Study on the Thermal Contraction Behaviors of Mg and Al

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Abstract. By using a device which could achieve the 1-Dimensional shrinkage instead of 3D shrinkage of the casting during the solidification and cooling, the cooling curves and the relationship between the shrinkage / temperature and time were investigated. Then, the thermal shrinkage behaviors of pure Mg and Al ingots were obtained. As a result, the characterization of the thermal shrinkage behavior of Mg and Al was systematically investigated. The results indicate that the contraction rate of pure Mg ingot increases with the increase of growth rate of dendrites in quantity during solidification. The maximum contraction rate \(v_{l,\text{max}}\) will be reached when the formation of primary dendrite ends, and the value of \(v_{l,\text{max}}\) is \(1.12 \times 10^{-2} \text{ mm} \cdot \text{s}^{-1}\). However, the shrinkage will not be present until the solid state cooling starting for the pure Al ingot. The contraction of pure Mg ingot in solid state can be divided into two stages: high temperature solid shrinkage stage and low temperature solid shrinkage stage. And the rate of shrinkage firstly increases then decreases with the temperature dropping at the stage of high temperature solid shrinkage. The rate of solid shrinkage of pure Al ingot is present at the beginning of solid-state cooling. And its value is \(9.69 \times 10^{-3} \text{ mm} \cdot \text{s}^{-1}\), which is more than 3 times of that of pure Mg ingot. The shrinkage behaviors of both pure Mg and Al ingots tend to be uniform shrinkage when the temperature is below 400°C.

1. Introduction

Hot cracking is an acute defect for the metal materials during solidification. This defect is usually present in the as-cast aluminum alloys, magnesium alloys and iron. So it is necessary to study the hot cracking resistant of different metal materials. Based on the formation process of cracking, thermal contraction is the driving force to form cracking during solidification [1, 2]. And the study about contraction behaviors during solidification plays an important role in studying on hot cracking susceptibility.

The theories of hot cracking formation include solidification shrinkage-repairing theory [3], dendritic bridging theory [4], liquid film theory [5] and strength theory [5]. But these studies were usually focused on the solidification process of aluminum alloys or other metal materials. The corresponding researches on the solidification process of pure aluminum and pure magnesium were few. However, studies on thermal contraction behaviors and hot cracking susceptibility of pure aluminum and pure magnesium are the foundation for the researches on the hot cracking of aluminum alloys and magnesium alloys.

Some literatures reported the hot cracking behaviors of aluminum alloys and magnesium alloys. Novikovet al. [2] studied the effect of Li, Cu and Mn content on hot cracking susceptibility of aluminum alloys. Li et al. [6] found that the hot cracking susceptibility of Mg-6Al-0.5Mn alloy
decreased with the increase of Sr content. Huang et al. [7, 8] studied the hot cracking trend of AZ31, AZ61 and AZ80 magnesium alloys according to the researches on the welding cracks. They found that aluminum could promote the hot cracking susceptibility. Wang et al. [9] studied the hot cracking of AZ91 alloy. Bracinni et al. [10] reported the effect of grain refinement on the hot cracking trend of Al-Cu alloy. L. Katgerman, D.G. Eskin et al. [11] reported the hot cracking susceptibility of aluminum alloys in details.

Firstly, the number of researches on the hot cracking susceptibility of aluminum alloys and magnesium alloys is large, but few literatures focus on that of pure aluminum and pure magnesium. On the other hand, the number of studies on the influence factors of thermal contraction behaviors which are the driving force of hot cracking formation, is few either. Therefore, the hot cracking can be studied by means of testing the change of thermal contraction displacements with the temperature dropping during solidification and cooling by experiments. As a result, the data could further provide the basis for hot cracking trend.

In this paper, a self-made device, which could achieve the cooling curves and the curves of thermal contraction displacements of pure aluminum and pure magnesium, was used to study their thermal contraction behaviors. As a result, the influence factors of their thermal contraction behaviors could be obtained.

2. Experiments procedure

The preparation of pure magnesium casting: High purity Mg ingots were melted in a electrical resistance furnace using a mild steel crucible, after stirring for 2 min, the melt was held for 5 min at 700°C; after that, it was poured at 720°C into a preheated mould which was called contraction displacement tested module. Some CO₂ gas was bled into the mould to avoid the oxidation of casting before the molten liquid being poured into the mould. The preparation of pure aluminum casting: High purity Al ingots were melted in an electrical resistance furnace by using a graphite crucible. After being degassed and slag removed at 720°C respectively, Al molten liquid was also poured into the mould.

The cavity of the mould mentioned above, with the size of 20mm×20mm×190mm, is joined by two pieces of insulation boards, two metal molds with the ability of heating, a movable steel slider and an immovable steel slider. The low thermal conductivity of two insulation boards and the heating design of metal molds result in the temperature of two steel sliders being the lowest. As a result, the main heat flow direction of the melt was from the center of the cavity to its both ends. Therefore, the shrinkage of the casting should be almost carried out from both ends of casting to the center, resulting in the transformation of approximate one-dimensional shrinkage from the three-dimensional shrinkage. The immovable steel slider which is connected with the casting is fixed on the pedestal, and the movable steel slider which is connected with the casting on the other side could show the whole variation of casting in size during solidification and cooling.

In order to measure the tiny displacement of casting during solidification, the linear variable differential transformer (Type: 250 DC-SE) with high sensitivity and high accuracy was used. K-thermocouple wire was placed at the center of cavity to weaken its resistance to the shrinkage of casting during solidification and cooling. HIOKI data collector also with high sensitivity and high accuracy was used to record the temperature and the signal from the 250 DC-SE. The collection cycle of HIOKI data collector was set up 10 ms. As a result, the dependency of temperature and displacement variation on time would be obtained.

3. Results and discussion

3.1 Study on thermal contraction of pure Mg

Figure 1 indicates the curves of Time (t)-Temperature (T), Time (t)-Displacement (l) and Time (t)-Displacement change rate (dl/dt) respectively for pure Mg during solidification and cooling. The maximum displacement change rate (vl, max) reaches to 1.12×10⁻² mm·s⁻¹ when the temperature at the center of casting drops to 647°C. Besides, the time of v_l, max corresponds to the beginning of crystallization platform.
The presence of the beginning of crystallization platform means that the primary dendritic starts to form at the center of cavity, which indicates the accomplishment of connection of primary dendritic for the pure Mg casting. Before that, the contraction rate of the casting increases due to the formation of the primary dendritic, secondary arms, third arms at the same time. In addition, the growth of primary dendritic from both ends to the center of cavity results in the remarkable increasing of growth rate of dendritic in number. However, when the temperature drops to the beginning of crystallization platform shown in Fig. 1, the solidification front of casting reaches to the center and the connection of primary dendritic is completed. As a result, the number of melt pool decreases gradually as well. Although the formation of secondary arms and third arms will continue to emerge, the growth rate of dendritic in number will slow down significantly. So the contraction rate of casting will decrease and as a result the maximum contraction rate $v_{l,\text{max}}$ is present at the beginning of crystallization platform.

Figure 1. Curves of Time-Temperature/Displacement/Displacement change rate ($dL/dt$) of pure magnesium ($t=$Time)

Therefore, it can be concluded that the growth rate of dendritic in number, especially that of primary dendrites in number, should be the main reasons to influence the contraction rate of casting. The increase of growth rate of dendritic in number results in the increment of contraction rate of casting.

In addition, it also can be found from Fig. 1 that the starting point of second peak of $t-dL/dt$ curve corresponds to the end of crystallization platform. The end of crystallization platform which is a part of the cooling curve for the position of the center of pure Mg casting indicates the end of solidification and the start of the solid shrinkage for the whole pure Mg ingot. Therefore, the solid shrinkage of the ingot can be divided into two stages according to the dependence of the contraction rate on time in $t-dL/dt$ curve as shown in Fig. 1: ① solid shrinkage at high temperature; ② solid shrinkage at low temperature. The solid contraction rate $v_s$ at high temperature (stage ①) firstly increases then decreases with time. The maximum solid contraction rate $v_{s,\text{max}}$ is $-3.125\times10^{-3}\text{ mm·s}^{-1}$, whose corresponding temperature is 568°C. Therefore, it can be indicated that the solid contraction rate increases instead of decreasing with temperature dropping at 647°C ~568°C for the solid shrinkage of pure Mg ingot. Besides, this trend is present once the solid shrinkage of pure Mg ingot starts. The solid contraction rate $v_s$ at low temperature (stage ②) is almost a constant (>0), which means that the Pure Mg ingot contracts at a constant rate.

3.2 Study on thermal contraction of pure Al

Figure 2 shows the curves of Time ($t$)-Temperature ($T$), Time($t$)-Displacement ($L$) and Time($t$)-Displacement change rate ($dL/dt$) respectively for pure Al casting during solidification and cooling. Rapid expansion is present at the temperature above solidification temperature. It is mostly
because of the some hydrogen containing in the Al molten liquid being discharged with temperature dropping during solidification. The max value of the rapid expansion reaches to ~0.07mm in 9 seconds.

**Figure 2.** Curves of Time-Temperature/Displacement/Displacement change rate (d/dt) for pure aluminum (t=Time)

The rapid expansion finishes when the crystallization is present at the center of cavity, whose corresponding temperature is the starting point of crystallization platform in Fig. 2. After that, the expansion is still carried out slightly until the end point of crystallization platform. The value of expansion which occurs among the stage of crystallization platform is about 0.027mm. It is well known that the end point of crystallization platform indicates the end of solidification for pure Al. It can be found from Fig. 2 that the obvious contraction does not occur until the temperature drops to 640°C; it is interesting that almost no displacement change is present at the temperature range of the end of solidification to 640°C. However, the maximum solid contraction rate (vs_max=9.69×10⁻³ mm·s⁻¹) is also present at 640°C. After that, the solid contraction rate decreases and finally tends to be a constant with temperature dropping.

In summary, it can be concluded that no contraction but expansion is present during the solidification of pure Al casting, including the rapid expansion in liquid phase zone and slight expansion in mushy zone. No obvious contraction can be found when the temperature drops to 640°C from the temperature corresponding to the end of crystallization platform of pure Al. In addition, the maximum solid contraction rate vs_max is also present at 640°C. After that, the solid contraction rate decreases with temperature dropping and finally the uniform contraction occurs.

### 3.3 Comparison of thermal contraction behaviors between pure Mg and pure Al

There are some similarities and differences of thermal contraction behaviors between pure Mg and Al by comparing Figs. 1 and 2.

It can be found that both the pure Mg ingot and pure Al ingot shrink uniformly at the temperature below 400°C. Their corresponding linear fitting curves are shown in Fig. 3. As a result, the mean linear expansion coefficients of pure Mg and pure Al are 29.38×10⁻⁶ K⁻¹ and 24.87×10⁻⁶ K⁻¹ respectively below 400°C based on Fig. 3.
Figure 3. Temperature-Displacement curves and the corresponding linear fitting curves of the tested materials below the temperature of 400°C: (a) Pure Mg; (b) Pure Al

However, more differences of thermal contraction behaviors between pure Mg and pure Al can be drawn as below:

1) Expansion will be present when the pure Al molten liquid being poured into the cavity, while no expansion is present in the process of casting for pure Mg.

2) Contraction will be present during the formation of dendrites for the pure Mg solidification, and maximum contraction rate $v_l,\text{max}$ at this stage reaches to $1.12\times10^{-2}\text{ mm}\cdot\text{s}^{-1}$. However, a slight expansion is present during the solidification of pure Al casting.

3) At the stage of solid state cooling, the solid contraction rate $v_s$ of pure Mg ingot firstly increases and then decreases with the temperature dropping, and its max value $v_s,\text{max}$ is $3.125\times10^{-3}\text{ mm}\cdot\text{s}^{-1}$. However, at the stage solid state cooling for pure Al ingot, the maximum solid contraction rate ($v_s,\text{max}$) of $9.69\times10^{-3}\text{ mm}\cdot\text{s}^{-1}$ will be present once the cooling shrinkage occurs. And then $v_s$ will decrease with the temperature dropping.

4. Conclusions

(1) The growth rate of primary dendrites in number is the main reason to influence the contraction rate of pure Mg during solidification. Larger growth rate of primary dendrites in number results in the
faster contraction rate of pure Mg casting. The maximum contraction rate during solidification is \( v_{l, \text{max}} = 1.12 \times 10^{-2} \text{ mm·s}^{-1} \).

(2) The solid contraction of pure Mg ingot can be divided into two stages based on the dependence of contraction rate on time: solid shrinkage at high temperature and solid shrinkage at low temperature. The solid contraction rate of pure Mg ingot \( v_s \) at high temperature firstly increases and then decreases with temperature dropping.

(3) No contraction but minor expansion is present during the solidification of pure Al casting. The contraction starts when the whole ingot becomes into solid state and the maximum solid contraction rate \( (v_{s, \text{max}}) \) is \( 9.69 \times 10^{-3} \text{ mm·s}^{-1} \). This value is 3 times larger than that of pure Mg ingot present at the beginning of solid shrinkage.

(4) Both the pure Mg ingot and pure Al ingot shrink almost at the constant speeds at the temperature below 400°C.

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6. References
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