

Effect of casting parameters on the microstructure and mechanical properties of squeeze cast A380 aluminum die cast alloy

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Abstract

A380 Al-Si-Cu die casting alloy is the most common of all die casting Al alloys and is used especially in the automotive industry due to the best combination of utility and cost. A high percentage of these components are produced by a high pressure die casting process; however, the quality and performance of these components need to be improved. Therefore, different approaches to component-making have been introduced such as semi-solid forming or squeeze casting over the last four decades. In the present study, direct squeeze casting of A380 alloy as a function of applied pressure was investigated. Applied pressures from 10 MPa to 50 MPa were considered and compared with gravity die cast samples. SDAS values ranging from 5.70 μm to 10 μm have been obtained by squeeze casting whereas 13.70 μm was found in gravity die casting. Density measurements and mechanical tests show us that the porosity level and presence of micro-voids were greatly decreased with increasing pressure while ultimate tensile strength and elongation increased in squeeze cast parts.

Key words: squeeze casting, A380 alloy, Al-Si-Cu alloy, dendrite arm spacing

1. Introduction

Lightweight metals are used extensively by the automotive and transport industries, both in wrought and cast forms. Recently the European Aluminum Association (EEA) reported that the amount of aluminum used in new European cars had risen from 50 kg in 1990 to 132 kg in 2005 [1], so it is not surprising to see there is a growing tendency to employ aluminum and aluminum alloys in the automotive and transport industries in the near future. Cast aluminum components are mainly used in chassis and suspension applications, wheels, steering parts, cylinder heads, brake drums, connecting rods, etc. Today, based on data from the EEA, some 73 % of cast alloys go into the transport sector in Europe and due to high production rate and dimensional stability as well as excellent surface finish and high volume production, a large number of these parts are produced by high pressure die casting method. However, the quality of the die-casting products is influenced drastically by the existence of porosity and micro voids which prevent

usage of the components in some advanced applications. In the search for improved alloy properties, a number of casting techniques have been developed and introduced to the market in last four decades, such as semi-solid forming or squeeze casting.

Squeeze casting is a casting method of producing near net shape parts in which the liquid metal charge is forged to shape inside closed dies. It combines the strength and integrity of forging with the economy and design of flexibility of casting. The process originated in the Soviet Union, then in the mid 70's became commercially available for custom manufacture of nonferrous components [2]. The process is also known as "extrusion casting", "liquid pressing" or "pressure crystallization" [3]. Compared with conventional casting techniques, squeeze cast products have a very good combination of strength and elongation, which mainly comes from high density, finer and more homogenous microstructures. Squeeze casting is also regarded as the most popular fabrication route for Metal Matrix Composites (MMCs) [3].

In literature there are numerous publications which

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discuss the advantages of squeeze casting [4–7]. They all report an increase in yield and tensile strength of squeeze cast components compared with conventional methods. Many researchers have carried out research work in the effect of pressure on the mechanical properties of castings. For example, Chatterjee and Das studied LM6 alloy and concluded that mechanical properties were improved by the application of pressure during solidification [8]. Improvements of mechanical properties were attributed to the remarkable decreasing of the secondary dendrite arm spacing and increasing refinement of the eutectic phase. Cast Al6Si0.3Mg alloys were studied by Abou El-khair and it was found that squeeze pressures decreased the percentage of porosity and decreased the grain size of α -Al and modified the Si eutectic [9]. He reported an increasing trend of UTS values from 128 MPa to 132 MPa with the squeeze pressure of 70 MPa to 160 MPa respectively for that alloy. Suzuki, who studied and compared the car wheel of A356 alloy against conventional castings and forging, found that squeeze cast A356 alloy exhibited better physical and mechanical properties than other alloys [10]. Chadwick and Yue have examined LM24 (similar to A380) alloy and reported 126 MPa YS and 133 MPa UTS values as squeeze cast conditions [6], and Ghomashchi and Strafford have found 210 MPa UTS and 2–2.5 % elongation for the same alloy [7]. On the other hand, some researchers have worked on wrought alloys and claimed that wrought products can be squeeze cast with the aid of pressure. Skolianos et al. conducted a research on a heat treatable AA6061 wrought alloy used in structural application [11]. They found that the tensile strength and elongation of the alloy was increased to 179.8 MPa and 15.3 % respectively under 100 MPa applied pressure. Yue reported that application of 50 MPa was found to be sufficient to produce pore-free AA71010 composition squeeze-cast simple cylindrical casting components [12]. Several reports have demonstrated that the mechanical properties of cast Al-Si alloys depend on mainly shape and distribution of eutectic Si phase, secondary dendrite arm spacing (SDAS), type and shape of iron aluminide crystals as well as porosity and entrapped oxide films [13–15]. Many researchers state that change in silicon morphology, reduced SDAS, close to zero porosity and fine grain structure derived from a high cooling rate is the main reason for this improvement in Al-Si squeeze cast products [16, 17]. However, after many years of extensive R&D, there are few comprehensive studies of squeeze cast A380 alloy and any information about the process parameters and resulted properties would be useful to improve the casting technique. In this paper, one of the most common high pressure die casting alloys, A380, was squeeze cast under different pressure levels. The mechanical properties – such as yield strength, tensile strength and porosity levels of

Table 1. Chemical composition (wt.%) of A380 alloy used in this study

Element	Si	Fe	Cu	Mg	Zn	Al
Content (wt.%)	8.73	0.603	3.09	0.216	0.453	Rest.

squeeze cast and gravity die cast samples are compared. The improvement of the properties of squeeze cast alloys and microstructure is discussed.

2. Experimental procedure

2.1. Material

The raw material used in this study was commercially purchased Al-8.73wt.%Si-3.09wt.%Cu aluminum die casting alloy (equivalent to A380) and its chemical composition is shown in Table 1. The A380 alloy family is the most widely used aluminum die casting alloy due to the best combination of material properties [18].

2.2. Alloy preparation

The test specimens were fabricated by squeeze casting using cylindrical H13 tool steel molds with an average internal radius of 66 mm, external radius of 180 mm and a height of 200 mm (Fig. 1). The lower die was mounted on a supporting unit and the upper die was attached to a hydraulic press ram. The steel dies were coated with Zyp Coatings Boron Nitride Aerosol[®] and then air dried. Prior to squeeze casting, the dies were preheated to 150 °C with an electric resistance furnace. About 1 kg of A380 alloy was prepared in a 15 kW Lepel induction furnace using a SiC crucible. The melt was subjected to dross removal at 680 °C and was degassed with a hexachloroethane tablet. After degassing, the temperature rose to 730 °C to enable the metal to have sufficient superheat to avoid premature solidification in the die cavity, then the melt was poured into the lower die.

2.3. Casting conditions

For the gravity die cast, a two part steel die was used. The die was preheated to 150 °C, which was the same as the temperature for the dies used in squeeze casting and coated with Boron Nitride Aerosol. The same alloy was melted in the Lepel induction furnace and after degassing the liquid metal was poured into the preheated die cavity. The cast piece was allowed to remain in the steel die for about 10 min and then removed.

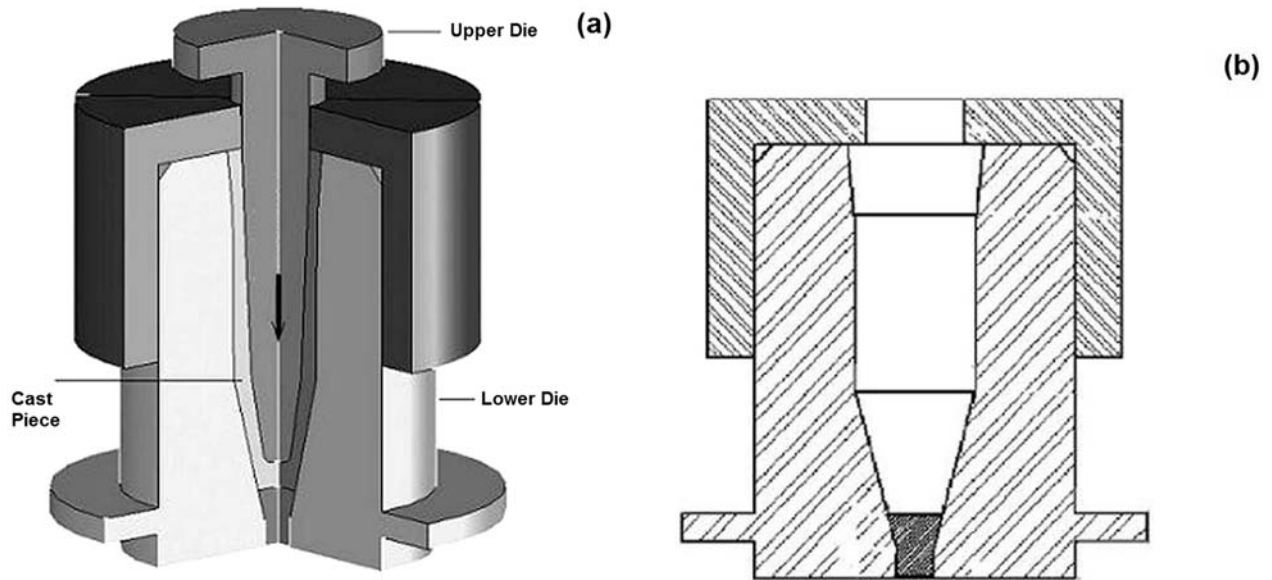


Fig. 1.(a) Schematic representation of squeeze casting process and (b) cross section of lower die.

Squeeze casting was done in a 100 ton hydraulic press. The upper die was lowered into the lower one for heating and just before the casting process it was withdrawn. Then the prepared liquid metal was poured into the lower die and the required squeeze casting pressure was applied for 30 s, long enough for solidification. The cast piece was removed from the mold with the assistance of an ejector at the bottom of the die. To investigate the effect of applied pressures on the microstructure and properties of A380 alloy; 10, 30 and 50 MPa pressures were considered.

2.4. Microstructural analysis

The gravity die cast piece was cut into small cubic specimens and the squeeze cast pieces were cut into four parts longitudinally to investigate the effect of applied pressure on the microstructure. Specimens were etched with Keller's agent after polishing for a period of 30 s. A SDAS measurement was carried out using a LEICA image analyzer. A fracture study of tensile test specimens was carried out on a JEOL JSM 5410 LV electron microscope.

2.5. Porosity measurement

The amount of porosity was measured using approximately $1 \times 1 \times 2 \text{ cm}^3$ specimens for each casting method with the Archimedes' principle as described by Taylor et al. [19]. According to pycnometry theory, the density of an object can be found by using a liquid with well-known density, such as water. Taylor et al. recommended three weight measurements: W_s is dry-weight sample measurements, W_{sb} is buoyant-weight sample plus basket measurements, and W_b is buoyant-

-weight basket measurements. Then, the porosity in percent can be computed as given below:

$$P = 100 \left(1 - \frac{\rho_L}{\rho_{th}} \frac{W_s}{W_s - (W_{sb} - W_b)} \right), \quad (1)$$

where ρ_L is the density of the liquid and ρ_{th} is the theoretical value of the porosity-free density of the alloy.

Five specimens were taken at different regions in the middle of the casting pieces for all casting methods so that the effects of other parameters were eliminated. Solidification simulation of the squeeze casting process was also done using NovaFlow & Solid casting simulation software to predict the amount of porosity at various pressure levels and then compared with the actual data.

2.6. Tensile test

For comparison of the tensile properties of the gravity die cast and squeeze cast pieces, three specimens were taken from the middle of both castings for the tensile test which was performed in a Mohr-Federhaff machine with 5000 kg maximum load and at a tensile rate of 10 MPa s^{-1} . The size of the test specimens corresponded to the EN 10002-1 standard for the $6 \times 10 \text{ mm}^2$ test specimens.

3. Results and discussion

Typical microstructures of sand casting, gravity die casting and squeeze casting of A380 alloy obtained from different pressure levels are shown in Fig. 2. It

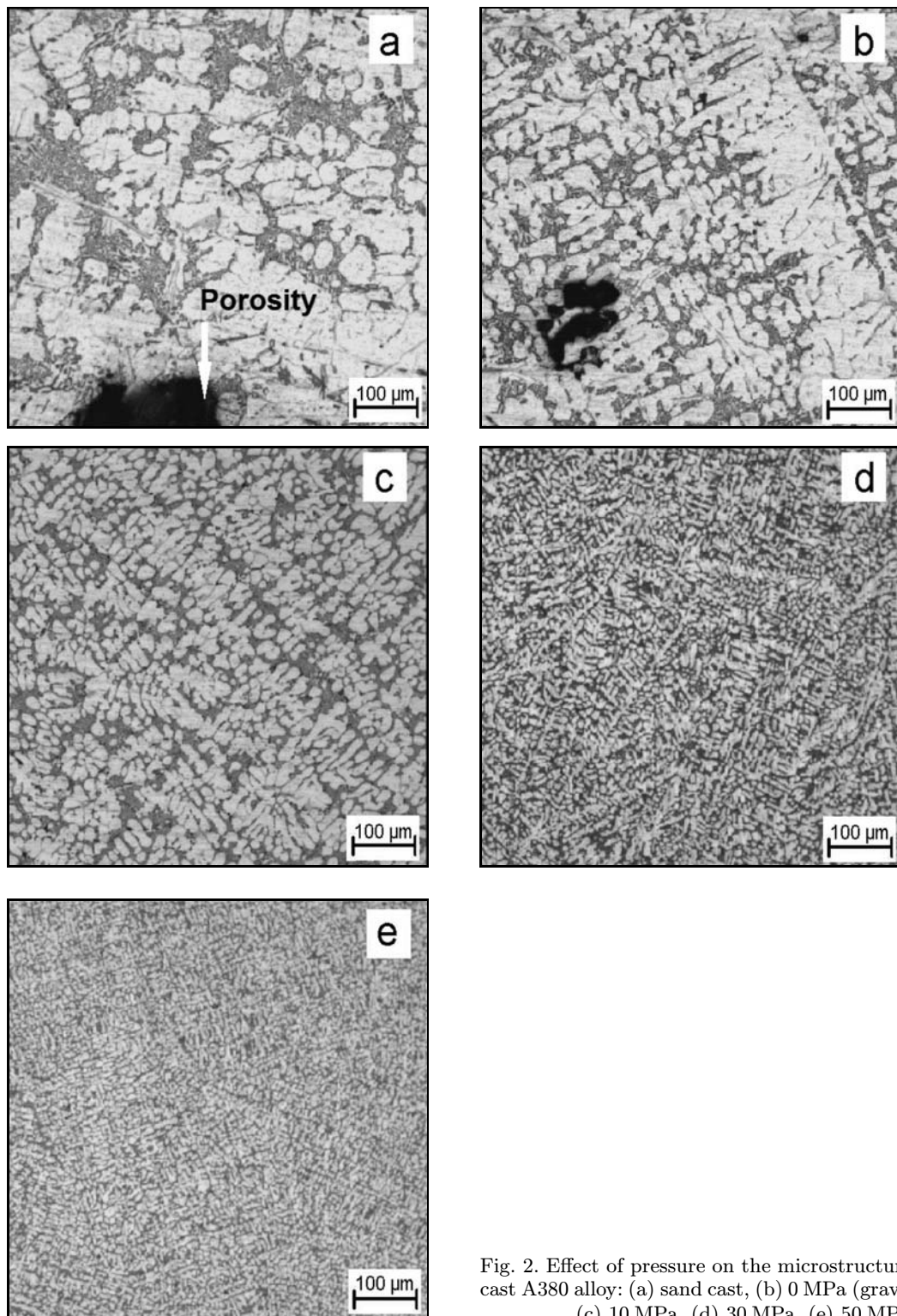


Fig. 2. Effect of pressure on the microstructure of squeeze cast A380 alloy: (a) sand cast, (b) 0 MPa (gravity die cast), (c) 10 MPa, (d) 30 MPa, (e) 50 MPa.

can be seen that the pieces produced from the squeeze and the gravity die casting processes present α -Al dendritic type morphology with Si eutectic across the cast section. As shown, the average SDAS values of A380 alloy have reduced with the increase in squeezing pressure, which is extremely important because SDAS is the most important factor next to the grain

size and eutectic silicon morphology, which influence the mechanical properties of casting alloys [20]. In addition, dendritic microstructure controls the other microstructural properties such as microsegregation. Figure 3 shows when the applied pressure was increased from 10 to 30 and 50 MPa, average SDAS was decreased to finer scale and was found as 10 μ m,

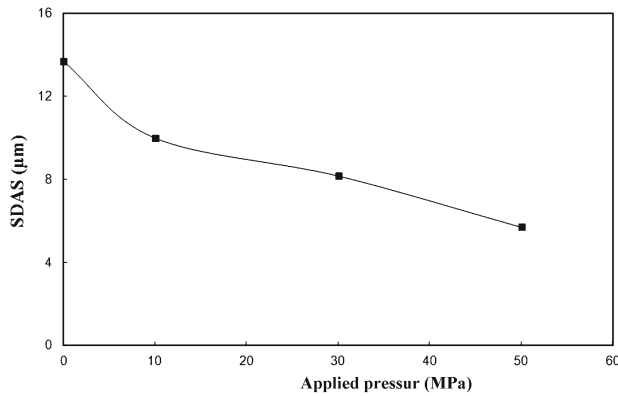


Fig. 3. The average measured SDAS as a function of applied pressure in squeeze casting.

8.17 μm and 5.7 μm , respectively. Reduction of dendritic cell size is attributable to increase in cooling rate which occurs by the higher heat transfer coefficient due to good contact between the melt and die wall, and brings about finer grain size. Microstructure of squeeze and gravity die cast A380 alloy containing 0.603 wt.% Fe shows that some Fe-containing intermetallic compounds such as βAlFeSi distributed along the cast part.

Many cast products have tremendous amount of porosity due to shrinkage voids and air gaps formed between die walls and first solidified parts depending on casting geometry [21]. Shrinkage porosity is a common casting defect which occurs when the solidified region cannot be compensated by liquid metal [22]. However, shrinkage pore, gas pore or air gaps are reduced in squeeze or swage casting by applied pressure which can help the liquid metal to fill into the micropores easier. Moreover, gas solubility in the melt increases under an applied pressure which makes nucle-

ation of gas formation more difficult [3]. On the other hand, prediction of shrinkage or gas porosity in die cast process is not very simple calculation considering the multiple casting parameters such as melt and dies temperature, melt flow, die geometry, etc. Heat transfer between the melt and die wall is very crucial when the boundary conditions are described in solidification model. Heat transfer is usually characterized by heat transfer coefficient which depends on die surface, coatings, die materials, etc. However, among them, air-gap formation due to shrinkage of the solidified casting and expansion of the die, is the key factor which influences the heat transfer. In squeeze casting, the applied pressure during solidification eliminates the air-gap formation, therefore direct contact interfacial heat transfer occurs on the axis of pressure throughout the cast piece. Cho and Hong [24] carried out the experiments on squeeze casting of Al-4.5%Cu and reported that IHTC rapidly increased from 1000 $\text{W m}^{-2} \text{K}^{-1}$ to around 4700 $\text{W m}^{-2} \text{K}^{-1}$ value with the application of 50 MPa pressure. Aweda and Adeyemi investigated heat transfer coefficients during squeeze casting of aluminum and reported that IHTC reached maximum values of 3351 $\text{W m}^{-2} \text{K}^{-1}$ in the bottom flat surfaces at an 85 MPa pressure level [25].

In the present study, solidification of same casting shape was simulated under high pressure by NovaFlow & Solid software to predict the porosity formation. NovaFlow & Solid does not include squeeze casting module but it contains die pressure and high pressure die casting package. The software predicts macro shrinkages with the shrinkage criteria and micro shrinkages with the Niyama criteria. Due to lack of squeeze casting module, the simulations were done by using high pressure die casting package. To use this package, it was necessary to describe pressure point on the cast piece (Fig. 4a). Simulations were conducted at all applied pressure levels and the die material (H13

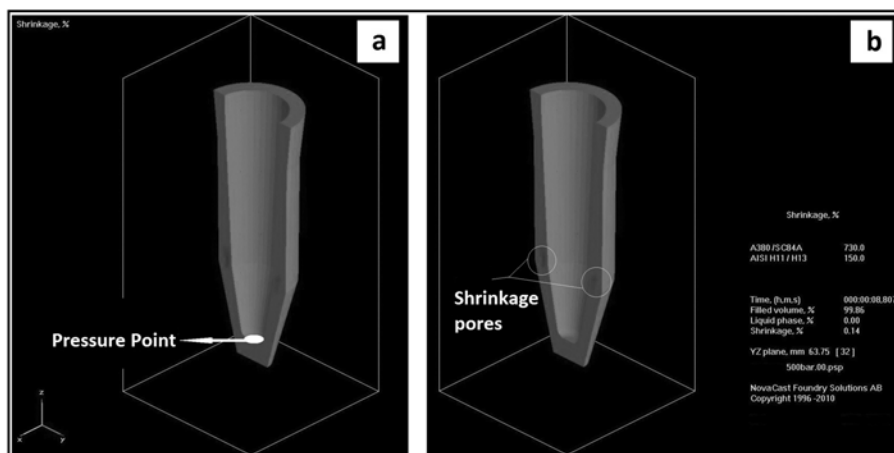


Fig. 4. Defined pressure point of cast part for simulation (a) and calculated shrinkage percent at 50 MPa (b) using NovaFlow & Solid software.

Table 2. Density and porosity percent of cast samples

Process techniques	Gravity die cast	Squeeze cast		
		10 MPa	30 MPa	50 MPa
Density (g cm^{-3})	2.667	2.749	2.752	2.754
Measured porosity, \pm % 4.6**	3.348	0.392	0.265	0.187

* Nominal density of A380 alloy is 2.76 g cm^{-3} [23]

** Expanded measurement uncertainty is calculated at $k = 2$ for 95 % level of confidence

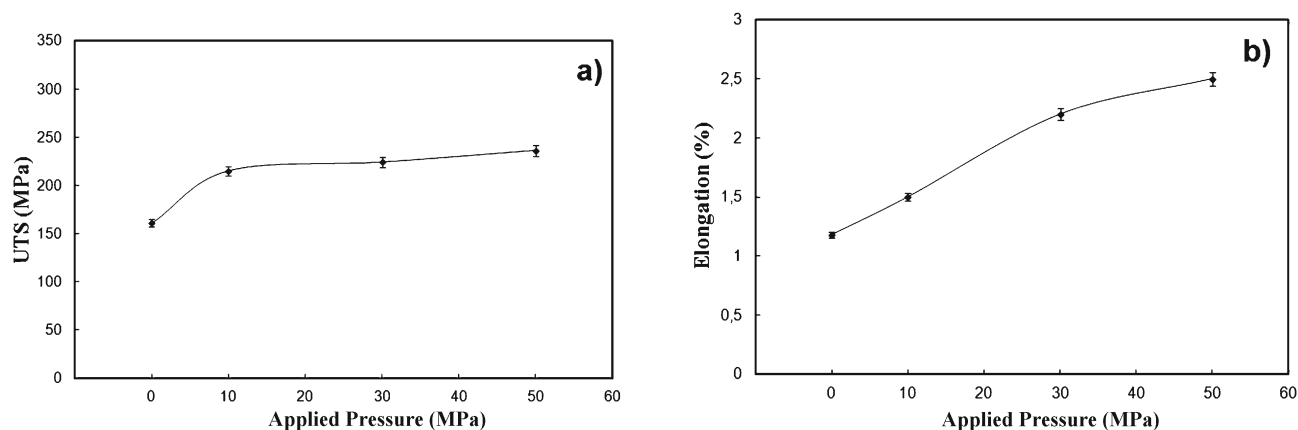


Fig. 5. The effect of applied pressure on the ultimate (a) tensile strength and (b) elongation on the A380 Al alloy.

hot work tool steel) and casting material (A380 Al-Si-Cu alloy) properties were picked up as provided in the NovaFlow & Solid database. All other parameters for simulation were the same as actual casting conditions. The cast piece/die interfacial heat transfer coefficient (IHTC) was calculated as direct IHTC at the contact area between upper die, lower die and the melt and air gap formation at the lateral side of cast piece by NovaFlow & Solid software.

The average density values obtained from gravity die cast and squeeze cast alloys with various pressure levels are shown in Table 2. The final porosity results of simulation are given in Fig. 4b. It is found that simulated porosity values moderately compares with the actual data. In every applied pressure levels NovaFlow & Solid software predicts small amounts of 0.14 % shrinkage porosity at the lower part of cast piece (Fig. 4b). On the other hand, experimental average porosity values are found to be 0.392 % for 10 MPa and 0.187 % for 50 MPa. Although the experimental porosity results are slightly over simulated data, it can be concluded that measured and predicted shrinkage porosity percents are in very close agreement. Lack of gas porosity, shrinkage pores and hot tearing are extremely important because it is widely accepted that tensile strength and elongation of Al cast pieces highly depend on microstructural refinement as well as pores and micro-voids. It is seen that cast piece solidified under atmospheric pressure has substantial amount

of porosity, however, by increasing pressure, average porosity values of squeeze cast alloy reduce dramatically.

Tensile strength and elongation values of specimens belonging to the gravity die cast and squeeze cast alloys with different pressure levels are shown in Fig. 5. The results show us the tensile strength and elongation of the alloy increase gradually with increasing the applied pressure. As shown in Fig. 6, UTS value of specimen cast under 50 MPa is 45 % higher than gravity die casting. As for elongation values, there are at least 27 % and maximum 111 % improvement over gravity die casting. This can be attributed to both of lack of porosity and finer SDAS. Squeeze cast LM 24 (similar to A380) and LM25 alloys were examined and compared with conventional casting by Chadwick and Yue [6] and they found that LM24 in squeeze cast form yielded 233 MPa ultimate tensile strength and 2.7 % elongation. Vijian and Arunachalam also studied the modeling of squeeze cast LM24 alloys and found 270 MPa ultimate tensile strength and 97 HB values for squeeze pressure of 106 MPa and these values are well compared with the data of this study [26]. It is well known that the mechanical properties of cast part are dependent on the very existence of entrapped gas or shrinkage pores, large needle-like iron aluminide intermetallic compounds, uniform grains and SDAS value throughout the entire part. However, in this study, improvement in elongation is

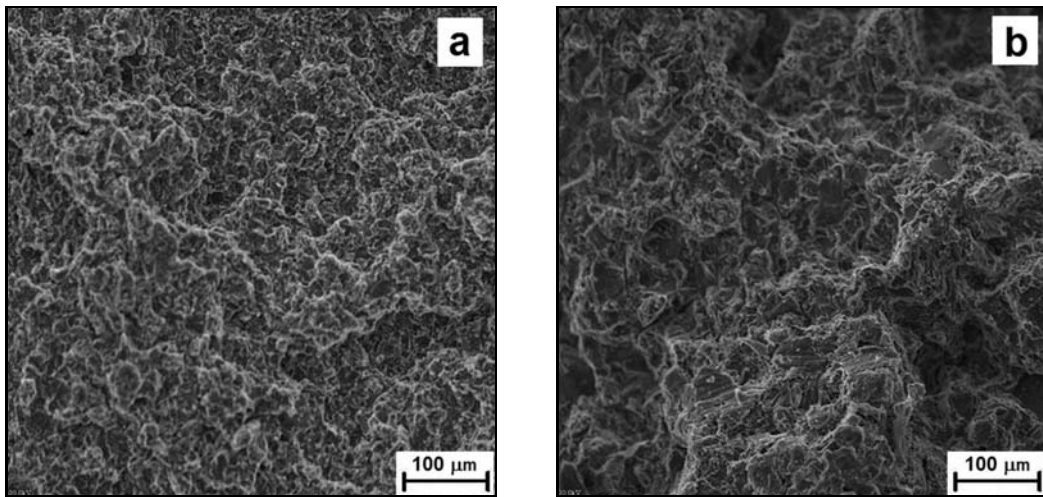


Fig. 6. Fracture morphologies of (a) squeeze cast – 50 MPa and (b) gravity die cast alloys.

much more significant compared to tensile strength. In normal casting condition, Si particles have rather coarse needle-shaped morphology which can act as crack initiator resulting lower ductility [25]. The improvement of ductility with increasing squeeze pressure may be explained by altered eutectic Si morphology, increased volume fraction of a primary phase and the elimination of pores.

Figure 6 presents typical SEM views of fractured surfaces of gravity die cast and squeeze cast alloy. The fractured surface of gravity die cast alloy reveals typical cleavage-fracture mode, on the other hand squeeze cast alloy shows medium developed surface. In addition, there are no signs of gas or shrinkage pores in SEM views of squeeze cast samples. It is worth to say the effect of applied pressure also helps to suppress the nucleation of gas pores.

4. Conclusion

The following results were found in this study that:

(a) The A380 alloy was successfully cast under different pressure level by direct squeeze casting process. Metallographic investigation of squeeze cast specimens indicated that the secondary dendrite arm spacing, SDAS, decreased with decreasing local solidification time due to applied pressure.

(b) It was also observed that porosity-free cast parts (below 0.5 %) were achieved by high pressure in squeeze casting. 50 MPa squeezing pressure was found to be sufficient to produce 99.78 % of nominal density of A380 alloy.

(c) Tensile test results show us that the squeezing process significantly improves the mechanical properties over those of the gravity die casting. For the squeeze casting, 215 MPa, 224 MPa and 236 MPa UTS and 1.5 %, 2.2 % and 2.5 % elongation values were

obtained for 10 MPa, 30 MPa and 50 MPa pressure levels, respectively. Decrease in secondary dendrite arm spacing with high pressure and elimination of porosities in the alloy are concluded as the main reason of improvement in mechanical properties in A380 aluminum alloy.

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