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Investigation of the microstructure and mechanical properties of squeeze cast Al-11%Si alloy heat treated

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Abstract

Squeeze casting is the combination of casting and forging processes, which solidifies the molten metal under high pressure. Applying pressure during melt-solidification can change several characteristics of the material. The present paper aims to evaluate the effect of pressure levels and T6 heat treatment on the microstructure and mechanical properties of Al-11%Si alloy produced by gravity and squeeze casting process. The results have shown that the applied pressure refines the microstructure, improves the tensile properties and increases the Vickers hardness. Additionally, when the T6 heat treatment was applied, spheroidized eutectic Si particles and fragmented β phase particles were formed, and the mechanical properties were improved.

Key words: Al-11%Si, squeeze casting, T6 heat treatment, microstructure, mechanical properties

1. Introduction

Aluminum-silicon based alloys are well-known casting alloys with high wear resistance, low thermal expansion coefficient, good corrosion resistance and improved mechanical properties in a wide range of temperature. These properties lead to the application of Al-Si alloys in the automotive industry, especially for cylinder blocks, cylinder heads, pistons and valve lifters [1, 2]. In recent years, based on data from the EEA (European Aluminum Association), 73 % of cast alloys go into the transport sector in Europe due to high production rate [3]. The major problem in shaping these alloys consists in their high tendency to form casting defects caused by the traditional casting processes. In the search for improved alloy properties, some casting techniques, such as liquid metal forging or squeeze casting, have been developed.

Squeeze casting is a casting method of producing in which metal is solidified by the direct action of pressure sufficient to prevent the cast defects. It is a process which combines, in a single operation, the desirable features of both mold casting and die forging where molten metal is solidified under applied hydrostatic pressure [4, 5].This new casting technique leads to a very good combination of mechanical properties, which mainly comes from the high density, the finer and more homogeneous microstructures of the squeeze casting material.

Many research works have discussed the advantages of squeeze casting process. For example, Chatterjee et al. [6] studied the LM6 alloy and concluded that mechanical properties can improve by the application of pressure during solidification. The evolutions of the mechanical properties are attributed to the remarkable decrease of the SDAS (Secondary Dendrite Arm Spacing) and increasing refinement of eutectic phase. Similarly, Abou El-Khair [7] found that squeeze pressures decrease the percentage of porosity and the grain size of α-Al and modify the Si eutectic. A380 alloy was studied by Chadwick and Yue [8] and was reported to have an increasing trend of yield strength (YS) 126 MPa and ultimate tensile strength (UTS) 133 MPa values as squeeze cast conditions compared to the conventional casting process. Also, Ghomashchi and Strafford [9]found 210 MPa UTS and 2.5 % elongation for the same alloy (A380). Hajjari and Divandri [10] studied 2024 aluminum alloy and found that the

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Table 1. Chemical composition (wt.%) of Al-11%Si alloy used in this study

Si	Mg	Mn	Ni	Fe	Cu	Cr	Zn	Pb	Al
11.1	0.11	0.06	0.1	0.29	0.09	0.03	0.15	0.03	Rest.

UTS of the alloy increased from 220 to 260 MPa with the squeeze pressure of 30 to 70 MPa, respectively.

Another method of improving the mechanical properties of casting Al-Si is by conducting heat treatment. Therefore, the eutectic structure of Al-Si can be refined, and its properties can be improved by T6 heat treatment (solution treatment, quenching, and artificial aging) [11]. In this regard, Zhao et al. [12] reported that the precipitation hardening through heat treatment would precipitate the alloying elements in the form of fine coherent particles of Mg_2Si and Al_2Cu inside the grains. That would harden the alloy during the aging stage. The long duration of solution heat treatment can alter the morphology of the Si phase into spheroidal shape, and hence, change the mechanical properties of the aluminum alloy [13].

This study aims to present the results of the effect of pressure levels and T6 heat treatments on the microstructure characterizations and mechanical properties of Al-11%Si alloy manufactured by applying direct squeeze, and gravity die casting.

2. Experimental procedure

2.1. Material

The material used in this study, Al-11%Si aluminum die casting alloy, was purchased commercially. Its chemical composition is shown in Table 1.

2.2. Squeeze casting process

The material was melted in an electrical resistance furnace. The melt was kept at 750 ℃ for 60 min, and the mold cast was preheated to 250 ℃. The squeeze casting experiment was performed on a hydraulic press consisting of steel mold (Fig. 1), where the pressure on the molten metal was kept constant until the end of solidification. In gravity casting, the molten metal was poured directly into the mold without external pressure. The device was also equipped with a system which provided temperature regulation of the mold. The punch-and-die set was made of hot-die steel, and the cast billets were cylindrical in shape of 23 mm in diameter and 120 mm in length. Three pressures were tested: 0, 40, and 110 MPa.

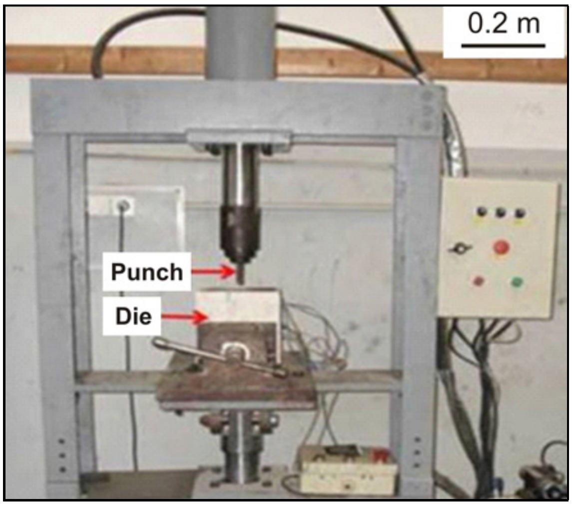

Fig. 1. Experimental setup with steel mold used in the squeeze casting process.

2.3. Heat treatment

Some specimens were subjected to heat treatment T6 consisting of solution treatment and aging treatment. Firstly, the solution treatment was performed at 540 ℃ for 8 h and then the specimens were quenched into the water at room temperature. The aging treatment was then carried out at 160 ℃ for 4 h.

2.4. Microstructural analysis

The gravity die cast, and the squeeze cast pieces were cut from the middle into small cylindrical specimens to investigate the effects of applied pressure and the heat treatment on the microstructure. After polishing and etching with OPS solution of 0.05 micron, a series of optical micrographs were captured using an optical microscope. The image analysis, i.e. the calculation of the SDAS of the α-Al phase, was performed using Image-J software. The SDAS was defined as the length of primary dendrite divided by the number of secondary dendrite arm. The specimens were then analyzed using an LEO 435VP scanning electron microscope (SEM) equipped with energy dispersive spectrometry (EDS). The X-ray diffraction (XRD) was used to identify the intermetallic phases.

2.5. Tensile test and hardness measurement

To evaluate the tensile properties of the gravity and squeeze cast specimens, the tests were performed at room temperature under an MTS 810 universal ten-

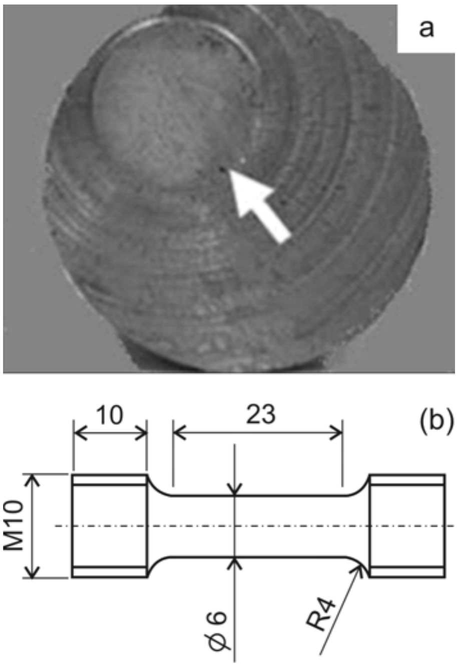

Fig. 2. The dimensions of the tensile test specimen (mm).

sile testing machine. As shown in Fig. 2a, tensile test specimens were taken and machined from the edge location of cast billets. The geometry of complete specimen is displayed in Fig. 2b. The tests were conducted under displacement control with a strain rate start at $10^{-3}\,\mathrm{m\,s^{-1}}$. For each casting condition, three specimens were tested, and the mean results were reported.

Microhardness analysis HV was performed on a transverse section of the polished specimen. The measurements were taken using an MEKTON Vickers Hardness Tester applying a load of 0.3 kg for 10 s. Ten measurements were taken for each condition, and the average value was determined.

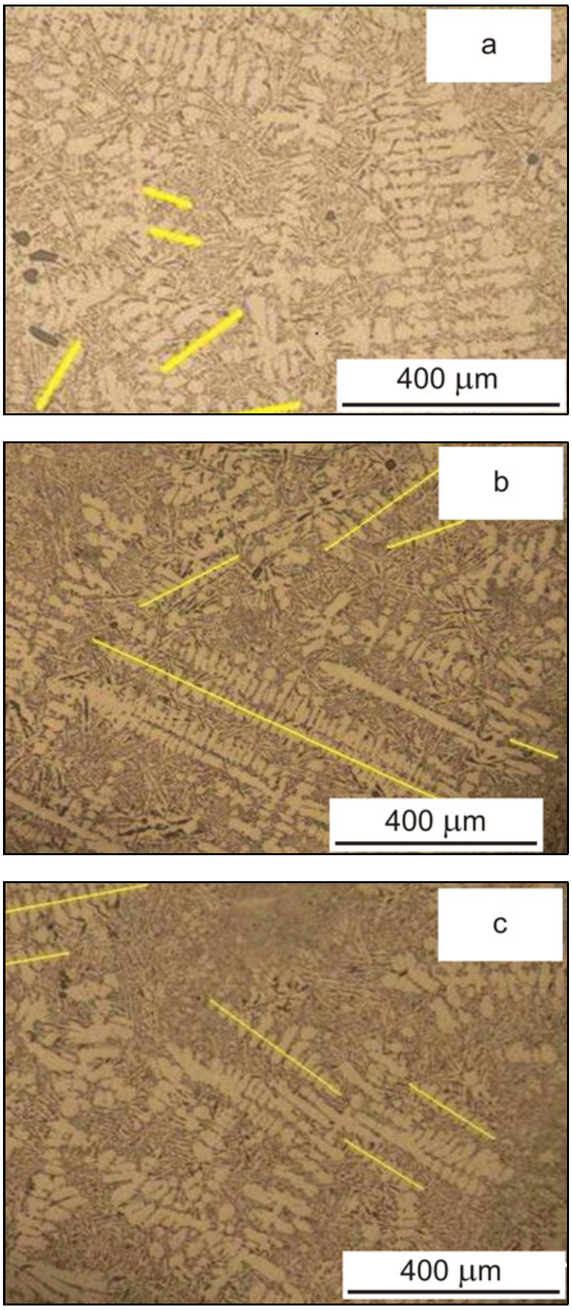

Fig. 3. Microstructure of Al-11%Si alloy in as-cast conditions: (a) $P = 0$ MPa (gravity die cast), (b) $P = 40$ MPa, and (c) $P = 110$ MPa.

3. Results and discussion

3.1. Microstructure of as-cast alloy

The microstructures of gravity die casting and squeeze casting of near-eutectic Al-11%Si alloy obtained for different pressure levels are shown in Fig. 3. It can be seen that the microstructures in gravity specimen (0 MPa) present two main constituents: a primary α phase Al-rich seen as light dendritic areas and a eutectic matrix of α phase and silicon particles seen as darker areas in the micrographs. Applying pressure on molten metal during solidification was found to decrease and eliminate the air gap between the solidified metal and mold after the formation of the first solidified layer, and to increase intensively heat transfer rate between solidified metal and mold [15]. These features of squeeze cast process considerably change the morphology of eutectic silicon particles, which can be seen in this figure. This change results from the increase of the solidification rate, and, therefore, decreases dendrite arm spacing (DAS). The results show that the grain size of the alloy decreases with the increase of the squeezing pressure as shown in Table 2. Souissi et al. [16] have studied Al-13%Si alloy and found that the dendrite size of the alloy decreases with the increase of the squeezing pressure in the center and

Table 2. Average grain size of the cast specimens under various conditions

Applied pressure (MPa)	Average grain size (µm)
0 (gravity)	74.213
40	53.499
110	31.428

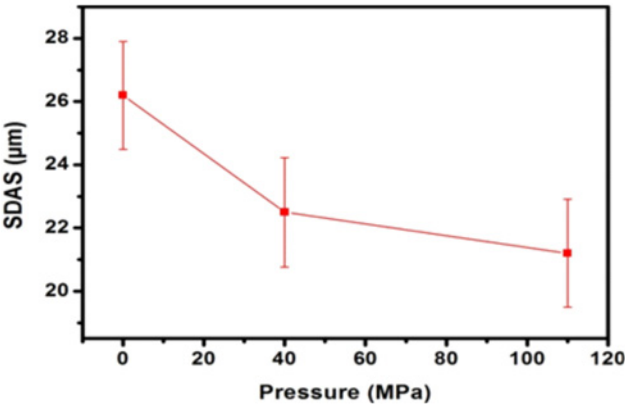

Fig. 4. The average measured SDAS as a function of applied pressure in squeeze casting.

the edge of specimens. Furthermore, the inter-metallic phases in the alloy with no applied pressure are coarser than those under high squeezing pressure. The applied pressure influences the as-cast microstructure. This effect can be justified by the equation suggested by Ghomashchi and Vikhrov [17]:

$$P = P_0 \exp\left(\frac{-\Delta H_\mathrm{f}}{RT_\mathrm{f}}\right). \quad (1)$$

The above equation shows that an increase in the freezing point (T_f) of the alloy is caused by the increase in pressure (P). In this equation, ΔH_f is the latent heat of fusion and P_0 and R are constants. Increasing the freezing point causes undercooling in the alloy that is already superheated. The higher freezing point brings about the larger undercooling in the initially superheated alloy and thus elevates the nucleation frequency, resulting in a more fine-grained structure.

Besides, the average values of the secondary dendrite arm spacing of aluminum alloy were found to decrease with the increase of the applied pressure. The low values of SDAS are the most important factor in squeeze casting, which induces better mechanical properties and improves micro and macro structural characteristics compared with the conventional ones [17].

Figure 4 shows that when the applied pressure increased from 0, 40 and 110 MPa, the average SDAS decreased to finer scale and was found to be 26.2, 22.5 and 21.2 µm, respectively. The reduction of SDAS can be attributed to the increase in cooling rate, which occurs in the higher heat transfer coefficient due to the good contact between the melt and the die [18]. However, the evolution of SDAS confirms that the microstructures of squeeze cast specimens, which were prepared under higher applied pressures (Fig. 3c), are much finer. Consequently, it is clear that the applied pressure has a significant influence on the microstructure of the Al-11%Si alloy. This result is comparative to the squeeze cast LM13 alloy studied by Maleki et al. [15]. It was found that when the applied pressure increased from 0 to 211 MPa, the SDAS decreased from 47 to 34.2 µm, respectively.

3.2. Microstructure after heat treatment

It is known that solution treatment leads to the spheroidization of eutectic silicon. T6 heat treatment was performed on the squeeze cast Al-11%Si alloy and the typical optical microstructures are shown in Fig. 5. According to this figure, the morphology of the microstructure obviously changed after T6 heat treatment. It can be noted that the coarsening of aluminum grains besides the Si particles broke down into smaller fragments and became gradually spheroidized. A similar result of gravity die cast of A356 aluminum alloy was reported in the literature [13]. As it can be seen from this microstructure, the spheroidization and coarsening of the discontinuous phase occur at elevated temperatures. This can be explained by the fact that the interfacial energy of a system decreases with the reduction in interfacial surface area per unit volume of the discontinuous phase. The reduction in interfacial energy is the driving force for the spheroidization and the coarsening processes which are also diffusion-controlled [19]. This result is the effect of T6 heat treatment; when this alloy is solution treated at 540 °C for 8 h, all precipitates dissolve into a single structure. The subsequent quenching forms a supersaturated solid solution at room temperature and traps excess vacancies and dislocation loops which can later act as nucleation sites for precipitation. While aging, the precipitates form more quickly at elevated temperature, typically from 150 to 210 °C [20]. Thus, the changes in the size and morphology of the silicon discontinuous phase are significant since they have a direct influence on the tensile properties. The processes occurring during the heat treatment, therefore, have an opposite effect on the number of particles per unit area eutectic structures. Consequently, the morphology of eutectic Si plays a vital role in determining the mechanical properties of Al-Si alloys [21, 22].

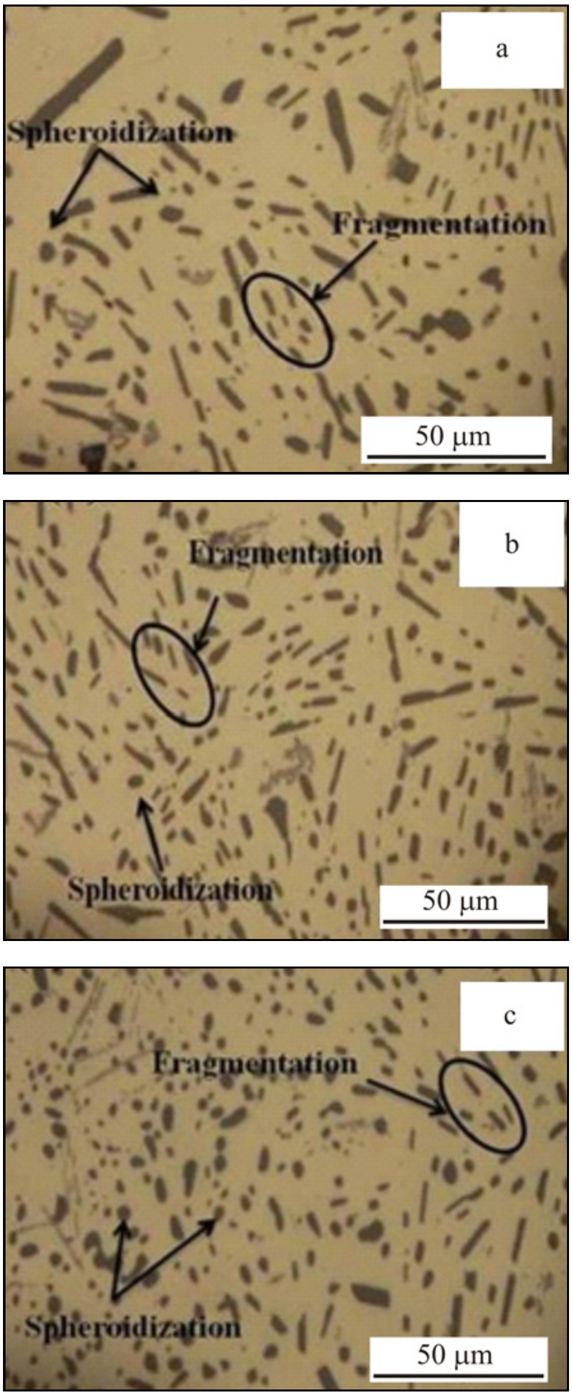

Fig. 5. Microstructure of Al-11%Si alloy in T6 condition: (a) $P = 0$ MPa (gravity die cast), (b) $P = 40$ MPa, and (c) $P = 110$ MPa.

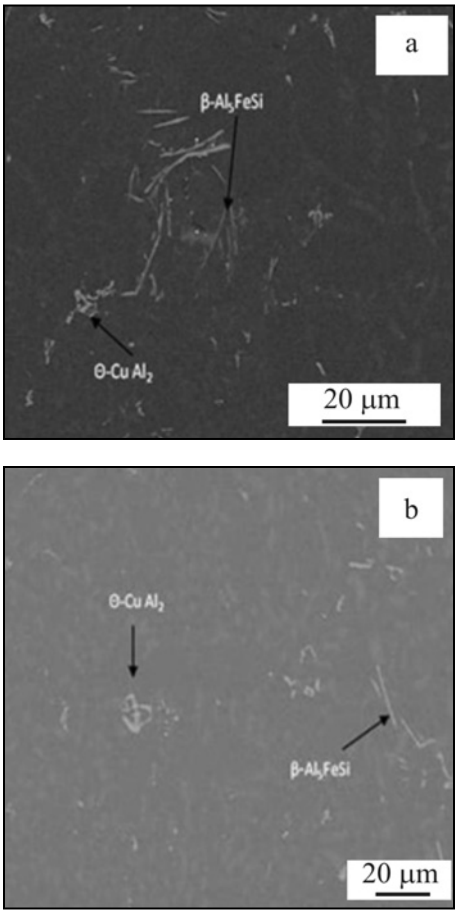

Fig. 6. SEM image of Al-Si alloy: (a) as-cast alloy at 110 MPa, (b) 110 MPa in heat treated conditions.

The identification of the intermetallic phases of the squeeze cast alloy under 110 MPa before and after heat treatment was realized firstly with the help of SEM (see Fig. 6). SEM micrographs show that the θ-Al_2Cu phases (the clearest phase) are around the very fine needles of β-Al_5FeSi phase. The comparison between the two states shows that the amount of β phases declines depending on the heat treatment. However, after heat treatment, the number of θ phases increased (Fig 6b). The needle-shaped β phases have negative effects on the mechanical properties. The existence of the θ phase and the refinement of α-Al phase caused an improvement in the mechanical properties [23].

The results of SEM were confirmed with X-ray Diffraction (Fig. 7). Four phases were found in all samples and identified to be α-Al solid primary phases, θ-Al_2Cu, eutectic silicon particles Si and β-Al_5FeSi phases, which is consistent with other reported studies [24–26].

3.3. Tensile properties

Ultimate tensile strength (UTS), yield strength (YS) and elongation percent (El %) belonging to the gravity die cast and squeeze cast alloy with different pressure levels of the as-cast and heat treatment states are shown in Fig. 8. The results show that the tensile strength and elongation of the alloy increase with the increase in the applied pressure. The UTS value of the specimen cast under 110 MPa is 231.2 MPa and

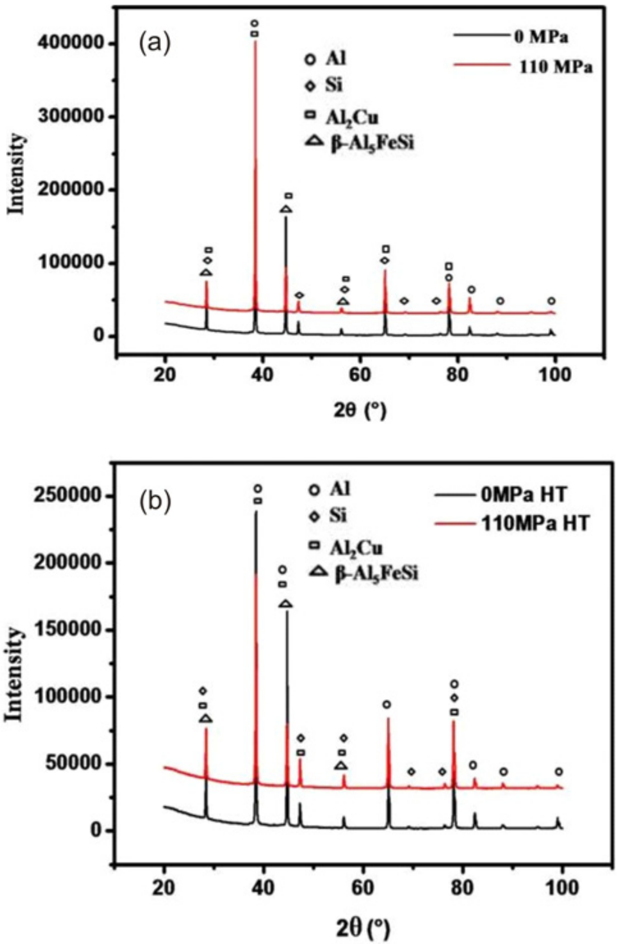

Fig. 7. XRD test results of Al-11%Si alloy at 0 MPa and 110 MPa in as-cast (a) and heat treated conditions (b).

gravity die casting is 198.2 MPa. As for the elongation values, they are at least 2.8 %, with a maximum of 6.8 % improvement over gravity die casting. This can be attributed both to the lack of porosity and fine SDAS.

It is well known that the mechanical properties of cast part are dependent on the existence of entrapped gas or shrinkage pores, large needle-like iron aluminide intermetallic compounds, uniform grains, and SDAS values throughout the entire region. However, in this study, the improvement in elongation is much more significant compared to tensile strength. In normal casting condition, Si particles have a rather coarse needle-shaped morphology which can act as crack initiator resulting in lower ductility [27]. The improvement of ductility with the increasing squeeze pressure may be explained by the altered eutectic Si morphology, increased volume fraction of a primary phase and the elimination of pores.

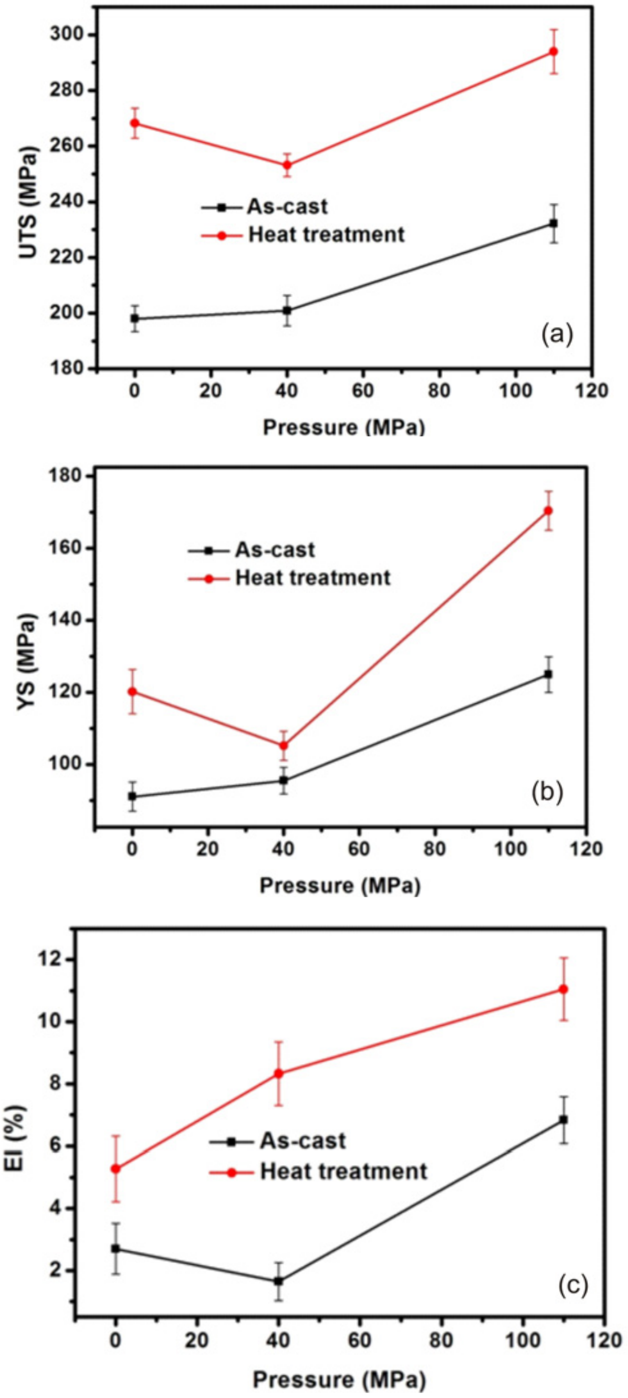

Fig. 8. Mechanical properties: ultimate tensile strength UTS (a), yield strength YS (b), and elongation El % (c) of investigated alloy.

As shown in Fig. 8, the results of the as-cast compared with those of heat treatment have shown that the enhancement of strength properties obtained during the aging treatment is primarily owing to the metastable phase from the supersaturated solution [28]. The change of the morphology of the Si from acicular to spheroidized shape improves the mechanical properties [29–31]. Therefore, the eutectic Si morphology plays a vital role in determining the mechanical properties. The particle size, shape and spac-

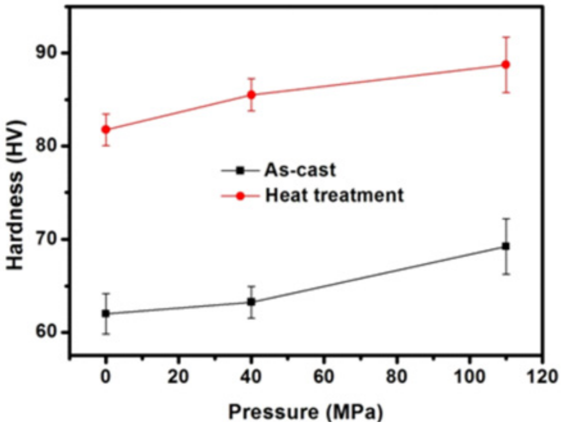

Fig. 9. Graphical representation of hardness values of Al--11%Si alloys in as-cast and heat treated conditions.

ing are factors that characterize Si morphology. Under normal cooling conditions, Si particles are present as coarse acicular needles which act as crack initiators and lower mechanical properties. The Si particle characteristics can be altered by subjecting the casting to a high heat treatment for long periods. Thus, for prolonged solution treatment, the observed change in tensile properties is attributed to the change in Si particle characteristic [30, 32, 33].The present results, therefore, agree quite well with the results reported in the literature. After testing traction, the low percentage of elongation to 40 MPa pressure can be explained by the existence of many defects. So, porous microstructures cause a weaker elongation compared to the other pressures.

3.4. *Microhardness*

Figure 9 shows the graphical representation of microhardness measurements of Al-11%Si alloy in various pressure levels before and after T6 heat treatment. It is obvious that increasing the pressure in the alloy increases the microhardness with or without heat treatment. The microhardness values of as-cast samples increased from 62 HV for the sample solidified under atmospheric pressure to about 70 HV at an external pressure of 110 MPa. This can be explained by the sudden increase of cooling rate caused by the improved contact between the metal and the die surface. It is postulated again that 110 MPa is the external pressure at which a complete contact between the metal and die surface is realized.

It is also shown that the microhardness of the alloy increases remarkably after T6 heat treatment, which may be accredited to the refinement of the microstructure and modification of eutectic silicon particles as well. The same results are confirmed by Abou El-Khair [7].

4. Conclusions

In this study, the effects of applied pressure during solidification and T6 heat treatment on the microstructure and mechanical properties of squeeze cast Al-11%Si alloy were investigated. The results have shown that the application of pressure has a significant effect on the morphology of the phases. The SDAS was found to increase with the increase in squeeze pressure. On the other hand, the morphology of T6 heat treated Al-11%Si microstructure is modified and changes the morphology of eutectic silicon. The eutectic is converted into fine spheroidized Si phase uniformly distributed in the aluminum matrix. The applied pressure and the T6 heat treatment have shown an improvement in the mechanical properties, which can be due to the enhancement of the mechanical strength (UTS), elongation (%) and yield strength (YS) seen as an increase in the microhardness test result.

Finally, the T6 heat treatment and pressure give a good combination for microstructure observation and an enhancement of mechanical properties of the gravity cast and squeeze cast Al-11%Si alloy.

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