Control of Foaming of Al Alloy Melt

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The optimal quantity of TiH₂ (foaming agent) and the most suitable temperature for producing foamed Al alloy in a non-isothermal process are determined. Experimental results show that the initial foaming temperature must be higher than the solidifying point of Al alloy, and as TiH₂ decomposition starts, the melt temperature drops down to the solidification temperature interval, meanwhile bubbles become stable and drainage of foaming layer slows down. In the experiments, foaming temperature of 680°C and 2 wt% TiH₂ (<300 mesh) are the optimal combination for making foamed Al alloy of good quality. It is found that the wide solidification temperature region is an important factor for better controlling the foaming process.

KEY WORDS: foamed metal; Al alloy; thermal decomposition; TiH₂; foaming temperature; foaming agent.

1. Introduction

The foamed metal (porous metal with porosity of 40–98%) is in growing use as a novel functional material, for it possesses unique combinations of many mechanical and thermal properties.¹⁻³ Many methods have been developed to produce foamed metals. Each method has its own feature, but only two of them are industrialized, which are the seepage flow cast process and the melt foaming process. The latter is superior in manufacturing large-size parts. In this process, key problems are the control of foaming procedure.⁴ Based on the previous work,⁵ a study is made on the relationship between the initial foaming temperature and the addition amount of foaming agent TiH₂ as well as the influence of the thermal behaviors of TiH₂ on the foaming behaviors of melt.

2. Experiment

Figure 1 shows the schematic drawing of the experimental apparatus. Al is smelted in a graphite crucible with an inner diameter of 80 mm and depth of 200 mm, the calcium and magnesium are added to increase the viscosity and decrease the surface tension of the molten Al alloys, respectively. Previous works show that 2wt%Ca–1wt%Mg–Al alloy melt is proper to make quality foamed Al ingot.⁷ The agitating power is controlled by regulating the input voltage to the agitator, and the agitating time is about 10 to 15 min. When the melt becomes suitable for foaming, the foaming agent (TiH₂ or Ni₅Ti₃H₁₂) is added to the melt and the melt foams. After foamed melt is cooled in the air or in water-cooled iron mold, porous Al can be made. Table 1 presents the thermal analysis of foaming agent TiH₂ heated at 10°C/min.

3. Results

3.1. Evaluation of the Foaming Effect

Figure 2 provides a sectional view of the product, which shows that the product is composed of two layers: the foaming layer (Region A) and the non-foaming layer (Region B).

Table 1. Thermal analysis of TiH₂ (heated at 10°C/min).

| Size of TiH₂ particle (mesh) | Initial and final temperature of decomposition (°C) | Mass loss (wt.%) | Temperature with largest weight loss rate (°C) |
|-----------------------------|-----------------------------------------------------|------------------|-----------------------------------------------|
| 160                         | 402–775                                             | 0.65             | 570                                           |
| 300                         | 454–735                                             | 0.90             | 608                                           |
The former has a little sphere pores on top and bottom, while more polyhedrons prevail in the middle part, which demonstrates the evolution from spherical to polyhedral pores.

To assess the product ingot, an index of porosity is commonly adopted. But if the non-foaming layer is also taken into consideration, another index of the non-foamed metal fraction \( K \) should be added here:

Non-foamed layer fraction \( (K) \)

\[
K = \frac{V_d}{V_0} ................................(1)
\]

Porosity of the foaming layer (Region A) \( (\alpha) \)

\[
\alpha = \frac{(V_i - V_d) - (V_0 - V_d)}{V_i - V_d} = \frac{V_i - V_0}{V_i - V_d} ................................(2)
\]

From the definition of these two indices, it is obvious that only if \( K \) is very small, \( \alpha \) may be of meaning. When the pores are homogeneously distributed in the ingot, the latter index reflects the size and structure of pores in products. Also, substituting Eq. (1) into Eq. (2) results in

\[
\alpha = \frac{V_i - V_0}{V_i - KV_0} ................................(3)
\]

3.2. Effects of Initial Foaming Temperature and Foaming Agent

The so-called initial foaming temperature here refers to the actual temperature of the melt at the instant when the foaming agent is added. Figures 3 and 4 show the effects of initial foaming temperature \( T_f \) and foaming agent addition on non-foaming layer fraction \( K \), respectively. It is implied that only if \( T_f \) and addition of TiH\(_2\) match well and the granularity of TiH\(_2\) is quite perfect, product of the best quality can be obtained.

The effect of \( T_f \) and TiH\(_2\) on the foaming process may be based on the following reasoning: above all, certain conditions are required to enable the bubbles to grow against the internal pressure of melt; and then, a fairly high temperature is also controlled to keep the bubbles in the foaming melt from polymerizing or collapsing due to liquid-discharging. The fact is that the higher the temperature of the melt is, the more the melt froth, however, the less stable the bubbles are. And low temperature should be improper to ensure decomposition of TiH\(_2\). So the perfect foaming temperature ranges between certain limits to meet the needs of internal pressure and high viscosity of melt at the same time.

In the experiments, under the initial temperature of 680°C, TiH\(_2\) 2 wt%, Ca 2 wt%, Mg 1 wt%, the products of high quality were obtained.

4. Discussions

4.1. Relationship between Initial Foaming Temperature and Behaviors of TiH\(_2\) Decomposition

The chemical reaction describing the thermal decomposition of TiH\(_2\) is

\[
\text{TiH}_2 = \text{Ti} + \text{H}_2 ................................(4)
\]

The corresponding decomposition pressure is

\[
\ln p_{\text{H}_2} = \frac{\Delta H^o}{RT} - \frac{\Delta S^o}{R} ................................(5)
\]

As calculated theoretically, the decomposition pressure of TiH\(_2\) is 0.1 MPa when the temperature of the melt reaches
617°C. So the theoretical foaming temperature is 617°C. Since TiH₂ absorbs heat when decomposing, the actual temperature should be higher than 617°C.

Suppose that there is no heat exchange before and during the foaming procedure, the temperature decrease during the foaming procedure can be evaluated with

\[ \Delta T = \frac{\Delta H^\circ}{M_C} \times C_{TiH_2} \]

When \( \Delta H^\circ = 125.4 \text{ kJ/mol} \) and \( C = 914 \text{ J/(kg·K)} \), the real foaming temperature for Al alloy under different initial foaming temperature can be calculated with decomposition quantity of TiH₂ by Eq. (6), as shown in Fig. 5. In Fig. 5, the right ordinates axis represents decomposition pressures of TiH₂ at different \( T_f \). It can be assumed and has been substantiated by experiments that there is a critical lowest temperature under which no foaming melt would be obtained and most of TiH₂ remain unreacted, which has been proved by the experiment of post-foaming of Al alloy in previous work.

### 4.2. Relationship between Solidification Temperature Interval of Al Alloy and Initial Foaming Temperature

The higher the initial foaming temperature is, the more completely the TiH₂ decomposes, and thereby the melt froths well. But an exceedingly high temperature should be avoided because it may result in a high value of \( K \) due to decreased viscosity of the melt and prolonged solidification procedure.

Normally, the viscosity of the melt will increase significantly when some solid phase separates out from the liquid under the solidification temperature. This can be utilized in the practical process. Table 2 illustrates the relationship between the composition of Al alloy and the corresponding solidification temperature interval.

According to Eq. (6), if the added 2 wt% TiH₂ is fully decomposed, the temperature of the melt will drop down by 54.9°C. And if the initial foaming temperature is 650°C, it will put restraint on effective solidification temperature interval for foaming procedure because the theoretic terminal foaming temperature 593.1°C is below the decomposition temperature of TiH₂ at 0.1 MPa, and thereby uniform distribution of the foaming agent is hindered. On the other hand, if \( T_f \) reaches 720°C, the foaming will proceed above the temperature level for keeping alloy as liquid. But the melt is with low viscosity and bubbles are easy to aggregate to release so that poor quality of ingot is very likely. If \( T_f \) is at 680°C, the overall conditions are beneficial to TiH₂ decomposition and melt foaming: the melt with low viscosity helps the foaming agent TiH₂ to distribute and decompose, meanwhile foaming is completed within the solidification temperature interval with high viscosity to preserve bubbles in alloy. Figure 6 shows the difference under these three kinds of conditions, in which specimen 1 to 3 were produced with initial foaming temperature 650°C, 680°C and 720°C, respectively. When \( T_f \) is at 680°C, the influence of the addition of TiH₂ on the product is similar. Selecting size and purity of TiH₂ should be taken into consideration, whose influence is displayed in Figs. 3 and 4.

It is reported that calcium can act as another sort of additive to increase the viscosity of melt. We support this opinion and believe that calcium and magnesium work not only by improving the melt viscosity, but also by broadening the solidification temperature intervals.

### 5. Conclusions

(1) The foaming procedure with TiH₂ as a foaming agent is a non-isothermal process. Two principles should be followed:

#### Table 2. Compositions and solidification temperature intervals of Al alloy (By thermal analysis, heated at 10°C/min).

| Composition of Al Alloy (wt.%) | Melting Point (°C) | Solidifying Point (°C) | Solid-liquid phase temperature intervals (°C) |
|------------------------------|-------------------|------------------------|---------------------------------------------|
| Al                           | 630               | 682                    | 52                                          |
| Technical grade              | 2                 | 1                      | 580                                          |
| Technical grade              | 2                 | 1                      | 572                                          |
| Technical grade              | 2                 | 1                      | 644                                          |

Note: 1) Composition of Al (wt.%): Al 99.03, Fe 0.50, Si 0.45, Cu 0.02.
(a) The initial foaming temperature should be higher than the solidification temperature of Al alloy;
(b) The addition of foaming agent should be limited so that the temperature of frothing melt will be in the solidification temperature interval after TiH₂ is decomposed completely.

(2) Using calcium and magnesium as additives can extend the two-phase temperature interval of Al alloy, and contributes beneficially to the control of foaming parameters.

(3) In the experiment, for Al alloy with Ca=2 wt%, Mg=1 wt%, the optimal conditions are: when the size of TiH₂ is 300 mesh, \( T_f = 680°C \), TiH₂=2 wt%, when the granularity of TiH₂ is 160 mesh, \( T_f = 660°C \), TiH₂=4 wt%.

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Nomenclature

\[
\begin{align*}
C & : \text{Specific heat of Al alloy [J/(kg \cdot K)]} \\
C_{TiH_2} & : \text{Weight fraction of TiH}_2 \text{ in Al (1)} \\
\Delta H^o & : \text{Enthalpy of TiH}_2 \text{ decomposition (kJ/mol)} \\
K & : \text{Non-foaming layer fraction (1)} \\
M_\ell & : \text{Molecular weight of TiH}_2 \text{ (50 g/mol)} \\
P_{H_2} & : \text{Decomposition pressure of TiH}_2 \text{ (10}^{-1} \text{ MPa)} \\
R & : \text{Gas constant (8.314 J/mol)} \\
\Delta S^o & : \text{Change of entropy of TiH}_2 \text{ decomposition [kJ/(K \cdot mol)]} \\
T & : \text{Decomposition temperature (°C)} \\
T_f & : \text{Initial foaming temperature (°C)} \\
\Delta T & : \text{Temperature drop (°C)} \\
V_o & : \text{Initial volume of Al before foaming (m}^3\text{)} \\
V_d & : \text{Dead volume of the foamed Al in non-foamed part (m}^3\text{)} \\
V_f & : \text{Final volume of the foamed Al (m}^3\text{)} \\
\alpha & : \text{Porosity of foamed Al (%)}
\end{align*}
\]

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