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An investigation on the microstructure and tensile properties of direct squeeze cast and gravity die cast 2024 wrought Al alloy

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ABSTRACT

2024 aluminum alloy, conventionally is used for wrought products. If this alloy is subjected to cast process, a large number of shrinkage porosities will be produced within its microstructure due to its long solidification range. Therefore, in order to see the effect of pressure on the microstructure and reduction of shrinkage porosities of this type of alloy, the effect of squeeze pressure on the microstructure and tensile properties of the alloy was investigated in this research. The results showed that, squeeze casting caused the refinement of the microstructure and reduction in the DAS of the cast structure possibly due to increasing the cooling rate. Increasing the squeeze pressure also led to formation of finer microstructure. Furthermore, higher pressures decreased the percentage of porosity and increased the density of the cast alloy. The ultimate tensile strengths of the squeezed cast samples improved when the squeeze pressure increased.

1. Introduction

Squeeze casting is a general term to specify a fabrication technique where, liquid metal is fed into a permanent die and pressure is applied via a hydraulic ram until solidification is complete [1]. Other terms used to describe the same or similar processes are liquid metal forging, extrusion casting and pressure crystallization [2]. Squeeze casting has a number of advantages over sand-casting and gravity die casting.

The high pressure used in this process, reduces the degree of microsegregation [3] and leads to excellent feeding of solidification shrinkage and a refined microstructure, both of which result in excellent mechanical properties [1,4]. In addition squeeze cast components have superior weldability, electrical conductivity and surface finish [5–7] and also show improved response to heat treatment [8]. However, the majority of components are currently squeeze cast from conventional Al–Si casting alloys such as the sand-casting alloy A356 and the piston alloy (A332). It has been reported that the pressure applied during squeeze casting also allows wrought Al alloys, particularly the heat-treatable 2000 (Al–Cu), 5000 (Al–Mn–Mg), 6000 (Al–Si–Mg), and 7000 (Al–Zn–Cu–Mg) group, to be cast to shape to give high-strength, ductile components [1,9–11].

For example, Chadwick and Yue [1] have shown that squeeze cast 7010 alloy has a UTS of 551 MPa and a ductility of ~12.2%, similar to the UTS and ductility of the same alloy in the wrought condition. Despite the above mentioned advantages few studies have investigated the effect of processing parameters on the resulted microstructure [9].

This work presents results of the study on microstructures and tensile properties of a 2024 Al alloy manufactured via direct squeeze and gravity die casting and the correlation between their characteristics and applied pressures.

2. Experimental procedure

2.1. Material

Material used in this study, was a 2024 wrought Al alloy and had the composition shown in Table 1. The alloy has high strength in the heat treated condition and is commonly used in wrought condition for aircraft structural components. The alloy has also a relatively long freezing range [12].

2.2. Casting method

A cylindrical H13 tool steel die with an internal radius of 30 mm, external radius of 65 mm and a height of 170 mm, used for preparing cast samples. The die was preheated up to 250 °C and the melt was poured into the die at 750 °C. A hydraulic ram was used for applying pressure to the melt, in the case of squeeze casting, until solidification was completed. The effect of applied pressure and its variation on microstructure and mechanical properties of the alloy, was investigated. The manufacturing conditions of prepared samples are presented in Table 2.

2.3. Microstructural analysis

To investigate the effect of applied pressures on the microstructure, each sample was prepared and etched with Keller's reagent [13]. Quantitative microstructural analysis and DAS measurement was carried out using an OMNIMENT image analyzer. In order to measuring DAS of the samples, the lengths of primary

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Table 1
Chemical composition (wt%) of the alloy used in this work

Al	Cu	Mg	Si	Mn	Zn
Remainder	4.3	1.14	0.42	0.32	0.09

Table 2
Process conditions of the samples

Casting condition	Die preheating temperature (°C)	Pouring temperature (°C)	Applied pressure (MPa)
Gravity			No pressure
Squeeze	250	750	30
			50
			70

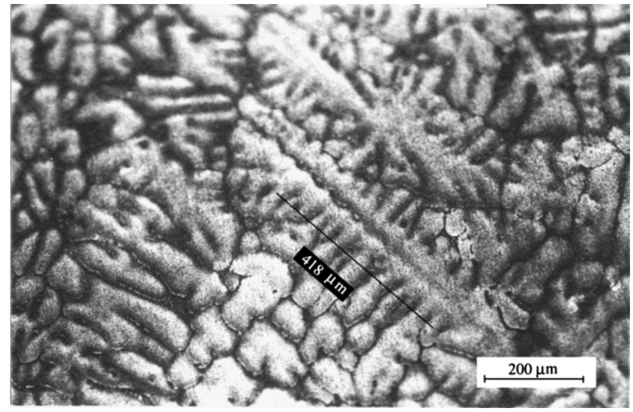

Fig. 2. Micrograph of a typical gravity cast sample.

dendrite's arms were measured in three different points of microstructure. Then by dividing these lengths to number of secondary dendrite's arms, DAS values were calculated and the mean and rounded results of three measurements are reported here as DAS, in different processing conditions. Fracture study was also carried out on samples using JEOL electron microscope.

2.4. Density measurement

The gravity and the squeeze cast samples, fabricated in various applied pressures, were assessed for their specific weight using the Archimedes principle.

2.5. Tensile tests

To evaluate mechanical properties of the gravity and squeeze cast samples, tensile tests were carried out on specimens having 10 mm diameter and gauge length of 50 mm using an Instron-5564 tensile test machine at a crosshead speed of 1 mm/min. To eliminate the effect of time delay after pouring and before pressurizing, that may led to partial solidification of metal under gravity condition, all of tensile specimens were taken from the center of cast billets. For each casting conditions three specimens were tested and the mean results are reported. Fig. 1 shows 2024 aluminum alloy cast billets and the specimens used for tensile tests.

3. Results

3.1. Microstructure

Fig. 2 shows the microstructure of a gravity cast sample that contains coarse size dendrites. Micrographs (a–c) in Fig. 3, show the microstructure of squeeze cast samples that were produced under 30, 50 and 70 MPa pressures, respectively. These micrographs show that the microstructures of squeeze cast specimens, prepared under higher applied pressures, are much finer. The results of DAS measurements are presented in the Table 3. These results indicate that the DAS in squeeze cast samples are smaller in comparison to the gravity cast samples.

Fig. 4a shows the SEM micrograph of typical fracture of the gravity cast specimens. Casting defects such as shrinkage porosities are visible on the fracture surface. Fig. 4b shows typical dendrites shape and size formed within the microstructures of the gravity cast sample. Porosities within the microstructures of the squeeze cast samples were not seen on the fracture surface or they were relatively rare and/or very small.

3.2. Density

The specific weight of the specimens, corresponding to different processing conditions, are shown in Table 4. Results presented in this table indicate higher densities in the samples produced by squeeze casting. The density difference between the samples cast at 50 and 70 MPa pressures is not appreciable.

3.3. Tensile strength

Fig. 4 shows a bar graph of the UTS of the gravity and squeeze cast samples. This chart shows the gravity cast samples has the lowest UTS compare with the squeeze cast samples. Increase of density with squeeze pressure (see Table 4) shows a good synchronized effect with increasing strength (see Fig. 5) in the same group of the samples relative to the sample produced by gravity cast.

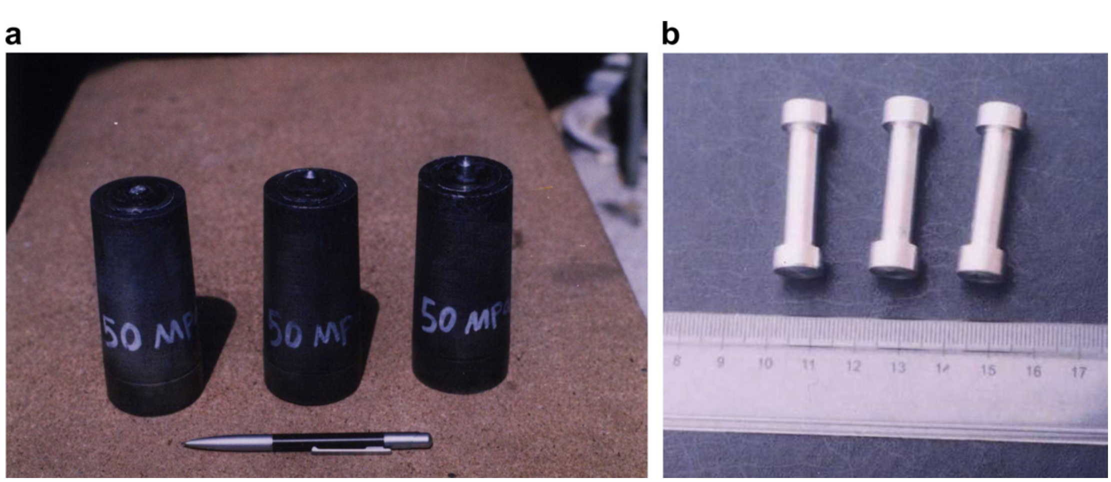

Fig. 1. (a) Prepared 2024 aluminum alloy cast billets, (b) tensile test specimens taken from cast billets.

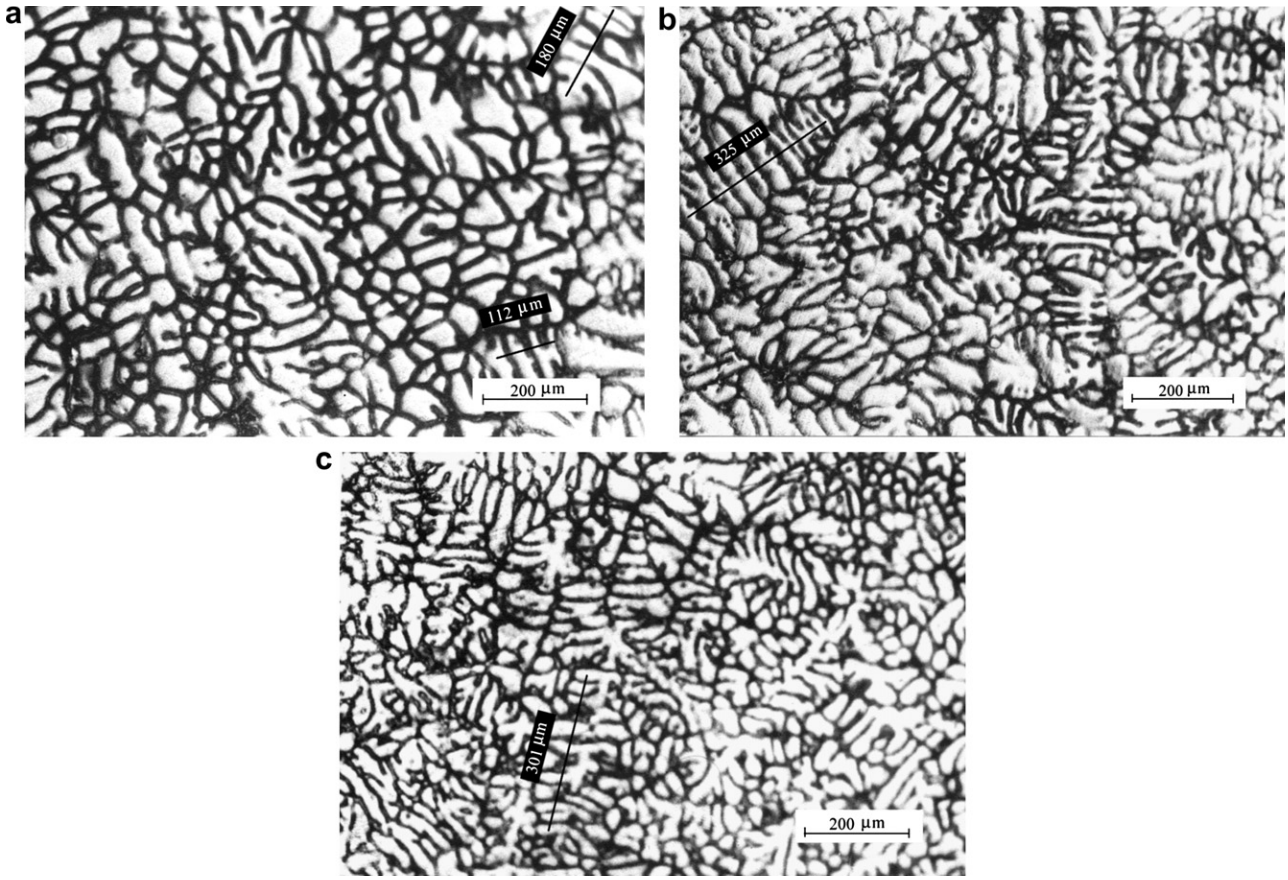

Fig. 3. Micrograph of the squeeze cast samples, (a) 30 MPa, (b) 50 MPa and (c) 70 MPa applied pressure.

Table 3
The average measured DAS in various casting conditions

Casting conditions	DAS (μm)
Gravity cast	35
Squeeze cast (30 MPa)	29
Squeeze cast (50 MPa)	27
Squeeze cast (70 MPa)	25

4. Discussion

4.1. Microstructure

The results of this research showed that application of high pressure on the melt influences the microstructure in two different ways. This effect can be justified by the equation suggested by Ghomashchi et al. [5]:

$$P = P_0 \exp\left(\frac{-\Delta H_f}{RT_f}\right) \tag{1}$$

Increasing pressure (P) causes an increase in the freezing point (T_f) of the alloy. In this equation, ΔH_f is the latent heat of fusion and P_0 and R are constants. Increasing the freezing point brings about undercooling in an initially superheated alloy and thus increases nucleation frequency; causing a finer grain size structure [5]. Furthermore, the fine grained structure observed in the squeeze casting specimens seems to be due to increase in cooling rate occurs by the higher heat transfer coefficient as a result of the intimate contact between the melt and the die wall [1,15].

The results of DAS measurement of the gravity and squeeze cast 2024 Al alloy presented in Table 3 and the suggested relation (Eq. (2)) between DAS and C.R. (cooling rate) in Al-3.9–4.5Cu alloys [16], indicates that the cooling rate has been increased by increasing the pressure.

$$DAS = 60\ C.R.^{-0.33} \tag{2}$$

Using this equation, the cooling rate of samples prepared in various applied pressures can easily be calculated. Fig. 6 shows C.R. values as a function of the applied pressure for various samples in this work.

As can be seen in this figure, applying pressure on the melt in squeeze casting process has increased the C.R. values and thus seems to be the main reason for grain refinement of the alloy microstructure.

Fig. 4 indicates that gas and shrinkage porosities and/or a combination of them have formed in the gravity cast condition, due to long freezing range of the alloy. Similar defects were rarely seen in the squeeze cast samples as one may expected. It is also worth mentioning that the effect of pressure and the resulted higher cooling rate on the DAS has to be added to its impact on the refining of probable gas and shrinkage porosities [11,17,18].

4.2. Tensile strength

The results of density measurements in Table 4 indicate that the alloy in the gravity casting condition contained about ~7% porosity. Low tensile strength of the alloy in gravity cast condition can be related to high volume fraction of porosities in its microstructure due to long freezing range and low interdendritic fluidity of the molten metal. The increase of the strength with increasing the pressure up to 50 MPa, seems to be due to decrease in the micropore size and/or the virtual elimination of porosities. This is

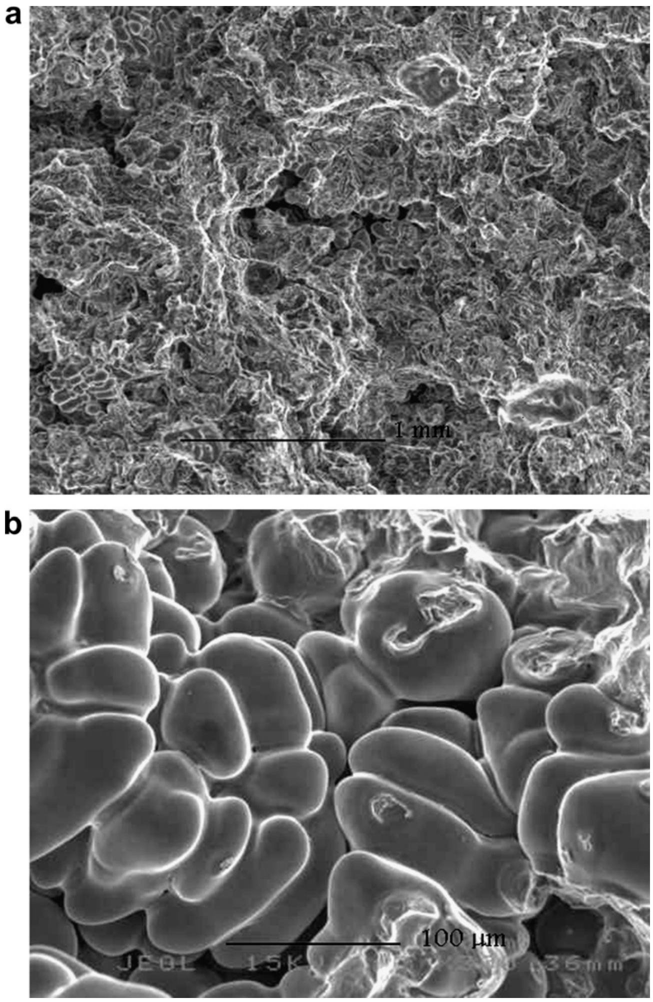

Fig. 4. SEM micrographs showing, (a) a typical fracture surface of gravity cast samples and (b) typical shrinkage porosity within the dendrites structure.

Table 4
The density measurements and porosity percent

	Gravirty cast	Squeeze cast		
		30 Mpa	50 Mpa	70 Mpa
Density (g cm^{-3})	2.588	2.722	2.769[a]	2.778[a]

[a] This values are very close to the nominal density of the 2024 Al alloy [14].

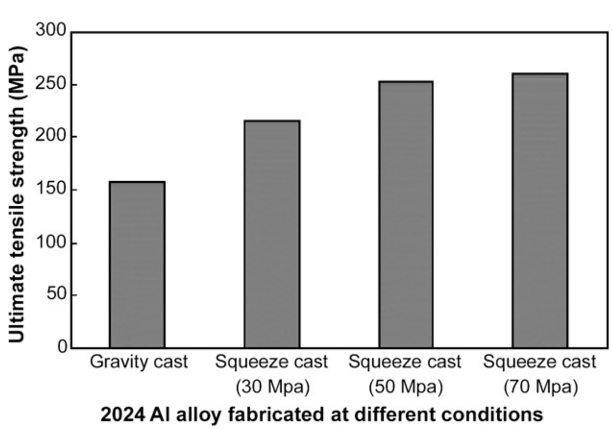

Fig. 5. Ultimate tensile strength of 2024 Al alloy fabricated in various conditions.

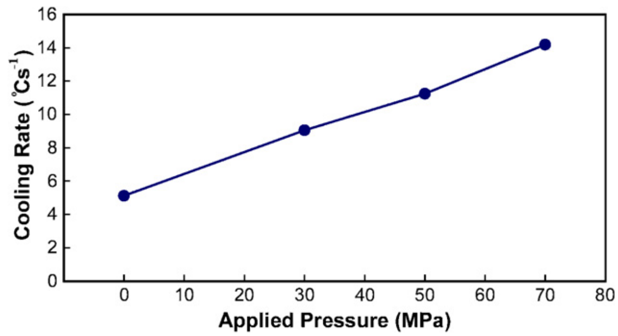

Fig. 6. The effect of applied pressure on the cooling rate of various 2024 Al alloy samples.

in agreement with the results shown in Table 4. Higher tensile strength of the 2024 Al alloy squeeze cast samples up to 70 MPa applied pressure, can be also due to the finer grain size [4] and smaller DAS of the microstructure due to higher C.R. in comparison with other cast samples.

5. Conclusions

(a) The 2024 Al alloy, conventionally used for wrought products, can successfully be cast using direct squeeze casting process.
(b) Squeeze casting of 2024 Al alloy, caused the refinement of the microstructure and the reduction of DAS of the alloy and therefore decreased the porosity and increased the density and tensile properties of the cast alloy.
(c) The elimination of porosities was the main reason for increasing the tensile strength of the alloy up to 50 MPa, however above 50 MPa applied pressure, finer microstructure due to higher cooling rates seemed to be the cause of increase in tensile properties.

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