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EFFECT OF STRONTIUM CONTENT ON THE MECHANICAL PROPERTIES OF HYPO AND HYPER AL-SI CAST ALLOYS

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ABSTRACT

Al-Si alloys are the most important aluminium cast alloys because of their superior casting properties such as good castability, low specific gravity, low viscosity and high resistance to wear and corrosion. The effect of strontium (Sr) addition -as a modifier- on the microstructure, hardness and tensile strength properties of the Al-Si alloys at different silicon contents (3.4, 6.7, 9.3, 12.4, and 13.4 %) was investigated. Sr content in these groups ranged between 0.086 to 0.181 %. The nanohardnesss and maximum displacement for Al-Si alloys with different percentages of silicon (6.65, 9.14, 12.23 and 13.5 % respectively) at constant Sr (0.02%) were introduced and strain hardening was detected**.** The results indicated that the addition of Sr to Al-Si alloy modified the Al-Si morphology from large plates or needle-like silicon structure to fine-scale fibrous silicon structure and hence improved the tensile strength and hardness. The values of hardness and tensile strength of Al- 13-14 Si % were increased from 64.5 to 72 BHN and from 154.8 to 172.4 MPa respectively with increasing the percentage of Sr from 0.086 to 0.17 %. The hardness percentage in nanoindentation measurements was increased by about 26%, while the maximum displacement was decreased from about 7400 nm to about 4930 nm when the Si % increasing from 6.65 to 13.5 %.

Keywords: Al-Si cast alloy, Modification, Mechanical properties, Si-morphology, Nanoindentation, Contour maps

1. INTRODUCTION

Al–Si casting alloys are used extensively in many industrial applications due to an excellent combination of castability and mechanical properties, as well as good corrosion resistance and wear resistivity. However, a serious drawback of Al–Si alloys is coarse-grained structure responsible for a decrease in mechanical properties (mainly tensile strength and unit elongation) [1].

Microstructure evolution of hypoeutectic Al-Si alloys during solidification is in two stages: primary dendrite Al-phase formation (α-matrix), and the subsequent eutectic transformation (eutectic Si particles in matrix) [2]. Al-Si alloys containing more than about 12% Si exhibit a hypereutectic microstructure normally containing primary silicon phase in a eutectic matrix. Cast eutectic alloys with coarse acicular silicon show low strength and ductility because of the coarse plate-like nature of the Si phase that leads to premature crack initiation and fracture in tension. Similarly, the primary silicon in normal hypereutectic alloys is usually very coarse and imparts poor properties to these alloys. Therefore, alloys with a predominantly eutectic structure must be modified to ensure adequate mechanical strength and ductility [3-4].

Modification of the silicon particles in Al-Si alloys, by the transition from blocky, acicular and needle-like silicon phases to a fine fibrous silicon structure, improves the casting properties of these alloys [5]. Addition of strontium, antimony, sodium, barium, and calcium and rare earth elements is found to modify the coarse acicular morphology of Si into fibrous form [2]. Additions in the range of few 100 ppm from these modifiers promotes the eutectic Si morphology and have a beneficial effect on both strength and ductility [6-8]. Sr also frequently used due to, it is easy to handle, has a good modification rate and a long incubation time a low fading effect [9-11]. The improvement in mechanical properties generally has been attributed to the variations of the morphology and size of the eutectic silicon phase particles. It is worth noting, however, that at the same time when eutectic silicon particles change from acicular to fiber, the amount, morphology and size of dendritic α-Al phase are varying too[12]. The addition of 0.03% Sr makes a modest improvement to the yield strength, ultimate tensile strength and elongation percentage values, and the scatter of these properties, but makes a significant improvement to minimum strength and elongation results [13].
Instrumented nanoindentation technique has been extensively used for the micromechanical characterization of materials due to their high time resolution and spatial resolution. Nanoindentation technique usually doing the measurements in the Nano depth range [14–17]. Nanoindentation is considered as an excellent tool for probing the mechanical response of materials at Nano scales by continuously measuring the applied force (maximum load up to 500mN) and the corresponding displacement during an indentation. Hardness and elastic modulus are usually identified from such measurements [18]. Previous work also indicated that hardness measurement may be useful for characterizing residual stresses in materials [19].

Structure and mechanical properties of
Al-12%Si alloy with fast cooling Al-12%Si

T. Lipiński
In this work; three groups of experiments were carried out to investigate the effect of strontium addition on the microstructure, hardness and tensile strength of the Al-Si alloys at different silicon contents (3.4, 6.7, 9.3, 12.4, and 13.4 %). Sr content in these groups ranged between 0.086 to 0.181 %. The nanoindentation behaviour of the produced Al-Si alloys was studied for other group with different percentages of silicon (6.65, 9.14, 12.23 and 13.5 % respectively) at constant percentage of Sr (0.02 %).

2. EXPERIMENTAL WORK

2.1 Materials

The used materials in this study were commercial aluminum, silicon and Al-10Sr master alloy (as source of Sr). The chemical analysis of these materials was determined by using inductively coupled plasma (ICP) model OES. The chemical analysis of the used aluminum in this study is shown in Table1. The average main elements for these specimens are illustrated, and the purity of aluminum is about 99.8 %. The purity of the used silicon was 99.5%. The chemical analysis of the used Al- Sr master alloy is shown Table 2.

Table 1 Chemical analysis of the aluminum

Element	**Fe**	**Si**	**Mn**	**Mg**	**Na**	**Ti**	**Ca**	**Al**
%	0.059	0.05	0.008	0.001	0.0064	0.004	0.004	balance

Table 2 Chemical analysis of Al-Sr master alloy

Element	**Sr**	**Fe**	**Si**	**Al**
%	10	0.05	0.008	balance

2.2 Experimental Procedures

The melting process was done in anthracite with 20-30% graphite crucible set in a vertical muffle furnace. The melting temperature was kept at 720 °C. The work was carried out in three groups of experiments as follows:
A-The first group of samples was prepared with varying Si content in the range of (3.39, 6.68, 9.29, 12.37, and 13.4 %), without Sr addition,
B- The second one of samples was prepared with varying Si content in the range of (3.39, 6.65, 9.14, 12.23, and 13.5 %), but with different percentage of Sr addition in the form of Al-10Sr master alloy.
C-The third group of hypereutectic samples was prepared with Silicon in the range 13-14 %, with different percentages of Sr addition (0.086, 0.088, 0.153, and 0.17 %**)**.

In these A, B and C groups, each group of Si was added to the molten aluminum at a proper rate. The melt in each group was stirred using agitating rod to ensure complete homogenization.

The chemical composition of these A, B and C groups was analysed and illustrated as shown in Table 3. The obtained results can be summarized as:

- Iron percentage in the produced Al-Si alloys ranged from 0.07% to 0.16% (and most of iron presented in these alloys is coming from the aluminum used in experiments (0.06%)). Iron in these alloys formed the ternary compound β iron (Al-Fe-Si) which was present as needles and plates in the eutectic structure, it occurred in massive form causing brittleness. This can lead to a marked deterioration in the mechanical properties [20, 21]. The other elements (Mn, Mg, Cr and Na) in these alloys are considered as traces.
- Sr content in the second and third groups ranged from 0.086 to 0.181 %.

Sr addition not only modifies the Al-Si eutectic, but also affects the morphology and structure of primary α-Al dendrite. Sr decreases the growth temperature of α-Al dendrite and Al-Si eutectic, and it also affects the dendrite growth mechanism. It has been found that such effect becomes more significant with higher cooling rate [22]**.**

Table 3 Chemical analysis of the (A) as casted Al-Si Alloys, (B) after Sr addition and (C) at 13-14 % Si with different percentages of Sr

Group	Element,% Sample No.	Si	Fe	Mn	Mg	Cr	Na	Sr
A	1	3.39	0.07	0.001	0.001	0.001	0.0004	-
	2	6.68	0.11	0.002	0	0	0.0004	-
	3	9.29	0.11	0.002	0	0	0	-
	4	12.37	0.14	0.002	0.001	0.001	0	-
	5	13.40	0.11	0.003	0	0	0.0003	-
B	6	3.39	0.07	0.001	0	0.001	0.0004	0.157
	7	6.65	0.13	0.002	0	0.001	0.0004	0.160
	8	9.14	0.14	0.002	0	0	0	0.181
	9	12.23	0.16	0.003	0.001	0.001	0	0.125
	10	13.50	0.12	0.003	0	0.001	0.0004	0.135
C	11	13.13	0.09	0.002	0	0	0.0004	0.086
	12	13.35	0.1	0.003	0	0.001	0.0004	0.088
	13	13.16	0.1	0.002	0	0.001	0	0.153
	14	13.95	0.1	0.003	0	0	0	0.17

The produced alloys were subjected to a series of tests to evaluate some of the mechanical properties such as hardness and tensile strength. Tensile strength test was performed using tensile test on (VH-F1000 kN) SHIMADZU micro-computer controlled electronic universal testing machine, made in Japan, with strain rate 5x10-3 s^{-1} and the specimens were prepared according to ASTM standard test method (diameter was 10mm and the gage length was 60mm)[23]. The hardness test has been done by using Brinell hardness test and the specimens for this test were polished .The main dimensions of these cylinders were 30mm diameter and 20mm thickness, suitable specimens were prepared to carry out the microstructure examinations by polarized reflected light microscope (Model-OLYMPUS BX51, Japan) supplied with a digital camera (Leica DM500) and four objective lenses of different magnification.

Specimens for nanoindentation tests were cut from some selected samples and polished to a mirror like. The nanoindentation measurements were carried out by using a NanoTest Vantage nanoindentation device with a Berkovich indenter and applying maximum loads of 50 mN with loading rates of $10^{-2}$and 2×10^{-2} mN/s.

3-RESULTS AND DISCUSSION

Evaluation of the produced Al- Si alloys with and without strontium addition is illustrated as follows:

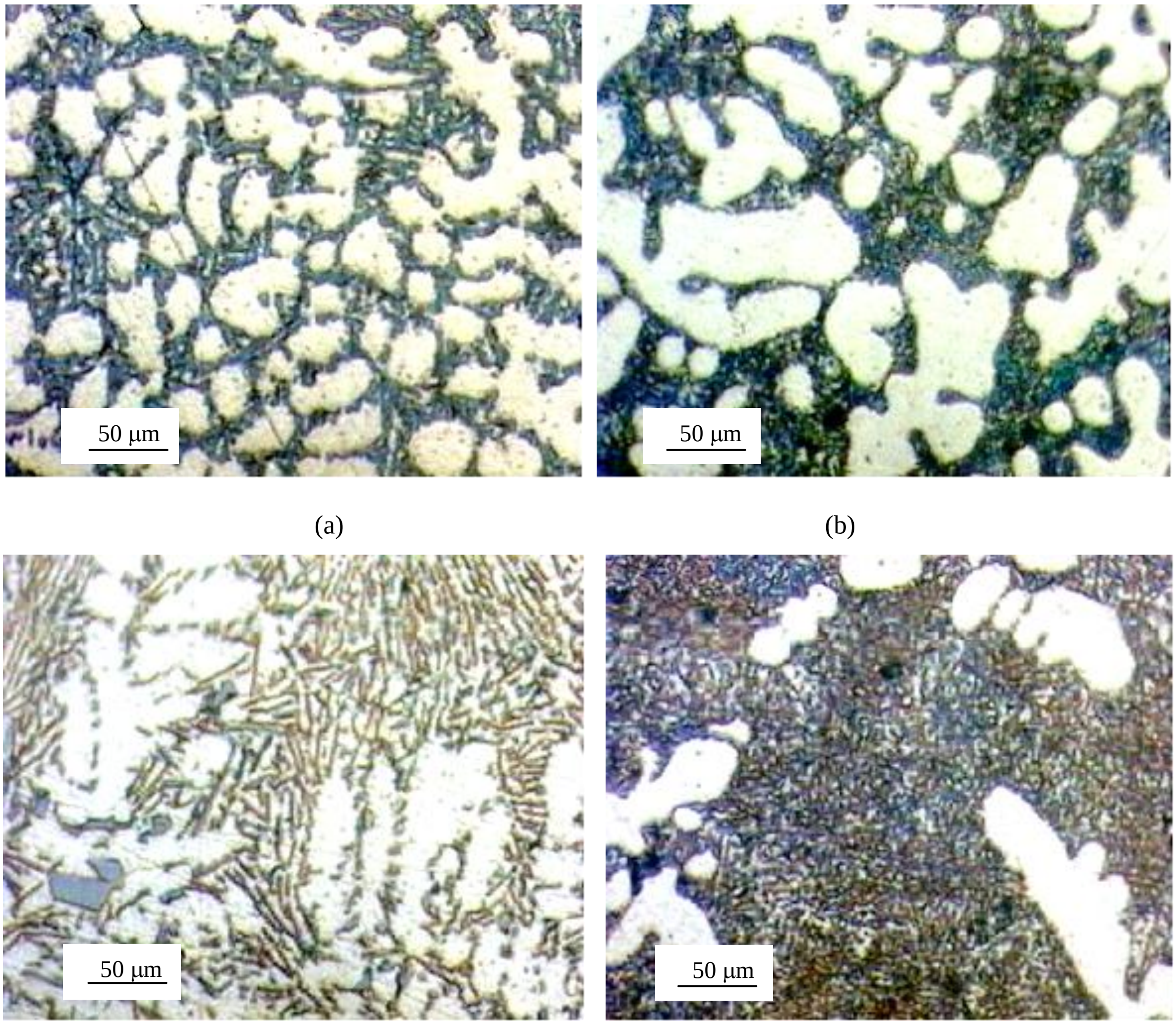
3-1 Microscopic Examination

Microstructure of binary Al-Si alloys, in the unmodified state, near to the eutectic composition (9.3 %Si) exhibits acicular or lamellar eutectic silicon, which is in the form of large plates with sharp sides and edges (Figure 1a). Modification of this alloy modifies the growth of the eutectic silicon to produce an irregular fibrous form rather than the usual (Figure 1b). While, unmodified Al-12.3% Si alloy exhibits a hypereutectic microstructure normally containing primary silicon phase in a eutectic matrix (Figure 1c). Addition of a small quantity of Sr causes modification of the microstructure as shown in Figure 1d. This addition effectively moves the eutectic point to a higher silicon concentration and lower temperature. The eutectic point has moved far enough to make the alloy, at this composition, hypo-eutectic instead of hyper-eutectic. So, by adding a very small amount of strontium, the microstructure of these alloys is changed and its properties may be greatly improved [24].

3-2 Mechanical Properties:

- Tensile strength and hardness results:

Figure 2 shows that the tensile strength of the produced Al-Si alloys increases with increasing the dissolved silicon in these alloys. The refinement of the eutectic Si phase by Sr can improve the tensile strength slightly (108-188.4 MPa) as compared with (102-178 MPa) for non-modified alloy when the silicon content varies between 3.39 and 13.45%. This result is good agreement with the data published in elsewhere[2]. In addition, the hardness of the produced Al-Si alloys increases with increasing the dissolved silicon in these alloys. The hardness values have slightly increased from (42.5-74.5 BHN) for non-modified to (45-78.5 BHN) for modified alloy when the silicon content varies between 3.4 and 13.45%. The obtained results are due to modification of the produced alloy. The eutectic Si in untreated Al-Si foundry alloys is often very coarse, leading to poor mechanical properties, particularly tensile and hardness. It has long been known that the mechanical properties of Al-Si alloys are heavily influenced by the morphology of eutectic Si. Changing the morphology of eutectic Si from its original coarse platelet structure to a less harmful, finer fibrous structure, known as eutectic modification, leads to a significant improvement in mechanical properties of castings [25, 26].



(a) (b)

(c) (d)

Figure 1 Microstructure of Al-Si alloys containing a) 9.3 % silicon, without strontium, (b) 9.3 % Si, with 0.5 Sr, (c) 12.3 % Si, without Sr, and (d) 12.3 % Si, with 0.5 Sr, etched by 0.5% HF acid.

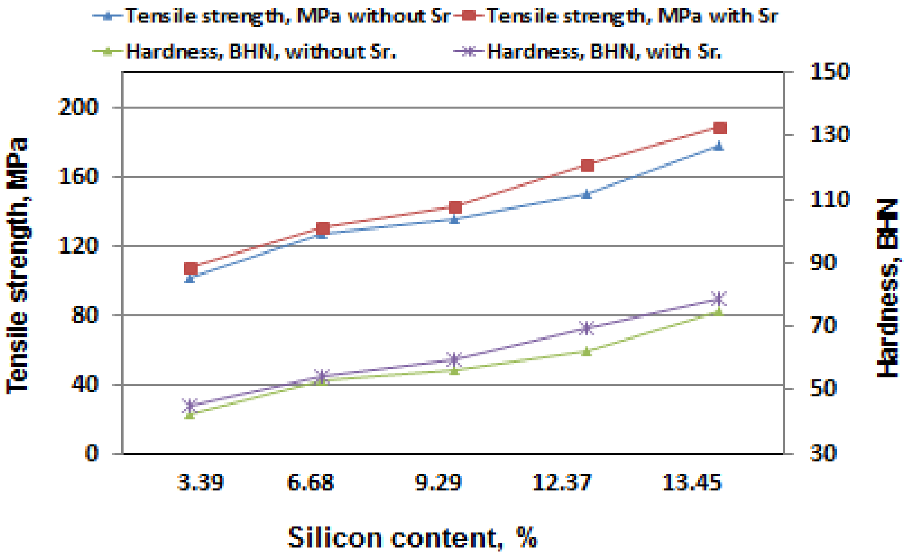


Figure 2 Relation between tensile strength and hardness with Si % at with and without Sr addition

3.3 Effect of Strontium Addition on Hardness and Tensile Strength

The effect of Sr addition on hardness and tensile strength at 13-14 Si % is shown in Figure 3. The figure shows that increasing the amount of the modifying Sr increases the hardness and tensile strength too. Results of hardness are comparable with results of tensile strength. The values of hardness and tensile strength increase from 64.5 to 72 BHN, and from 154.8 to 172.4 MPa respectively with increasing the percentage of strontium from 0.086 to 0.17 %.

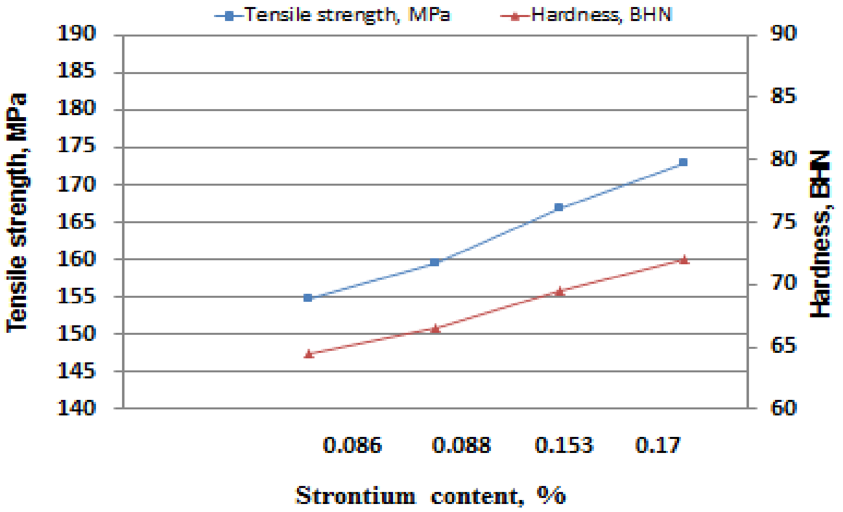


Figure 3 Relation between tensile strength and hardness with different percentages of Sr.

3.4 Nanoindentation Results:

To study the nanoindentation behaviour of the produced Al-Si alloys, other produced alloys with nearly the same percentages of silicon (6.65, 9.14, 12.23 and 13.5 % respectively), at constant percentage of Sr (0.02 %) was studied. These samples denote as 1, 2, 3 and 4. A series of about 100 indentations were recorded with the indents arranged in a 10×10 matrix with a neighbor spacing of 10 µm at a given maximum load and loading rate. Figure 4 shows the indenters matrix using SEM image for specimen 4 after the nanoindentation. It is clear that the indenters print on the sample surface, the same result was obtained for all the samples.

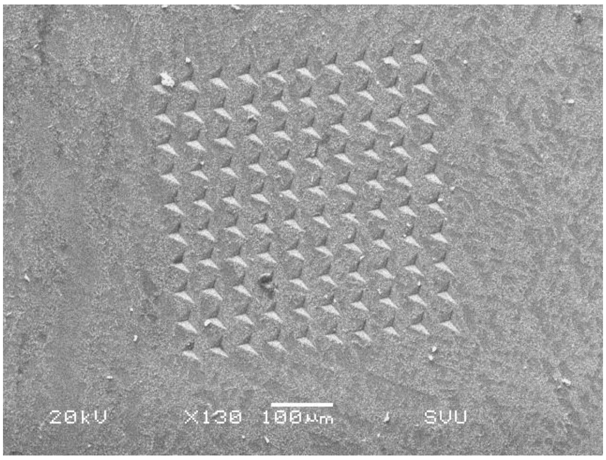


Figure 4 SEM image for sample 4 after the nanoindentation.

Figure 5 shows the contour graphs of hardness values for about 100 indentation points for the samples 1 to 4. Spatial variation of the hardness values appeared and the background hardness increases with increasing the Si % content in the produced alloys. Strain hardening is clearly observed according to the increasing of silicon content. Residual stresses can be defined as stress fields that exist in the absence of any external loads and are the result of any mechanical process which can cause deformation. Since residual stresses are difficult to calculate precisely by analytical methods, they are usually determined by experimental techniques [27]. Also, the increasing and inhomogeneity in the hardness contour maps as shown in Figure 5 is due to the increase of residual internal stress, because the samples were poured in metallic mold (high cooling rate from 720 °C to room temperature). During fast cooling □ □ aluminum solid solution can be supersaturated and then, as a result of its tendency to achieve the thermodynamic equilibrium, the dispersed particles of silicon precipitate. When the residual internal stress is increased further (a kind of rearrangement occurs at atom level and the mobility of the dislocation decreases), and it makes the metal harder and stronger through the matrix. This tends to increase the strength and hardness of the metal and decrease its ductility [28]. This result is in agreement with Figure 2.

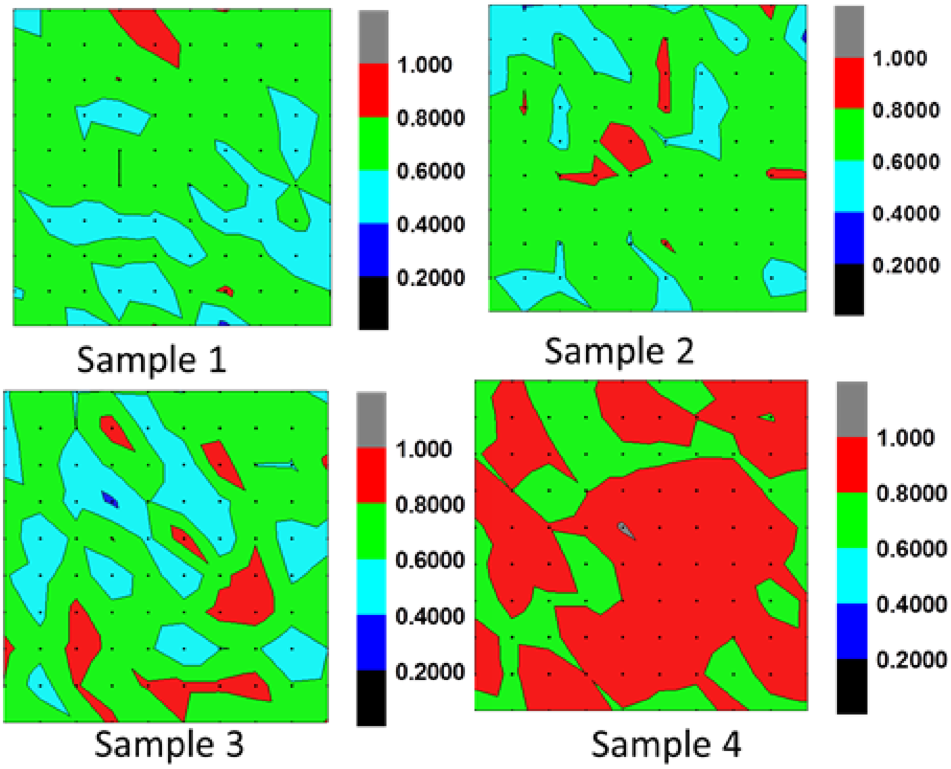


Figure 5 Hardness maps compiled from a matrix of nanoindentation measurements for the samples.

Figure 6a shows load – displacement curves for the samples with different Si %, the maximum load as shown is 500 mN for the samples. As clear in Figure 6b the hardness and elastic modulus are increased as the Si% increases in these alloys. Increasing of hardness percentage in nanoindentation measurements is reached to 26 % when the Si content increases from 6.65 to 13.5 %. The results illustrated the maximum displacement is decreased from about 7400 nm at 6.65 % Si to 4930 nm at 13.5 % Si. These results are in agreement with the data shown in Figure 2.

Figure 7 shows different shape and size of the indents (a and b) at different positions of the sample 4. The shape and size of the indents in Figure 7.a is more size and depth than shown in Figure 7.b. Hence, the hardness values in Figure 7.b is more than in Figure 7.a. This difference in hardness at different locations in the sample is related to the accumulation of Al-Si in some locations are higher than other, and this difference may be the cause of internal stresses.

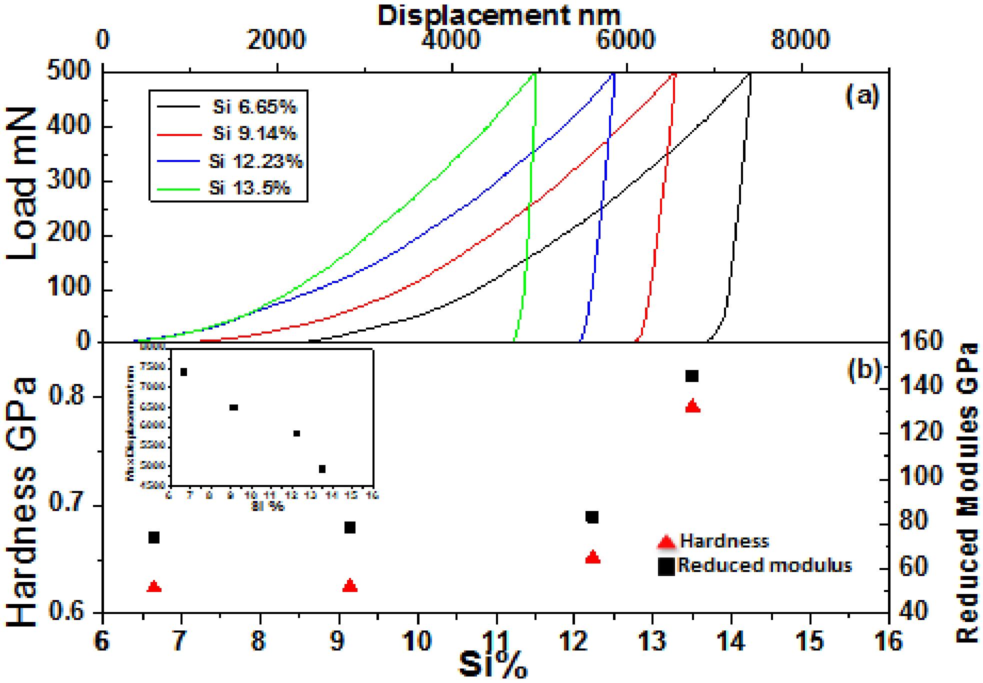
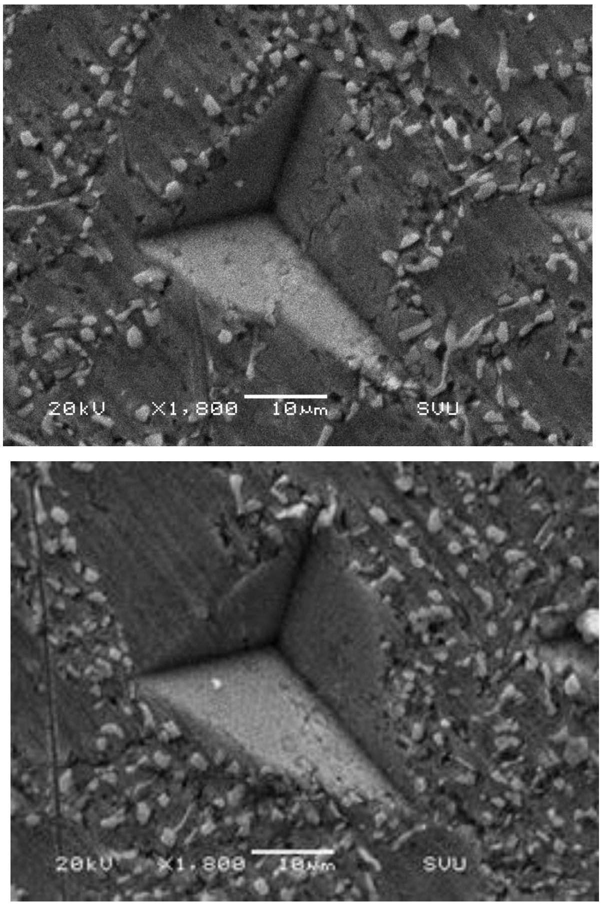


Figure 6 (a) The load – displacement curve for the four samples, (b) the relation between hardness, reduced modulus with Si% and the inset shows the max displacement –for the different samples



(a) (b)

Figure 7 SEM image for 2 different indenters at sample 4.

CONCLUSIONS

The present study was carried out to investigate the effect of strontium addition on the microstructure and some mechanical properties of Al-Si cast alloys. The conclusion could be summarized as follows:

1- Microstructure of Al-Si alloys by adding Sr was changed from acicular or lamellar eutectic silicon to a fine fibrous silicon structure.
2- Tensile strength and hardness of the produced Al-Si alloys were increased with increasing the percentage of dissolved silicon in these alloys.
3- The hardness maps and maximum displacement for four samples were introduced and strain hardening was detected. Increasing of hardness percentage in nanoindentation measurements was reached to 26 % when the Si content increased from 6.65 to 13.5 %. The maximum displacement decreased with increasing the Si % content; from about 7400 nm at 6.65 % Si to 4930 nm at 13.5 % Si.
4- The strain hardening is clearly observed with increasing the Si percentages.
5- The values of hardness and tensile strength of Al- 13-14 Si % increased from 64.5 to 72 BHN and from 154.8 to 172.4 MPa respectively with increasing the percentage of Sr from 0.086 to 0.17 %.

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