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How Mushy Zone Affect the Thermal Performance of Low-melting Alloy

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ABSTRACT

The low-melting alloys composed of Sn, Bi, Pb, Cd, In, Ga and Sb show good application prospect in phase change heat sink and heat storage system. Thereby, a well understanding of the melting behaviors of low melting-alloys is crucial to design efficient thermal heat storage appliances or heat sinks. In this paper, a one-dimensional enthalpy-based model is established to explore the melting process of an alloy bar. As the results, the effect of mushy zone temperature range which can be reflected by phase change temperature interval and average phase change temperature is discussed on the motion of mushy zone. The results indicates that the increase of surface temperature is significantly delayed by the release of latent heat. Moreover, the duration of mushy zone gradually increases along the vertical direction, which attributes to the increase of thermal resistance. Reducing the average temperature of mushy zone instead of increasing the temperature interval is an effective way to improve the thermal performance of alloy. Specifically, the effective protection time increases 22% with the average temperature decreases from 70 to 50 °C. The calculated results provide theoretical guidance for selecting the working medium of the thermal heat storage appliances or heat sinks.

Keywords:
Low-melting alloy; Mushy zone; Melting behavior; Thermal performance

NONMENCLATURE

Symbols	
ρ	*Density of alloy bar*
H	*Enthalpy*
k_S	*Thermal conductivity of solid zone*
k_L	*Thermal conductivity of liquid zone*
τ	*Time*
τ_p	Effective protection time
L	*Latent heat*
T_S	*Liquidus temperature*
T_L	*Solidus temperature*
c_s	*Specific heat of solid*
c_L	*Specific heat of liquid*

1. INTRODUCTION

The low-melting alloys composed of Sn, Bi, Pb, Cd, In, Ga and Sb show good application prospect in phase change heat sink and heat storage system, owing to the high thermal conductivity, good thermal cycle stability and long service life [1-3]. However, the heat transfer characteristics of the low-melting alloys are quite different from those pure phase change materials since the phase change process does not happen at a sole constant temperature but in a temperature range. The coexistence of solid and liquid is a typical feature of this temperature range, which named as a mushy zone. Thus, a well understanding of the melting behaviors of low melting-alloys is crucial to design efficient thermal heat storage appliances or heat sinks.

Up to now, the phase change process of pure materials which take place at a constant temperature has been widely investigated by many scholars. By contrast, studies of mixed materials are quite inadequate, and the existing works mainly focused on the organic materials (paraffin, lauric acid and etc.) instead of alloys [4, 5]. For instance, Wang et al. [1] investigated the effects of temperature and main components on the specific heat capacity and thermal diffusivity of Sn-Bi-Pb-Zn alloys, and proved the feasibility of using low-melting alloys as the heat storage material. X-ray was adopted by Jaoude et al. [6] to obtain the moving characteristic of mushy zone of Al-Cu alloy under a constant temperature gradient. Moreover, the solidification process of Pb-Sn alloy was experimentally investigated by Ferreira et al. [7]. The

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results indicated that the interface heat transfer coefficient was interactional with temperature field. In our previous research [8], the effects of cooling condition and alloy parameters on the moving characteristics of mushy zone during the solidification process were experimentally investigated, and dimensionless correlations were developed to predict the motion of mushy zone. It should be noted that a slight change in the main components of alloys can significantly affect the temperature range of the mushy zone. Unfortunately, the effect of mushy zone temperature range on the phase change process is not involved in the previous researches, which significantly restricts the application of alloys in the thermal heat storage appliances and heat sinks.

In this paper, a one-dimensional enthalpy-based model is established to explore the melting process of an alloy bar. Moreover, the temperature evolution and moving process of mushy zone along the vertical direction are obtained. Furthermore, the effect of mushy zone temperature range which can be reflected by phase change temperature interval and average phase change temperature is discussed on the motion of mushy zone. The calculated results are expected to provide theoretical guidance for selecting the working medium of the thermal heat storage appliances or heat sinks.

2. MATHEMATICAL MODELS

2.1 Establishment of the model

This model is established to explore the directional melting process of an alloy bar, that is, the side and top surfaces are insulated. Moreover, the influence of natural convection on the melting process is ignored, owing to tiny difference of density between solid and liquid zone of low-melting alloys. Furthermore, the total length of the alloy bar is set as 50 mm, the heat flux of the bottom surface is set as 3.5 W·cm^{-2}, and the initial temperature is set as 25 ^{o}C. In addition, some assumptions are made to simplify the model:

(1) The volume change of alloy during the melting process is ignored.

(2) The effect of temperature on the thermal conductivity of alloys in solid and liquid zones is ignored. Based on the above assumptions, the energy governing equations can be expressed as:

$$\rho \frac{\partial H(T)}{\partial \tau} = \frac{\partial}{\partial x}\left[k(T) \frac{\partial T}{\partial x} \right] \tag{1}$$

where the $k(T)$ and $H(T)$ can be expressed as:

$$k(T) = \begin{cases} k_S & (T < T_S) \\ k_S + (k_L - k_S)\dfrac{T - T_S}{T_L - T_S} & (T_S \le T \le T_L) \\ k_L & (T > T_L) \end{cases} \tag{2}$$

$$H(T) = \begin{cases} c_S T & (T < T_S) \\ c_S T_S + \dfrac{c_S + c_L}{2}(T - T_S) + L\dfrac{T - T_S}{T_L - T_S} & (T_S \le T \le T_L) \\ c_S T_S + \dfrac{c_S + c_L}{2}(T_L - T_S) + L + c_L(T - T_L) & (T > T_L) \end{cases} \tag{3}$$

The parameters of alloy (31.6%-Bi, 48.8%-In and 19.6%-Sn) used in this paper is borrowed from the previous research [9] and shown in Table 1.

Table 1 Physical property parameters of the alloy

ρ kg·m^{-3}	T_S ^{o}C	T_L ^{o}C	L J·g^{-1}
043	60	70	27.9
c_{ps} J·g^{-1}·K^{-1}	c_{pl} J·g^{-1}·K^{-1}	k_s W·m^{-1}·K^{-1}	k_l W·m^{-1}·K^{-1}
0.27	0.297	19.2	14.5

2.2 Model validation

Prior to the calculation, an experimental case of a directionally solidified alloy bar (Sn-5wt%Pb, the total length is 100 mm and the initial temperature is 262 ^{o}C) [7] was adopted to validate our model on phase change process. The temperature distribution comparisons at the position of y=5, 15, 30 and 50 mm between simulation results and experimental data are provided in Fig. 1. It illustrates that the simulation results match well with the experimental data, and the maximum error is 3.5%.

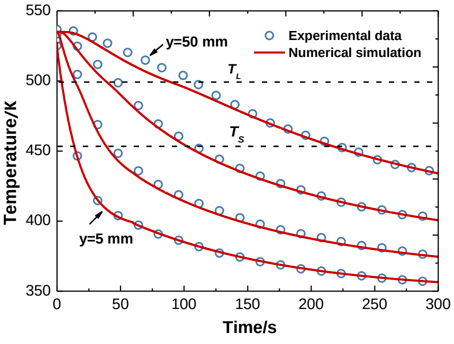

Fig. 1 Temperature comparison between the simulation results and experimental data.

3. RESULTS AND DISCUSSION

3.1 Melting process of low-melting alloy

The temperature distribution of low-melting alloy (31.6%-Bi, 48.8%-In and 19.6%-Sn) along the vertical direction is shown in Fig. 2. It indicates that the temperature of the position of y=0 mm rapidly increased to 60 ^{o}C, then the heating rate is reduced in the mushy zone which attributed to the release of latent heat, thereafter the temperature rises rapidly with a nearly constant rate. It proves that the increase of surface temperature is significantly delayed by the release of latent heat. By contrast, the heat rate is limited at T=50 ^{o}C for the position of y=10 mm, owing to the release of latent heat near the heating surface. Moreover, the reduction of heat rate gradually appears in a lower temperature along the vertical direction. Furthermore, the duration of mushy zone gradually increases along the vertical direction, which attributes to the increase of thermal resistance.

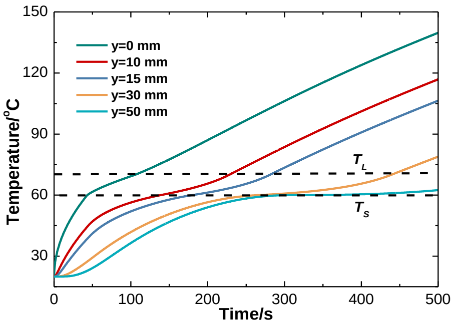

Fig. 2 Evolution of temperature distribution inside the alloy bar.

3.2 *Effect of mushy zone temperature interval*

The mushy zone is defined as the temperature range between the solidus temperature (T_S) and liquidus temperature(T_L), that is, it can be reflected by the temperature interval (T_L-T_S) and average temperature (0.5T_L+0.5T_S) of the mushy zone. The burnout temperature of chips (90 ^{o}C) and the effective protection time are key parameters to evaluate the performance of the heat sink with phase change materials. Therefore, they are adopted to reflect the influence of temperature range on the thermal performance of alloys. Fig. 3(a) shows the effect of temperature interval (the average temperature of mushy zone is set as 65 ^{o}C) on the temperature distribution at the position of y=0 mm. It illustrates that the effective protection time (τ_p) slowly increases from 209 to 228 s with the temperature interval of mushy zone increases from 1.0 to 30 ^{o}C. Moreover, the effect of temperature interval on the phase distribution along the vertical direction at τ=τ_p is obtained and displayed in Fig. 3(b). It indicates that the proportion of solid and liquid zone decrease with an increase in the temperature interval, whereas, the proportion of mushy zone increases rapidly. Thereby, the expansion of the τ_p is suppressed, owing to the reduction of liquid zone proportion and the increase of liquid zone proportion.

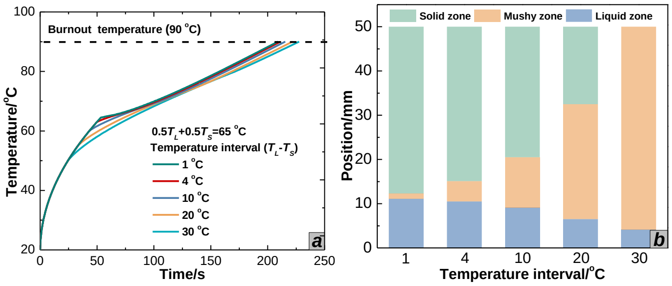

Fig. 3(a) Effect of temperature interval on the temperature distribution at y=0 mm (a) and phase distribution along the vertical direction at τ=τ_p (b).

Similarly, to explore the effect of mushy zone average temperature on the thermal performance, the temperature interval is set as 10 ^{o}C. Fig. 4(a) and (b) displays the effect of mushy zone average temperature on the temperature distribution at y=0 mm and phase distribution along the vertical direction at τ=τ_p, respectively. Fig. 4(a) shows that the τ_p increases 22% with the average temperature decreases from 70 to 50 ^{o}C. Correspondingly, the proportion of liquid and mushy zone increase from 13.4 and 19.6% to 33 and 46.4%, respectively, with the average temperature of mushy zone drops from 70 to 50 ^{o}C. That is, a lower average temperature of mushy zone is beneficial to improve the thermal performance of the alloy.

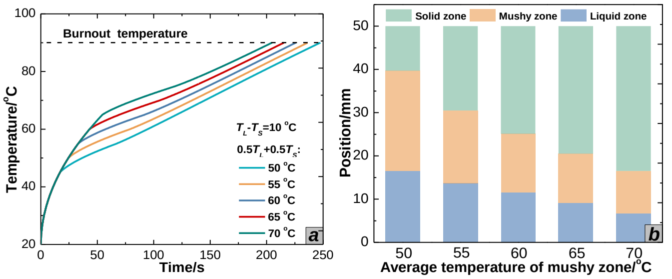

Fig. 4(a) Effect of mushy zone average temperature on the temperature distribution at y=0 mm (a) and phase distribution along the vertical direction at τ=τ_p (b).

4. CONCLUSIONS

In this paper, a one-dimensional enthalpy-based model is established to explore the melting process of an alloy bar. As the results, the temperature evolution and moving process of mushy zone along the vertical direction are obtained. Moreover, the effect of mushy zone temperature range is discussed on the motion of mushy zone. In accordance with the results and discussions, the main conclusions can be given as follows:

(1) The increase of surface temperature is significantly delayed by the release of latent heat. Moreover, the duration of mushy zone gradually increases along the vertical direction, which attributes to the increase of thermal resistance.

(2) Increasing the temperature interval of mushy zone is not an effective way to extend the effective protection time of alloy, owing to the increase of liquid zone proportion and the simultaneous reduction of liquid zone proportion.

(3) A lower average temperature of mushy zone is beneficial to improve the thermal performance of the alloy. Specifically, the effective protection time increases 22% with the average temperature decreases from 70 to 50 ^{o}C.

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