Numerical simulation of the thermal history of droplets during multi-stage atomization

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Abstract

Analyses are made on the characteristics of cooling and undercooled solidification of multi-stage atomized aluminum droplets. Models are established for Newtonian cooling, highly undercooled heterogeneous nucleation and steady-state continuous growth. They are used for numerical simulation of the thermal history of the droplets and the effects of the main atomization process parameters such as the extent of superheat and the speed of the rotating disk. Results show that large undercooling occurs mainly in the later stage of multi-stage atomization while recaescence and rapid quenching take place mainly in the forced cooling stage. The undercooling and cooling rates of the droplets are primarily dependent on the droplet diameter, and the main atomization parameters have little effect on the nucleation and solidification behavior of the droplets. © 2001 Published by Elsevier Science Ltd.

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1. Introduction

Multi-stage atomization is a new method of rapid solidification and powder-making that was developed by the authors [1–7]. It is a combination of gas atomization and centrifugal atomization. The melt is firstly atomized with an ordinary gas atomizer or a USGA nozzle into fine droplets. Then the droplets are sprayed onto the high-speed rotating disk and further pulvzerized by the disk. Water is sprayed onto the disk and is used as a forced cooling agent. The device can produce metallic powders with an average particle size of 10–15 μm, the cooling rates are $10^3$–$10^6$K/s and the production rate is 2–5 kg/min.

It is generally agreed that the heat flow conditions prior to and during solidification have the most pronounced effect on the achievable liquid/solid interface velocities and hence on the resulting microstructure. Yet, due to the difficulty of measurement, present understanding of the thermal history of multi-stage atomized powders and its relationship to process variables and interface kinetics is in an infant state.

2. Theoretical model

2.1. Interaction among droplets, flowing media and atomizer

(1) The flight law of droplets

The droplet velocities can be calculated from the equations shown in Ref. [1]. The relation between flying distance and time can be obtained by numerical integral.

(2) The particle size correlation of atomization

In the gas atomization stage, $d_m$ is given by Lubanska [10] as:

$$d_m = K_1 D[(1 + M_l/M_g)v_l/(y_g W_e)]^{1/2},$$

(1)

while in the centrifugal atomization stage, $d_m$ is given by Hazada [11] as:

$$d_m = K_2 (\omega R)^{(1/2)} (\rho_l / \rho)^{(1/2)},$$

(2)

(3) The correlation of heat transfer between droplets and coolants

According to the studies by the present authors [1], following correlation is suitable for multistage atomization:

$$Nu = 2 + 0.19 \Phi Re_1^{2/3} Pr_1^{1/3} + 0.25 (1 - \Phi) Re_2^{2/3} Pr_2^{1/3},$$

(3)

where $\Phi = 1$ for the gas atomization stage; $\Phi = 0$ for the...
forced cooling stage; \(0 < \phi < 1\) for the centrifugal atomization stage.

(4) The model of cooling

The following is the basic equation of the undercooled solidification of the droplets according to the Newtonian model [4]:

\[
(1 + 3B_1\Delta F_0)\theta_{k+1} + (\Delta C \theta_{k+1} - 1)f_{k+1} - (\psi_k - 1 - 3B_1\Delta F_0St) = 0. \tag{4}
\]

2.2. Nucleation and growth

The following is an empirical equation according to the DTA results of the undercooling of pure aluminum during multistage atomization [1]:

\[
\Delta T = 164.1 - 6.05 \ln d_m. \tag{5}
\]

The kinetic relationship suggested by Turnbull [8] for the steady-state continuous growth of a planar front is:

\[
V = \beta(D_{LM}/\delta)\exp(-E_{DL}/RT)[1 - \exp(-\Delta H_M/RT)]. \tag{6}
\]

The relation between \(f\) and \(\theta\) can be obtained from Ref. [4].

2.3. The cooling rates of the droplets during forced cooling stage

According to the Newtonian model, the cooling rates of the droplets can be calculated from the following:

\[
dT/dt = -6h(T_1 - T_2)/\rho C d_p, \tag{7}
\]

where \(h = (K/d_p)\rho \nu = (K/d_p)(2 + 0.25Pr^{1/3}Re^{2/3}), \ Re = \rho \nu d_p/\mu, \ Pr = cuK/\nu.

Based on the above models, pure aluminum was taken as an example to compute and simulate the thermal history of example droplets during multistage atomization. The values of the thermo-physical properties of pure aluminum used in the calculation are given in Refs. [8–11].

3. Numerical results and analyses

In Figs. 2 and 4, it can be seen that solidification mainly takes place at the forced cooling stage. The flight distance during solidification is very small and the time is very short. These show that rapid solidification occurs after nucleation.

As shown in Figs. 1 and 3, the thermal history of the droplets can be divided into three regimes. The first regime is that of undercooling which mainly includes the atomization stage and the early stage of forced cooling. In the atomization stage, the temperature of the droplets reduces slowly, but the multistage breakup of melts prepares for the formation of large undercooling. In the following early stage of forced cooling, the large reduction of temperature results in large undercooling. In this regime, the coolant absorbs the heat liberated by the droplets. The second regime is that of recalescence or solidification during which the droplets nucleate and solidify rapidly. Most of the liberated heat of fusion is absorbed by undercooled
melt and results in a sharp rise of the temperature of the droplets, which is still lower than the melting point. This regime is very transient. The following is the third regime: cooling of solid. The temperature of the droplets reduces quickly due to high specific heat and forced convection of water.

Fig. 5 shows that the cooling rates are mainly dependent on the diameters: the smaller the diameter, the higher the cooling rate. From Eq. (5), it can be concluded that the undercooling of the droplets is closely related to their diameters.

As shown in Figs. 1 and 2, the effect of superheat on the cooling and solidification procedure is not remarkable, while Figs. 3 and 4 show that the rotating rate of the disk not only affects the cooling and solidification process remarkably but also is closely related with the heat transfer and movement of droplets during the forced cooling stage. The higher the rotating rate of the disk, the higher the cooling rate of the droplets (Fig. 5).

As shown in Fig. 6, the velocity of the liquid/solid interface is very high at the primary stage of the highly undercooled solidification of droplets, but it declines rapidly when solidification and recalescence are in progress and a large amount of latent heat is liberated. At the later stage of solidification (when \( f \) is large), the role of recalescence becomes minor and the effect of external forced cooling becomes notable. These result in a short time for recalescence and a relatively long time for solidification, as shown in Figs. 1–4.

4. Conclusions

1. Large undercooling occurs mainly during the later stage of multistage atomization, while recalescence and rapid quenching take place mainly at the stage of forced cooling.
2. The undercooling and cooling rates are heavily dependent on the particle size of the droplets, the smaller the droplets, the higher the cooling rates. The direct effects of the key parameters for the atomization process such as superheat and the rotating rate of the disk on the cooling and solidification of droplets are different.

3. The thermal history of undercooled droplets during multi-stage atomization reflects the competition between external heat extraction and undercooled recalescence. This can be divided into three regimes: undercooling; recalescence and solidification; solid cooling. There are different laws for motion and heat transfer during the different regimes.

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