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A Simplified Model for Velocity and Temperature Evolution of Alloy Droplets in Centrifugal Atomisation and Spray Deposition

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Abstract A model has been developed for the velocity and temperature evolution of a metal alloy droplet with travel distance in centrifugal atomisation. The droplet velocity decreases rapidly with increasing travel distance. The degree of droplet cooling at a certain travel distance decreases with increasing droplet velocity, increasing diameter and decreasing temperature, and is also affected by the droplet physical properties. The solidification of the droplets is largely dependent upon the latent heat removal.

Introduction

Centrifugal atomisation is a specialised powder manufacturing method and has been used for processing a wide range of alloys [1]. It is particularly suitable for processing high purity or reactive metals and alloys of current interest to aerospace, biomedical and energy storage applications, because of its unique capability of operating under a reduced pressure or in vacuum. One of the problems of centrifugal atomisation in powder production, however, is that a large cooling chamber is usually needed in order to ensure complete solidification of all the spray droplets. Understanding of the heat transfer of the droplets in flight is therefore crucial for the process to realise its full commercial potential.

In centrifugal atomisation, the developments of the velocity, trajectory and temperature of the spray droplets are well defined once their initial conditions at the edge of the atomising disc are known. Unlike in gas atomisation, where the liquid metal is subject to a high velocity gas stream, the spray droplets in centrifugal atomisation can be considered to be travelling in a still gas medium. The droplet cooling is realised by the forced convection and radiation, both of which depend on the velocity development of the droplets in flight. Zhao has developed a semi-analytical model to calculate the variations of droplet velocity and temperature in flight [2]. However, it is only suitable for pure metals with no radiation heat losses.

This paper develops a simplified numerical model for the velocity and temperature evolution of an alloy droplet with travel distance as a function of droplet diameter, initial superheat and initial velocity. The model is illustrated by a typical alloy processed by centrifugal atomisation.

Model

Droplet Velocity In centrifugal atomisation, the liquid droplets travelling in still air conditions are subject to a gravitational force and a drag force exerted by the air as a result of the droplet movement. Neglecting gravity, the droplets ejected from the atomising disc can be treated as travelling horizontally along straight lines. Assuming that the droplets are spherical and maintain their shapes in flight throughout cooling and solidification, the drag force on a droplet with a diameter of D, F_D, is [3]:

$$F_D = \tfrac{1}{2} C_D r_a A_f v^2 , \qquad (1)$$

where C_D is the drag coefficient, r_a is the specific density of air, $A_f = (1/4)\pi D^2$ is the frontal area of the droplet, and v is the droplet velocity. The drag coefficient of a spherical particle is a function of the Reynolds number and can be calculated empirically by [4]:

$$C_D = \begin{cases} 24\mathrm{Re}^{-1} & \mathrm{Re} < 0.2 \\ 0.4 + 40\mathrm{Re}^{-1} & 0.2 < \mathrm{Re} < 1000. \\ 0.44 & \mathrm{Re} > 1000 \end{cases} \quad (2)$$

The Reynolds number of the droplet is $Re = (r_a Dv)/m$, where m is the viscosity of air.

The acceleration of the droplet as a result of the drag force is therefore:

$$\frac{dv}{dt} = -\frac{F_D}{\rho V} = -\frac{C_D \rho_a v^2}{4\rho D}, \quad (3)$$

where $V = (1/6)\pi D^3$ is the volume and r is the specific density of the droplet.

As an infinitesimal time interval, dt, corresponds to an infinitesimal travel distance, dr, by $dt = dr/v$, the relationship between the changes in droplet velocity, dv, and in travel distance is therefore:

$$dv = -\frac{C_D r_a v}{4rD} dr. \quad (4)$$

Droplet Temperature Droplet cooling is dependent upon radiation and convective heat transfer. The heat removed from a droplet when it travels an infinitesimal distance dr is:

$$dQ = [esA(T^4 - T_a^4) + hA(T - T_a)]\frac{dr}{v}, \quad (5)$$

where e is the emissivity of the droplet, $s = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is the Stefan-Boltzmann constant, h is the convection heat transfer coefficient for the droplet, $A = \pi D^2$ is the surface area of the droplet, and T and T_a are the temperatures of the droplet and the air respectively. The first and second terms on the right-hand-side of equation (5) are the amounts of heat removed due to radiation and convective heat transfer between the droplet and the air, respectively. The heat transfer coefficient h of a spherical droplet travelling in still air conditions can be calculated from the Ranz and Marshall correlation of the average Nusselt number Nu [5] and is expressed by:

$$h = \frac{kNu}{D} = \frac{k}{D}\left(2 + 0.6\, Re^{\frac{1}{2}} Pr^{\frac{1}{3}}\right), \quad (6)$$

where k and Pr are the thermal conductivity and Prandtl number of air, respectively.

When the droplet is still fully liquid or has completely solidified, the amount of heat removal, dQ, corresponding to a change in droplet temperature, dT, is simply:

$$dQ = -rVC_p dT, \quad (7)$$

where C_p is the specific heat of the droplet. The temperature range of interest to droplet cooling in centrifugal atomisation and spray deposition is between the initial melt temperature and the full solidification temperature. As this temperature range is relatively small, the specific heat of the droplet can be treated as constant, regardless of whether it is in the liquid or solid state.

When the droplet is in the freezing range of the alloy between the liquidus and solidus temperatures, the heat removal has a component due to latent heat and a component due to specific heat. As a first order approximation, the latent heat of solidification of the alloy at any specific temperature can be calculated from those of the alloying elements by the rule of mixture. As the latent heat of solidification of a pure element at a temperature T other than its melting point is equal to the latent heat at the equilibrium melting point [6], the latent heat of solidification of the alloy at any temperature T in the freezing range is therefore:

$$L = \sum w_i L_i \,, \tag{8}$$

where w_i and L_i are the weight fraction in the alloy and latent heat of solidification of a constituent element i.

At a temperature within the freezing range, the droplet is partly solid and partly liquid. Under equilibrium conditions, the compositions and amounts of the solid and liquid phases can be determined from the phase diagram. In practice, however, the cooling of the droplet is too fast for equilibrium conditions to be established. The information of the compositions and amounts of the solid and liquid phases as a function of temperature is extremely difficult to obtain either theoretically or experimentally. As a first order approximation, the solid and liquid phases can be assumed to have the same composition as the alloy and the fraction of the solid phase can be assumed proportional to the temperature drop from the liquidus relative to the freezing range:

$$f_s = \frac{T_l - T}{T_l - T_s}, \tag{9}$$

where T_l and T_s are the liquidus and solidus temperature, respectively. The change of the fraction of solid corresponding to a change in droplet temperature, dT, is therefore:

$$df_s = -\frac{dT}{T_l - T_s}\,. \tag{10}$$

The amount of heat removal, dQ, corresponding to a change in droplet temperature, dT, in the freezing range is the sum of the latent heat and specific heat components:

$$dQ = rV(df_s L - C_p dT) = rV\left(\frac{L}{T_l - T_s} + C_p\right) dT\,. \tag{11}$$

The term in the last pair of brackets in the above equation can be conveniently treated as the specific heat of the alloy in the freezing range. Combining equations (5) with (7) or (11) gives the temperature drop as a function of travel distance:

$$dT = -\frac{3[es(T^4 - T_a^4) + h(T - T_a)]}{2rCDv} dr, \tag{12}$$

where

$$C = \begin{cases} C_p & T \geq T_l \ or\ T \leq T_s \\ \frac{L}{T_l - T_s} + C_p & T_s < T < T_l \end{cases}. \tag{13}$$

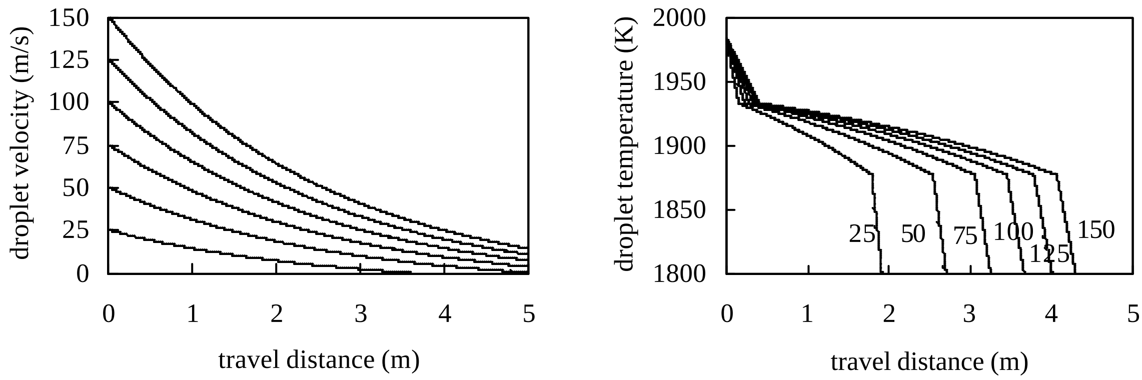
Solidification of pure metals or eutectic alloys takes place and completes at constant temperatures approximately equal to their melting points, T_m. The temperature of a droplet only starts to drop when the latent heat of solidification is removed. The travel distance between the start and completion of the solidification, r_s, can be calculated by:

$$\sum^{r_s} dQ\big|_{T=T_m} = r\,VL\,. \qquad (14)$$

The velocity and temperature of the droplet as a function of travel distance can be easily calculated based on equations (4) and (12) by a simple computer programme or by a spreadsheet package such as Microsoft Excel.

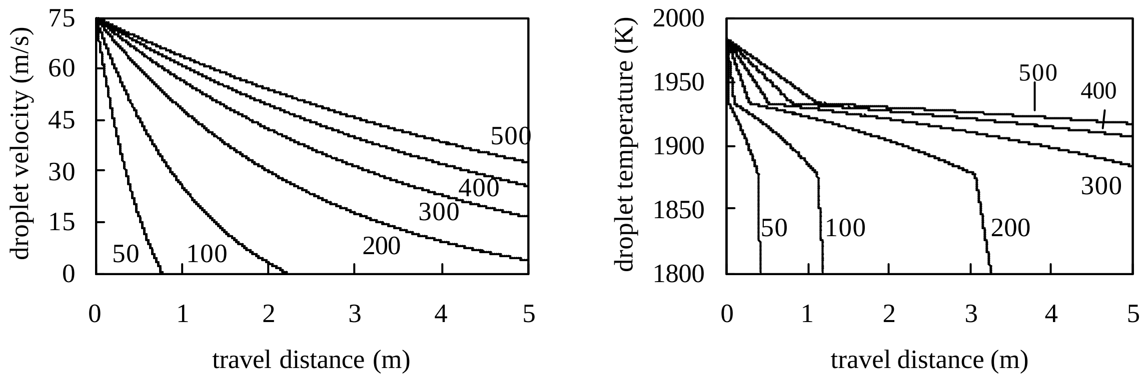
Discussion

To illustrate the model, a Matlab programme has been created to calculate the velocity and temperature of the droplet as a function of travel distance for Ti-6Al-4V alloy centrifugally atomised in air. In the calculations, the air is assumed to be at the atmospheric pressure and at a constant temperature of 298 K. The specific density, viscosity, thermal conductivity and Prandtl number of air at 298 K are 1.16 kg/m^3, 1.85$\times$10^{-5} N s/m^2, 0.026 W/m K and 0.707, respectively [3]. The physical properties of Ti-6Al-4V are assumed to be constant in the temperature range of interest and equal to those at the melting point in the liquid state. The density, specific heat,



(a) (b)

Fig. 1 Variations of (a) velocity and (b) temperature with travel distance for 200 μm Ti-Al-4V droplets at different initial velocities



(a) (b)

Fig. 2 Variations of (a) velocity and (b) temperature with travel distance for different sized Ti-Al-4V droplets at an initial velocity of 75 m/s liquidus and solidus are 4430 kg/m^3, 526.3 J/kg K, 1933 K and 1877 K, respectively [7]. The latent heats of Ti, Al and V are 365500, 388100 and 328600 J/kg [7], giving the latent heat of Ti-6Al-4V as 365380 J/kg. The emissivity of the Ti-6Al-4V droplet in air is assumed to be 0.1, which is typical of metals.

Fig. 1 shows the variations of droplet velocity and temperature with travel distance for 200-μm droplets with different initial velocities of 25, 50, 75, 100, 125 and 150 m/s. With a fixed droplet diameter, the initial velocity has a dominant effect on the development of droplet velocity and temperature. The travel distance at full solidification increases with increasing initial droplet velocity. The latent heat removal accounts for a large proportion of the total heat removal.

Fig. 2 shows the variations of droplet velocity and temperature with travel distance for 50, 100, 200, 300, 400 and 500-μm droplets with an initial velocity of 75 m/s. With a fixed initial droplet velocity, increasing droplet diameter leads to a decrease in the droplet deceleration and a significant increase in the travel distance before full solidification.

Because most alloys used in centrifugal atomisation contain less than 10% of alloying elements, it is reasonable to treat both the liquid and solid phases as ideal solutions. The specific heat and latent heat of an alloy can often be approximated by the rule of mixture if the data is not readily available. The calculations for Ti-6Al-4V also show that radiation is not significant (<5%) compared with convection. The value of emissivity is therefore not critical to the calculations.

Conclusion

A numerical model has been developed for calculating the variations of droplet velocity and temperature with travel distance as a function of droplet diameter, initial velocity and initial superheat for metal alloys in centrifugal atomisation. The droplet velocity decreases rapidly with increasing travel distance. The droplet diameter and initial velocity have a dominant effect on the development of droplet velocity and temperature. The solidification of the droplets is largely dependent upon the latent heat removal.

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