Temperature and Pressure Evolution during Al Alloy Solidification at Different Squeeze Pressures

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Abstract. Squeeze casting is an advanced and near net-shape casting process, in which external high pressure is applied to solidifying castings. The castings are characterized with fine grains and good mechanical properties. In this study, a series of experiments were carried out to measure the temperature and pressure histories in cavity of Al-Si-Mg direct squeeze castings with different applied solidification pressures of 0.1, 50, 75, and 100 MPa. The evolution of the measured temperatures and pressures was compared and discussed. The effect of pressure change on formation of shrinkage defects was analyzed. Further the friction between the castings and dies during solidification was calculated. It is shown that the applied squeeze pressure has significant influence on the friction at die and casting interfaces, which affects the pressure evolution and transmission. The results could provide some benchmark data for future thermal-mechanics coupled modeling of squeeze castings.

1. Introduction
Squeeze casting is a special fabrication technique in which solidification is promoted under high pressure. In the casting process, the high pressures applied during solidification can eliminate both gas and shrinkage porosity. The increased cooling rate caused by intimate contact between the solidifying alloy and die results in the formation of fine grains with small dendritic arm spacing. Consequently, casting soundness and mechanical properties are improved. Given the advantages of squeeze casting mentioned above, it is particularly used to fabricate high integrity near-net-shape components with high performance [1, 2].

In the process, the applied pressure improves contact between castings and dies and changes liquidus, hence affecting heat transfer and temperature distribution in the casting system. Meanwhile, solid formation and volume shrinkage have important effect on pressure transmission from plunger or punch [3]. Therefore, thermal-mechanics behavior is the essential problem for squeeze casting process. Several researchers have established mathematical models to simulate the behaviour [4-6]. However, due to the difficulty and complexity of measuring in-cavity pressures of castings with high forced pressures, the pressure in high pressure die casting were measured and reported by only few researchers [3, 7] and that in squeeze casting has not been reported yet. Hence, the models were only verified with the porosity results rather than validated directly with experiment measurement.

In this study, a series of experiments were carried out to measure the temperature and pressure histories in cavity of Al-Si-Mg direct squeeze castings with different applied solidification pressures. The evolution of the measured temperature and pressure was analyzed and discussed. It is shown that
the applied squeeze pressure has significant influence on the casting solidification and the friction of the die and casting interfaces.

2. Experimental works
Figure 1 shows schematic of the experimental squeeze castings. The experiments were conducted with a 1000kN hydraulic press with a PLC control. The materials used were AlSi7%Mg0.4% alloys and the die was made of H13 steels. The solidification was carried out at gravity condition and the forced pressures of 50, 75, and 100 MPa. The temperature changes in both casting centre and die side at 75 and 150 mm height were recorded with K type thermocouples. A quartz pressure sensor (Kistler 6175A2) designed for application up to temperatures of 700 and pressures of 200 MPa [8] was set to the casting bottom surface to evaluate the pressure transmission from the top punch. The castings were cut along the symmetric cross-sections in vertical direction for assessment of inside macro morphology. Also for each casting, a sample was obtained from the location of thermocouple TC1, and the sample microstructures were observed with a Leica microscope.

![Figure 1. Schematic of thermo-mechanical measurement in squeeze casting](image)

3. Results and discussion
Figure 2 exhibits the halves of experimental castings at the different solidification pressures. It is obvious that there exists a concave shrinkage cavity at the top of the gravity casting whereas the castings with applied pressures have flat top surfaces. The roughness of castings with squeeze pressures is finer compared to the gravity casting. Figure 3 shows the microstructures of the casting samples, which are consisted of the alpha cells and eutectics. It is indicated that the castings with the forced pressures are characterized with finer alpha grains and less eutectics than the gravity one.

![Figure 2. Experimental squeeze castings under different applied pressures](image)
3.1. Temperature and pressure evolution
3.1.1. Gravity solidification

Figure 4 shows the curves of temperatures of castings and dies as well as the pressure variation during solidification at the gravity condition. The pressure measured from the casting bottom surface kept unchanged and was of near zero. According to the temperatures change at the TC1 and TC2 points, the temperature of liquid melt after pouring dropped to the range about the alloy liquidus (635 °C). The phase transformation of primary alpha-cell formation happened from 12.6 to 63.8 seconds during which the temperatures dropped slowly. From 63.8 to 116.6 seconds after pouring the casting temperature kept constant at 595 °C. It is obvious that within the period the eutectic transformation occurred. After the transformation, the casting temperatures decreased quickly. Due to the effect of heat transfer from the casting to the bottom platen, the temperature drop at location TC1 closer to the platen was larger than that at TC2. From Fig. 4 the die temperatures increased dramatically before 28 seconds, and then went up quite slowly due to the formation of air gap at the casting and die interface caused by the solidification shrinkage.

3.1.2. Solidification at 50MPa

The evolution of the measured temperatures and pressures of the squeeze castings at 50 MPa was shown in Fig. 5. The casting solidification happened from 5.6 to 65.4 seconds. Compared with the data in Fig. 4, it is clear that with the squeeze pressure the solidification time decreased and the cooling rate increased. This is considered to be contributed to two factors. First, the pressure forced the solidified casting to deform and hence have an intimate contact with the die, increasing the heat flux through the interface. Second, the pressure made the eutectic point in equilibrium Al-Si diagram move to higher Si contents [9] and fraction of eutectic phases in the alloy was decreased, which could also be seen from the microstructures in Fig. 3a and 3b. The die temperatures in Fig. 5 increased quickly and finally had almost same values with those of the castings, which indicated intensive heat flux from casting to die when using squeeze pressure.

The pressure curve in Fig. 5 shows that after start of the forced pressure from the upper punch at 17.2 seconds, the pressure at the casting bottom increased quickly and reached to the peak value of 35.35 MPa. At the beginning of the casting solidification, the solidified shells encapsulated the casting.
were quite thin and could not against the forced pressure so that the solidifying casting was pressed to expand in radial direction and had well contact with die. The contact increased the friction between them and decreased the transmission of pressure from the upper punch. As a result, the measured pressure declined gradually after reaching the peak and had a minimum pressure of 18.01 MPa at 54.8 seconds. Along with the solidification, the growing solids increased the casting strength and prevented the further deformation under the forced pressure. Meanwhile, the solidification shrinkage made the casting detach from the side die surfaces, forming air gap at the interface. Then the friction declined and the measured pressure increased after the decrease.

It was pointed out by Stangeland [10] that the Al-7%Si-0.4%Mg alloys had a maximum solidification shrinkage at temperature of 560.8°C and the solid fraction of 88%, coinciding with the temperature when the minimum pressure was measured in Fig. 5. We considered that the tendency forming shrinkage defects increased at the period with the lower measured pressure due to large solidification shrinkage and insufficient squeeze pressure inside the casting, illustrated by the shade region in Fig. 5.

Figure 5. Temperature and pressure curves under 50MPa applied pressure

3.1.3. Solidification at 75MPa

Figure 6 displays the measured temperatures and pressures at the squeeze pressure of 75 MPa. The evolution of the temperature and pressure is similar with those in Fig. 5. The casting solidification lasted 50 seconds (from 19.6 to 69.6 seconds) a little less than that at 50 MPa. Compared to Fig. 5, the eutectic transformation time in Fig. 6 is shorter because of the larger forced pressure.

It is shown in Fig. 6 that the measured pressure at 75 MPa condition has the peak value of 48.38 MPa larger than that at 50 MPa. It should be noted that the experiments were performed with a press, and the velocities of the upper punch (please see Fig. 1) moving downwards with the different internal pressures set by PLC were different causing the different start times of measured pressure in Fig. 5 and 6. Since the larger squeeze pressure of 75 MPa could induce more intimate contact at the casting and die interface by forcing the solidifying casting to expand in radial direction, the measured pressure dropped dramatically to a minimum value of 17.25 MPa less than that in Fig. 5. Similar to Fig. 5, the pressure increased from the later period of solidification and then kept at a stable pressure of 33.97 MPa. Compared to the results in Fig. 5, the duration from 560.8°C (at which the alloy has maximum shrinkage ratio) to the end of solidification marked by the shade area in Fig. 6 was shorter decreasing shrinkage defects at the larger squeeze pressure.
3.1.4. Solidification at 100 MPa

The measured temperatures and pressures at the forced pressure of 100 MPa were plotted in Fig. 7. Compared with the solidification at 50 and 75 MPa cases, the solidification time at 100 MPa from 4.6 to 51.2 seconds is the shortest indicating large cooling rate. Also the eutectic transformation period usually with constant temperature in cooling curves was not very obvious due to less eutectic fractions under 100 MPa pressures. Although the die temperatures in Fig. 7 show the similar evolution tendency with those in Fig. 5 and 6, however, the die temperatures measured reached approximate 387°C higher than the other two cases.

As shown in Fig. 7, the measured pressure quickly reached its peak of 78.90 MPa. Due to the casting deformation under the forced pressure and the friction between the casting and die, the pressure during the solidification period decreased, similar with the results in Fig. 5 and 6. On contrary to Fig. 5 and 6, after the solidification the pressure continued to drop. The reason is that the 100 MPa pressure could make the casting at high temperature deform and hence keep well contact with the die during the whole casting process, maintaining large friction at the interface. The friction limited the squeeze pressure transmission, and hence the measured pressure declined continuously. Fig. 7 shows that the pressure applied in the solidifying casting is higher over 50 MPa, which could prevent formation of shrinkage defects.

3.2 Analysis of friction between casting and die

In squeeze casting process, the external pressures pressed castings against die walls inducing their well contact. The contact results in large friction between them, which is detrimental to die service lives. As a result, the lives of squeeze casting dies are usually less than those of low pressure die castings and even high pressure die castings.
Figure 8 shows the force schematics for the experimental castings. The applied forces are given by the set-up of hydraulic press. The support force can be calculated from the measured pressure. Then the friction at the casting and die interfaces can be determined by

\[ f = F \times S_u - P \times S_d \]  

where \( f \) is the friction between casting and die, \( F \) is applied pressure from punch, \( P \) is pressure measured from the casting bottom surface, \( S_u \) and \( S_d \) are the areas of casting upper and bottom surfaces, respectively.

Appling the Eq. 1 to the experimental results, the evolution of friction between the castings and dies is illustrated and compared in Fig. 9. In the figure, the open symbols express the friction during the solidification stages while the filled ones mean that after the solidification. It is obvious that the friction became larger with the increased applied pressures. The frictions at the applied pressures of 50 and 75MPa increased after the start of solidification, and then decreased from the later period of solidification due to the shrinkage. On the contrary, the friction at the 100 MPa pressure increased during the whole solidification process. The results have shown that in thermal-mechanics coupled modeling of squeeze casting process, the friction should be taken into account. As discussed in the literature [1], efficient pressure transmission during squeeze casting process is in favor of preventing or eliminating shrinkage defects, and the applied pressure after casting solidification would not contribute to feeding shrinkage but do harm to die life and waste energy. Therefore, the applied pressure of 100 MPa induced high internal pressure in the solidifying casting preventing shrinkage defects but the pressure dwelling after the solidification was harmful to the die life. It is indicated that applied pressure and its dwelling times should be properly set to prevent shrinkage defect and improve die lives.
4. Conclusion

(1) With increased applied pressures in the squeeze castings, the times of casting solidification and eutectic transformation decreased due to improved contact between the castings and dies as well as decreased eutectic fractions in the alloys.

(2) During the solidification period at 50 and 75 MPa, the measured pressures decreased first, and then increased since the solidification later period because of the declined friction at the casting and die interface. On the contrary, the measured pressure at 100 MPa showed a decrease tendency during the whole fabrication process. The higher squeeze pressure can induce more intimate contact of the casting and die maintaining larger friction between them.

(3) As the applied squeeze pressures increased, the friction was larger limiting the pressure transmission. It is shown that the friction should be considered in thermal-mechanics coupled modeling of squeeze casting process.

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