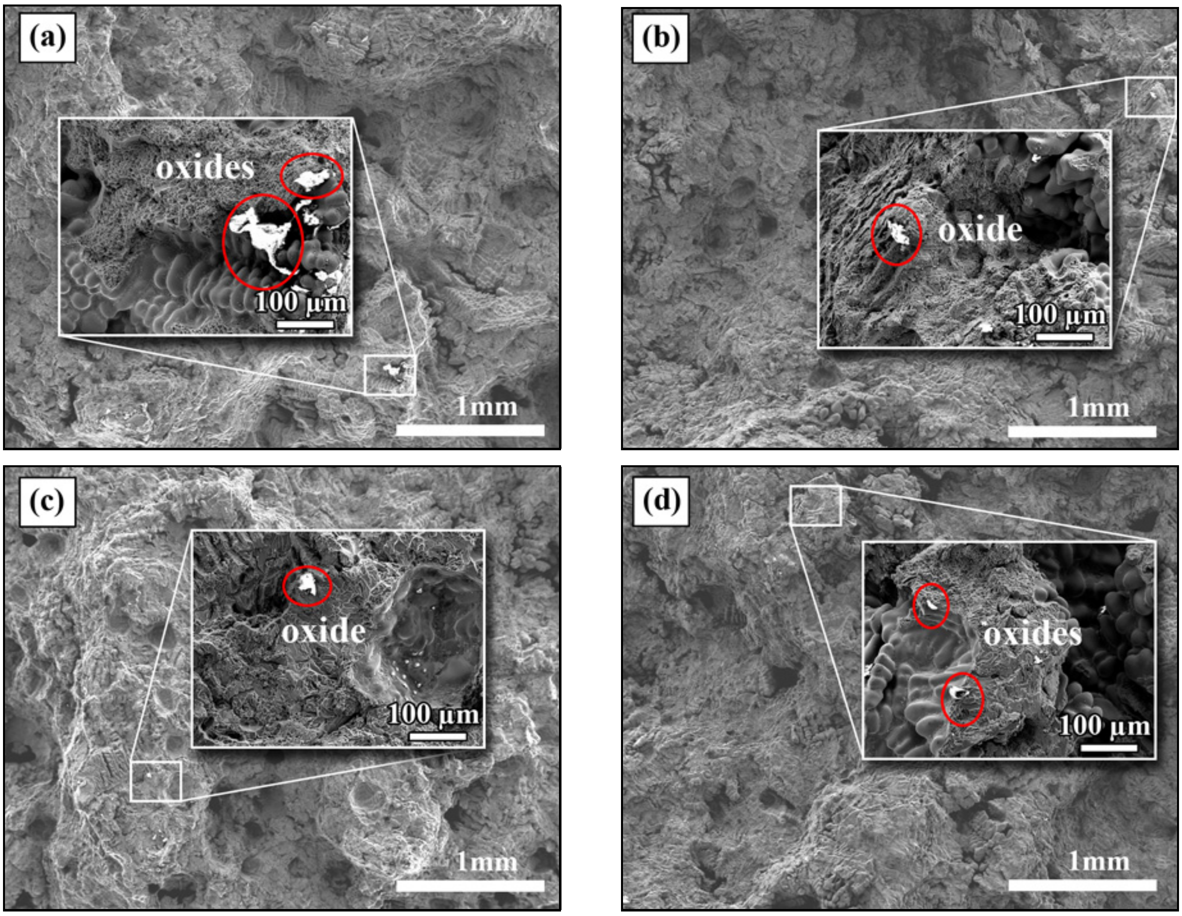


Fig. 8. SEM images of fractured surfaces of A356/Ni alloy groups after T6 heat treatment: A356 (a), A356 + 0.5Ni (b), A356 + 1.0Ni (c), and A356 + 1.5Ni (d).

the grain boundaries (compared to 0.5Ni and 1.0Ni) provides an area where the dislocations can move more easily. Therefore, it causes a decrease in hardness value. Many studies have stated that this increase in hardness is due to Mg_2Si precipitates [20–22]. It appears that the hardness of alloys containing 1.5 % Ni is reduced. It is also understood from SEM images that, since the Ni-based intermetallics nucleated around Al α-dendrite grain boundaries and around the Al-Si eutectic, are located tighter and more weblike at grain boundaries in the alloys containing 1.5 % Ni than in the alloys containing 0.5 and 1.0 % Ni. In their study, Lattanzi et al. [23] stated that increasing the amount of Ni had a negative effect on the precipitation of reinforcing intermetallic compounds and reduced hardness.

In Fig. 8, fracture surfaces are examined by SEM after the tensile test of A356/Ni alloy groups. It is observed that the fracture surfaces in the tensile test have casting defects such as oxide film, porosity, intermetallic phases, or phases formed during solidification. Secondary intermetallic phases formed in these regions, especially around the oxide film, are the most obvious factors in fracture occurrence because micro-fractures primarily occur in these regions of stressed material. With increased stress, the micro-cracks merge into macro-cracks, and the fracture occurs at the next stage. Some previous studies emphasize that fractures occurring in Al alloys start from where micro gaps, bifilms, and intermetallic phases form in the structure [24, 25].

4. Conclusions

Below are the results of this study, in which the effects of Ni addition to A356 alloy on the microstructure and mechanical properties of the alloy were investigated.

– In A356 alloys, aluminium dendrites, Al-Si eutectic between dendrites, Mg2Si precipitates are formed in the structure by ageing. With the addition of 0.5 and 1.0 % Ni to the A356 alloy, the morphology of the Al-Si eutectic shows a relatively homogeneous distribution; however, it clusters between the dendrite arms due to increased Ni content.

– The hardness values were increased by increasing Ni content up to 1.0 % Ni addition; hardness value was decreased with the addition of 1.5 % Ni. It is thought that hardness values were affected negatively due to an increase in morphological changes with the increasing Ni amount (1.0 to 1.5 %).

– The evaluation of Weibull analysis of ultimate tensile tests shows that the ultimate tensile strength is 229 MPa, the characteristic tensile strength is 231 MPa with modification and 0.5 % Ni addition, the tensile strength of the alloy with modification and 1.0 % Ni addition is 245 MPa, and the tensile strength of the alloy with modification and 1.5 % Ni addition is 248 MPa.

– The percentage elongation of the A356 alloy modified with strontium is 7.4 %, the percentage elongation with 0.5 % Ni addition is 6 %, the percentage elongation with 1.0 % Ni addition is 6.71 %, and the percentage elongation with 1.5 % Ni addition is 6.2 %.

– It is observed from the fracture surface of A356/Ni that oxide films and Ni-based intermetallics together caused deformation and fracture.

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