Study on the Effect of Casting Pressure on the Wear Resistance of Al-Si Alloy Prepared by Squeeze Casting

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Abstract. In this research the effect of applied casting pressure at constant pouring and die preheating temperatures on the microstructure and wear resistance of the squeeze cast Al-Si alloy was investigated. The results showed a refinement in the microstructure with increasing of the squeeze pressure. The results also showed that the density of the specimens decreased with application of a 7.5 MPa applied pressure, but it increased steadily for higher pressures up to 53 MPa. Increasing the squeeze pressure resulted in increasing the hardness and decreasing the wear rate. These results were explained based on the densification mechanism brought about by the application of pressure during solidification.

Keywords: Squeeze casting, Wear resistance, Al-Si alloy.

1. Introduction

Squeeze casting has been used for half a century in Russia and is now being exploited in the west. For example, Toyota Motor Company in Japan introduced squeeze cast aluminum alloys wheels into their product line for passenger cars in 1979^[1]. The aluminum alloy 357 (Al-7Si-0.5Mg) was prepared by sand, gravity die and squeeze casting, the properties of the alloy show to be clearly superior. The improvement in ductility is particularly notable^[2,3]. The commercial development of squeeze casting began to take place in Europe, North America and Japan only after 1960 as reported by Dorcic and Verma^[4].

Squeeze casting permanent mold is frequently used to produce safely critical aluminum suspension components. Squeeze cast aluminum components have replaced iron/steel control arms and front knuckles in volume recently. In late 1994, Delphi Chassis System and Casting Technology Company began a joint development program for an aluminum front knuckle conversion slated for application on mainstream passenger cast^[5]. Squeeze casting was selected based on the superior physical and mechanical properties, dimensional capabilities and integrated process controls. Davidson *et al.*^[6] studied fatigue properties for squeeze, semisolid and gravity die casting, fatigue cracks initiated from oxide defects in the squeeze cast castings of Al-7Si-xMg alloys and from both oxide defects and shrinkage pores in semisolid and gravity castings. Despite differences in the microstructures and in the defect populations in the squeeze and semisolid casting, their fatigue properties were similar.

Cay and Kurnaz^[7] studied the tensile and fatigue properties of Zinc-Aluminum (ZA-8, ZA-12, ZA-27) in squeeze and gravity cast forms. The squeeze cast alloys exhibited good fatigue resistance in proportion to the gravity castings.

Squeeze casting, also known as liquid metal forging, is a combination of casting and forging process^[8,9]. The molten metal is poured into the bottom half of the pre-heated die. As the metal starts solidifying, the upper half closes the die and applies pressure during the solidification process. The amount of pressure thus applied is significantly less than used in forging, and parts of great detail can be produced. Coring can be used with this process to form holes and recesses. The porosity is low and the mechanical properties are improved^[10,11].

The aims of the present work is to study the effect of casting pressure or applied pressure at constant pouring and die preheating temperatures on microstructure and wear resistance of squeeze cast samples and comparing it with those of gravity die casting.

2. Experimental Work

2.1 Materials

The Al-Si alloy (AlSi12) was selected since it has very good castability and excellent weldability, because of its eutectic composition

and low melting point of 570°C. The alloy is particularly suitable for intricate, thin walled, leak-proof fatigue resistant casting and good corrosion resistance^[12].

2.2 Gravity Die Casting

The Al-12%Si alloy was melted and poured in die or metallic mold by gravity casting. For each experiment about 200 gm of prealloyed (Al-12%Si) is put in graphite crucible in an electric furnace at temperature 700°C. The melt was poured into a metallic mold which was hot dried before casting operation at 200°C by using drier type (Heracus). The casting was left to cool down in the air. The specimens of prepared alloy had dimensions of 100 mm length, 15 mm in width and 30 mm in height. Table 1 shows the chemical composition of the (Al-Si) alloy.

Table 1. Chemical composition of the DIN1725 (Al-Si) alloy.

Element	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
Wt%	12.1	0.65	0.83	0.2	0.27	0.45	0.02	Remainder

2.3 Squeeze Casting System

2.3.1 Hydraulic Press

Figure 1 shows the hydraulic press with a hydraulic pump. A vertical hydraulic press is used (with a ram 70 mm in diameter) to apply the pressure in a perpendicular direction to the squeeze casting die. The press can apply a hydraulic pressure of (1-70) Kg/cm², with a constant ram speed of 25 cm/min.

Fig. 1. The hydraulic press.

2.3.2 Squeeze Punch

The selected squeeze punch shown in Fig. 2(a,b) was made of low alloy steel, and designed with a hole in its upper part to be fixed to the

ram with two steel bolts. The lower part of the punch is rectangular in shape with a semicircle ends. This lower part is used to squeeze the molten alloy.

2.3.3 Squeeze Die

Figures 2(a,c) show the squeeze die. The die is horizontal, made of low alloy steel and consists of two parts joined by four high temperature resistant steel bolts. This design allows the final squeezed composite casting to be removed from the die easily.

Fig. 2(a). The punch and the die on the press.

(b)

(c)

Fig. 2 (b,c). Schematic diagrams of the squeeze punch and the die (mm).

Figures 2(a, b, c) show the punch and the die on the press table. Table 2 illustrates the chemical composition of the punch and the die material which was done with the portable metals analyzer type 1650 from the ARUN Technology, Germany.

Table 2. Chemical composition of the punch and die steel.

Element	Weight Percent (%)	Element	Weight Percent (%)
Fe	93.9	Co	0.02
C	1.0	Cu	0.585
Cr	2.84	Mo	0.0599
Ni	0.936	Nb	0.01
Si	0.227	Ti	0.02
Mn	0.383	V	0.02
Al	0.0253	Sn	0.04

2.3.4 Squeeze Casting

The Al-Si alloy is melted in an electric furnace at the required weight and temperature using an alumina crucible. The next step is preheating the squeeze casting die to the required preheating temperatures 200°C and placing the die on the table of the hydraulic press. After that checking all required temperatures with digitally calibrated thermocouples and then pouring the molten Al-Si alloy into the die cavity. The pouring temperature that is used for all castings is 700°C. The final step is the application of the required squeeze pressure for 30 seconds at a delay time of 5 seconds and allowing for solidification. The casting pressures that were used for all castings are (7.5, 23, 38, 53) MPa, then removing the solidified casting from the die.

2.4 Tests and Measurements

2.4.1 Microstructure and Hardness Test

A small specimen of alloy (Al-12%Si), (alloy A) and squeeze cast samples (B,C,D and E) were prepared by turning processes in the dimensions of 100 mm length and 15 mm width. Wet grinding operation with water was done by using emery paper of SiC with the different grits (220, 320,500, and 1000). Polishing process was done to the specimens by using diamond paste of size (1µm) with special polishing cloth and lubricant in order to get 1µm surface roughness. They were cleaned with water and alcohol and dried with hot air. Etching process was done to the specimens by using etching solution which is composed of (99% H₂O+1%HF), then the specimens were washed with water and alcohol

and dried. Vickers hardness test was made by using Vickers hardness tester type (Einsingenbei U/M, Mode Z323). Diamond indenter was forced into the surface of the specimen being tested under a static load of (300 mg) for (15) sec. Measurements of the indentation diameter were made in (3-5) readings and the average hardness (VHN) was found.

2.4.2 Density and Porosity Measurements

The weight of squeeze cast samples were measured in air by using sensitive balance type (Denver –max 210 gm) with an accuracy of 0.0001 mg. The volume of cylindrical sample of 20 mm length and 10 mm diameter was calculated. The actual density (ρ_{ac}) can be found from the following equation:

$$\rho_{ac} = \frac{\text{weight}}{\text{volume}} \quad (1)$$

Where:

ρ_{ac} = actual density

The porosity percentage (P%) was measured for the squeeze cast samples by using both the actual density(ρ_{ac}) and theoretical density of reference alloy (ρ_{th}) , using equation as follows^[13]:

$$P\% = 1 - \frac{\rho_{ac}}{\rho_{th}} \quad (2)$$

Where:

P% = porosity percentage

ρ_{ac} = actual density

ρ_{th} = theoretical density

2.4.3 Wear Test

Wear specimens were machined from ingot and cut according to ASTM specification D2625-83 of 20 mm length and 10 mm diameter^[14]. Then one surface of each specimen was ground and polished to obtain clean and smooth surface. The initial surface roughness of the wear specimens was Ra= 0.20 μ m.

2.4.3.1 Wear Apparatus

A Pin-On-Disc wear apparatus was used, which was designed according to ASTM specification F732-82^[14]. The wear apparatus consists of motor with constant revolution speed of (510 rpm).

2.4.3.2 Wear Rate Measurement

Weight method was used to determine the wear rate of specimens. The specimens were weighed before and after the wear test by sensitive balance type (DENVER instrument, Max-210gm) with accuracy of 0.0001 gm. The weight loss (ΔW) was divided by the sliding distance and the wear rate was obtained by using equation as follows^[15]:

$$\text{Wear rate} = \Delta w / S_D \quad (3)$$

$$\Delta w = w_2 - w_1 \quad (4)$$

$$S_D = S_S * t \quad (5)$$

$$\text{Wear rate (Wr)} = \Delta W / \pi D \rho N t \quad (6)$$

Where:

S_D = Sliding Distance (m)

S_S = linear sliding speed (m/sec.)

D = sliding circle diameter (cm)

ρ = density of the specimen (gm/cm³)

t = sliding time (min)

N = steel disc speed (rpm)

Hardness of steel disc = 35 HRC

Diameter of specimen = 10 mm

Length of specimen = 20 mm

3. Results and Discussion

3.1 Hardness and Microstructure Results

Vickers hardness results are given in Table 3. It is seen that the squeeze cast samples have higher hardness values than that of gravity die cast sample. This is due to rapid solidification and high cooling rate of molten metal under applied pressure which gives smaller grain size and finer eutectic phase (Al-Si) than that of gravity die cast. Figure 3 shows the microstructure of gravity cast sample (A) which consists of primary phase (α -Al) and dark gray color of silicon phase (As flakes). A part of silicon phase is shown as massive silicon (Grey color) in some regions of matrix microstructure. As applied pressure increases, the refinement of eutectic phase increases and in comparison with squeeze cast technique, the α -dendrites were much bigger and dendrite structure forms as shown in Fig. (4-7) for squeeze cast samples (B, C, D and E) respectively.

Figure 8 shows the effect of casting pressure on the Vickers hardness number (VHN) of the different alloys. The hardness values increase from 82 HV to 118 HV at pressures 7.5 MPa to 53 MPa respectively. It was explained that the microstructural changes played an important role in the increase of hardness value of the squeeze castings.

Table 3. The Actual density, theoretical density, VHN and P%, determination for squeeze castings under different applied pressures.

Sample	P* MPa	Tp* °C	Td* °C	ρ_{ac} g/cm ³	ρ_{th} g/cm ³	P%	VHN
A	Gravity Die Casting	700	200	—	2.68	—	69
B	7.5	700	200	2.675	2.68	0.2	82
C	23	700	200	2.59	2.68	3.4	96
D	38	700	200	2.619	2.68	2.27	106
E	53	700	200	2.674	2.68	0.22	118

* ρ_{ac} : Actual density (g/cm³), T_p : Pouring temperature (°C), ρ_{th} : Theoretical density (g/cm³), T_d : Die (Mold) temperature (°C), P% : Porosity percentage, P_a : Applied pressure MPa, VHN: Vickers Hardness Number

Fig. 3. Microstructure of gravity die cast sample A: without pressure.

3.2 Density and Porosity Measurements Results

The effect of squeeze pressure on density and porosity are illustrated in Table 3. Although the density is expected to increase continuously with increasing the applied pressure of squeeze casting, it shows a drop at the minimum used pressure of 7.5 MPa. This is attributed to the existence and segregation of porosities at the center of sample. The main part of shrinkage for the samples solidified under atmospheric pressure has been accommodated by formation of a large shrinkage pipe

on the top surface of cast. Upon the application of squeeze pressure, such shrinkage pipe and cavities are pushed down toward the bulk of the samples. Consequently, if the applied pressure is not large enough to eliminate such cavities, smaller density values may be attained. With further increase in the applied pressure up to 53 MPa, gas and shrinkage porosities decrease and hence density increases. These results are in agreement with those of other researchers^[16,17,18].

Fig. 4. Microstructure of squeeze cast sample B: at P=7.5MPa.

Fig. 5. Microstructure of squeeze cast sample C: at P=23MPa.

Fig. 6. Microstructure of squeeze cast sample D: at P=38MPa.

Fig. 7. Microstructure of squeeze cast sample E: at P=53MPa.

Fig. 8. Effect of the squeeze casting pressure on Vickers hardness number of different alloys.

3.3 Wear Rate Results

Figure 9 shows the effect of applied pressure on the wear rate of different samples (A, B, C, D and E) under dry sliding conditions at a load of 20 N, sliding time of 20 min and sliding speed of 2.7 m/sec. The wear rate reduces or the wear resistance increases with increasing the applied pressure that was used to press the molten alloy in the die cavity during squeeze casting of alloy (Al-12%Si). This is due to increase in the hardness value and more refinement of the microstructure as the applied pressure increases because of the reduction of shrinkage porosity as a result of bulk deformation and improving of filtration feeding action during solidification under pressure in squeeze casting^[19].

Fig. 9. Effect of the squeeze casting pressure on wear rate of alloy (Al-12%Si) at a sliding speed of 2.7 m/sec, applied load in wear test of 20 N and sliding time of 20 min.

Figure 10 (a, b, c, d and e) shows micrographs of the worn surfaces of the cast samples (A, B, C, D and E) respectively at a sliding speed of 2.7 m/sec and a load of 20 N, and for sliding time of 20 min during wear test. The worn or damaged surfaces show continuous grooves and cracking of long wear track. In some places, some plastic deformation, together with presence of fine oxides debris particles are also observed in case of gravity die cast sample. While it is seen a smooth and glassy finish and faint wear lines in the direction of sliding on worn surfaces, which indicates a mild abrasion wear mode is present in the case of the samples which were squeeze cast at an applied pressure of (53 MPa).

4. Conclusions

- The microstructure examination showed that small grain size and refine eutectic phase morphologies had been obtained in squeeze casting with respect to gravity die casting.

Fig. 10. Micrographs of the worn surfaces of the alloy (Al-12%Si) at a sliding speed of 2.7 m/sec and a load of 20 N, sliding time of 20 min, Sliding direction: $\longrightarrow$
 (a) Gravity die cast sample
 (b) Squeeze cast sample at applied pressure 7.5 MPa
 (c) Squeeze cast sample at applied pressure 23 MPa
 (d) Squeeze cast sample at applied pressure 38 MPa
 (e) Squeeze cast sample at applied pressure 53 MPa

- The samples were produced by squeeze casting technique had higher Vickers hardness values and wear resistance than that of the gravity die technique.

- As the applied pressure for squeeze cast samples increases the hardness value increases up to 118 VHN at a squeeze pressure of (53 MPa) when compared to that of the gravity cast sample which was 69 VHN.

- The actual density of squeeze samples was improved and reached 2.67 gm/cm^3 and approached the theoretical density which was 2.68 gm/cm^3 , because of the reduction in shrinkage porosity as applied pressure increases during solidification in squeeze casting.

- Faint wear lines in the direction of sliding on worn surfaces indicate that a mild abrasion wear mode is presented for squeeze cast samples which was produced at higher applied pressure. That means a higher wear resistance was obtained.

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دراسة تأثير ضغط السباكة على مقاومة البلي لسبيكة الألومنيوم - سليكون المحضرة بطريقة السباكة بالعصر

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بغداد- العراق

المستخلص. في هذا البحث تم دراسة تأثير ضغط السباكة المسلط عند درجات حرارة صب وتسخين مسبق لقالب الصب ثابتة على التركيب المجهري ومقاومة تآكل البلي لسبيكة الألومنيوم - سليكون المحضرة بطريقة السباكة بالعصر. أظهرت النتائج حصول تنعيم في البنية المجهرية مع زيادة ضغط العصر. وأظهرت النتائج أيضا أن كثافة العينات قد قلت عند تطبيق ضغط مسلط مقداره (7.5MPa)، لكنها قد زادت بصورة ثابتة عند تسليط ضغوط أعلى إلى حد (53MPa). إن زيادة ضغط السباكة أدت إلى زيادة الصلادة وتقليل معدل تآكل البلي. تم تفسير هذه النتائج بالاعتماد على آلية زيادة الكثافة الناتجة بواسطة تطبيق الضغط أثناء التجمد.