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Materials and Design 27 (2006) 745–750

Materials & Design

www.elsevier.com/locate/matdes

Considerations in designing a centrifugal atomiser for metal powder production

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Received 6 September 2004; accepted 12 January 2005
Available online 25 February 2005

Abstract

In centrifugal atomisation for metal powder production, the key to the control of the particle sizes is the design of the atomiser. This paper studies the main issues concerned in designing a centrifugal atomiser and provides guidance on the selection of an electric motor, radius of atomiser, slope angle of atomiser wall and flow rate of cooling water. In the selection of the atomiser radius, the power and material constraints as well as the hydraulic jump radius need to be considered. A cup atomiser with a slope angle of 60–70° would result in small spray droplets and thus a fine powder. The water cooling system needs to be assessed by examining the heat flow in the solid metal layer and in the atomiser.

Keywords: Centrifugal atomisation; Atomiser; Design; Powder production

1. Introduction

Centrifugal atomisation is a well-established process for manufacturing particulate products from water-based liquids and slurries in the chemical and agricultural industries [1]. In the last three decades, centrifugal atomisation has been used for processing metals for powder production or spray deposition [2–9]. The properties of the end products are largely determined by the sizes and velocities of the spray droplets ejected from the atomiser. In powder production, droplet sizes are particularly important because they dictate the particle sizes of the as-produced powder. The key to the control of the droplet size range in centrifugal atomisation is the design of the atomiser.

From a theoretical point of view, a flat disc would suffice, as long as it wets the liquid to be atomised. Because droplet sizes decrease with increasing disc rotation speed and with increasing disc radius [10–12], any droplet size could be obtained simply by varying disc rotation speed and/or disc radius. In practice, however, the disc rotation speed and disc size are limited not only by the capability of commercially available electric motors but also by the mechanical stability of the atomiser assembly. Furthermore, it is practically impossible to fabricate an atomiser that fully wets the liquid metal to be processed. A practical measure to tackle the wetting problem is using a cup shaped atomiser so that the liquid is pressed against the cup wall by the centrifugal force [13,14].

In designing a centrifugal atomiser, the most important parameters to be considered are diameter, rotation speed and geometry. In the centrifugal atomisation of liquid metals, water cooling of the atomiser also needs to be given due consideration because of the elevated temperatures involved. In the absence of adequate theoretical and empirical knowledge, the geometry and operating conditions of the atomiser are often chosen on the basis of the easiness of fabrication and best guesses. The information on the atomiser designs, for metal processing in particular, is lacking in the public domain.

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doi:10.1016/j.matdes.2005.01.011

This paper studies the main issues concerned in designing a centrifugal atomiser and provides guidance on the selection of an electric motor, radius of atomiser, slope angle of atomiser wall and flow rate of cooling water.

2. Selection of electric motor

2.1. Rotation speed

For most industrial applications of metal powders, the desirable particle size range falls within 20–100 μm. In order to obtain a powder with a narrow particle size distribution below 100 μm, a powerful and high-speed electric motor is required to drive the centrifugal atomiser.

In selecting an electric motor, the first criterion is the maximum rotation speed. Standard electric motors with a variable rotation speed up to 18,000 revolutions per minute (rpm) are readily available in the market. These motors are usually robust, do not have stability problems and do not require special cooling measures. Electric motors with rotation speeds up to 60,000 rpm are also available. However, atomisers operated at these speeds pose significant stability problems so they must be balanced carefully. There may also be loading and cooling constraints. Due to these problems, together with the associated high cost, electric motors with extremely high rotation speeds may not be the best option for industrial-scale production.

2.2. Power

The second criterion in selecting an electric motor is its power, which should be high enough to accelerate the liquid metal to a high velocity and to break it up into droplets. In atomisation of liquids, only a small amount of the input energy is consumed in creating the surface area of the droplets. The ratio between the surface energy of the droplets and the input energy is termed as energy efficiency. Each atomisation technology has an energy efficiency that does not vary very much with operation conditions. The energy efficiency of centrifugal atomisation is typically in the region of 0.5% [8]. The power required to produce a powder with a certain mean droplet size can therefore be estimated quite easily.

Given a volume flow rate of the liquid metal, Q, and the intended mean droplet size, D, the total surface area created in unit time is:

$$S = \frac{6Q}{D}. \quad (1)$$

The minimum power specification of the electric motor is therefore

$$W = \frac{\gamma S}{\eta} = \frac{6\gamma Q}{\eta D}, \quad (2)$$

where γ is the surface tension of the liquid metal and $\eta \approx 0.005$ is the energy efficiency of centrifugal atomisation. The power demand is roughly proportional to the volume flow rate and inversely proportional to the droplet size.

Take the atomisation of liquid tin as an example. Liquid tin has a surface tension of $\gamma = 0.57$ N/m [8]. To produce a tin powder with a mean droplet size of $D = 100$ μm at a rate of 5 kg/min ($Q = 1.2 \times 10^{-5}$ m^3/s), the minimum power required is calculated to be 82 W. To produce a powder with a mean droplet size of $D = 20$ μm at the same flow rate, the power demand is increased to 410 W.

3. Atomiser radius

3.1. Maximum radius – power constraint

The majority of the input energy in centrifugal atomisation is consumed in accelerating the liquid metal to a high velocity at the edge of the atomiser. The power consumption can therefore be approximated by

$$W = \frac{1}{2}\rho Q v^2, \quad (3)$$

where ρ is the specific density of the liquid metal and v is the velocity of the spray droplets ejected from the atomiser.

The spray droplets or ligaments leaving the atomiser have two velocity components. The radial component is usually much lower than the azimuthal component and can be neglected. The azimuthal velocity of the liquid is lower than the circumferential velocity of the atomiser because of slippage. The degree of slippage depends on atomiser geometry and rotation speed, the volume flow rate of the liquid metal and the wettability between the liquid metal and the atomiser. However, it is not necessary to consider the slippage in the design stage, because what we are concerned is the maximum possible velocity of the liquid metal. As a first order approximation, the velocity of the spray droplets at the edge of the atomiser can be regarded as equal to the circumferential velocity of the atomiser. The highest velocity is simply:

$$v = \omega R, \quad (4)$$

where ω is the rotation speed (radian/s) and R is the radius of the atomiser.

At the chosen operational rotation speed and a given liquid metal flow rate, a direct relationship between the power consumption and the atomiser radius can be established by combining Eqs. (3) and (4). The maximum radius of the atomiser is limited by the power of the electric motor as follows:

$$R_{\max} = \frac{1}{\omega}\sqrt{\frac{2W}{\rho Q}}. \quad (5)$$

It is worth noting that the unit of the rotation speed to be used in the calculations is radian/s. The rotation speed of an electric motor is often given in RPM only. To convert the rotation speed from RPM to radian/s, a factor of π/30 must be multiplied.

3.2. Maximum radius – material constraint

In addition to the constraint set by the electric motor power, the strength of the atomiser material must also be considered. The atomiser is subject to high tension at both the radial and azimuthal directions due to the centrifugal force at a high rotation speed. Let us consider a flat disc that has a radius of R, a thickness of t and a density of ρ_a, and rotates at a speed of ω (radian/s). Given a ring with an infinitesimal radial thickness dr at a radius r, the mass of the ring is:

$$m = \rho_a \cdot 2\pi rt\,dr. \quad (6)$$

The centrifugal force exerted on the ring is therefore [15]:

$$dF = m\omega^2 r = \rho_a \cdot 2\pi\omega^2 r^2 t\,dr. \quad (7)$$

Assume that the centrifugal force is balanced by a radial tension in the ring. The difference in the tensile forces between the inner and outer circumferences of the ring must be equal to this centrifugal force. The tension difference along the radial direction is therefore:

$$d\sigma_r = -\frac{dF}{2\pi rt} = -\rho_a\omega^2 r\,dr. \quad (8)$$

Because there is no tension at the outer circumference of the disc, i.e., $\sigma_r = 0$ at $r = R$, Eq. (8) can be integrated as follows:

$$\int_0^{\sigma_r} d\sigma_r = \int_R^r -\rho_a\omega^2 r\,dr, \quad (9)$$

which gives the radial tension at any radius r as:

$$\sigma_r = \frac{1}{2}\rho_a\omega^2(R^2 - r^2). \quad (10)$$

Now assume that the centrifugal force is balanced by an azimuthal tension in the ring. The ring can thus be considered to be a thin cylindrical shell subject to an internal pressure. The internal pressure is positive and quantitatively equal to the radial tension difference between the inner and outer circumferences of the ring as derived in Eq. (5). The azimuthal tension in the ring is therefore [16]:

$$\sigma_\theta = \frac{-d\sigma_r r}{dr} = \rho_a\omega^2 r^2. \quad (11)$$

In practice, the centrifugal force results in both radial and azimuthal tensions in the disc. From a designer point of view, however, it is unnecessary to consider the proportion between the radial and azimuthal tensions. Eqs. (10) and (11) give the maximum values of the radial and azimuthal tensions in the disc. The material of the atomiser must be able to withstand both the maximum radial tension and the maximum azimuthal tension without plastic deformation or fracture. In other words, both the radial and azimuthal tensions must be below the yield or fracture strength of the material with an appropriate safety factor.

Fig. 1 shows schematically the variations of radial and azimuthal tensions with radial distance up to the disc radius R. It is shown that the maximum possible tension is the azimuthal tension at the circumference of the disc. Given the yield or fracture strength of the atomiser material, σ_y, and the safety factor, s, the condition that needs to be met is:

$$\sigma_\theta|_{r=R} \leqslant \frac{\sigma_y}{s}. \quad (12)$$

The maximum radius of the atomiser that can be chosen is therefore:

$$R_{\max} = \frac{1}{\omega}\sqrt{\frac{\sigma_y}{s\rho_a}}. \quad (13)$$

3.3. Minimum radius

The liquid flow on a rotating disc or cup is very complex. A hydraulic jump often occurs on the atomiser. The hydraulic jump is an annular discontinuity in the flow manifested by an abrupt increase in the melt thickness and correspondingly a reduction in the radial velocity. Whilst the behaviour of the flow prior to the hydraulic jump is affected by the continuity and velocity of the liquid stream at the impingement of the atomiser, the flow after the hydraulic jump is completely controlled by the rotating atomiser and is insensitive of the fluctuations in the liquid stream. From a practical point of view, it is advantageous for the liquid metal to disintegrate after the hydraulic jump has occurred so that the effect of any fluctuations is minimised. The radius of the atomiser should be greater than the

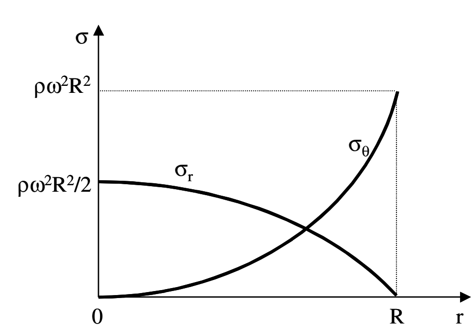

Fig. 1. Schematic diagram showing the variations of maximum radial and azimuthal tensions in a rotating disc with radial distance.

hydraulic jump radius. The minimum atomiser radius is therefore the hydraulic jump radius and can be approximated by [17]:

$$R_{\min} = 0.55\left(\frac{\rho Q^2}{\mu\omega}\right)^{\frac{1}{4}}, \tag{14}$$

where μ is the viscosity of the liquid metal.

4. Slope angle of cup wall

In practical atomisation conditions, the liquid metal does not fully wet the atomiser. The liquid metal film on a flat disc tends to disintegrate into ligaments or droplets before reaching the disc edge when the film thickness is reduced to a certain critical value [13]. This critical film thickness largely determines the minimum droplet size that can be obtained. In order to produce small droplets, it is desirable to have a high degree of spreading and thus a small critical film thickness. A cup shaped atomiser can increase the spreading significantly compared with a flat disc, because the centrifugal force exerts a pressure in the liquid film towards the cup wall.

The main consideration in designing a cup is the selection of a suitable slope angle of the cup wall. The slope angle is defined as the angle between the cup wall and the cup bottom plane. Varying the slope angle affects the liquid film thickness prior to film disintegration in two different ways. On the one hand, the film thickness at the cup edge increases with increasing slope angle, provided the film is continuous [12]. This means that a smaller slope angle is preferred if the liquid metal fully spreads on the atomiser. On the other hand, increasing slope angle increases the radius at which the liquid film starts to disintegrate prematurely and decreases the film thickness at the point of disintegration [13]. This means that the slope angle has to be great enough to ensure a good spreading of the liquid metal on the cup. As a consequence, there is an optimum slope angle for a fixed set of operation parameters.

A numerical model has been developed for calculating the optimum slope angle of a cup atomiser [13]. However, it requires the knowledge of the dynamic contact angle between the liquid metal and the cup, which is not readily available. The slope angle of the atomising cup is usually determined experimentally. The work by Xie et al. [14] showed that a slope angle in the region of 60–70° produced the finest powder.

5. Water cooling

In the centrifugal atomisation of liquid metals, the atomiser is normally water cooled because of the high temperatures involved. In processing reactive or high-melting-point liquid metals, such as titanium, water cooling is an essential measure to create a solid layer of the metal at the surface of the atomiser, so that the liquid metal does not erode the atomiser and the contamination of the liquid is also eliminated. Designing a water cooling system for an atomiser rotating at high speeds is not a simple task. This article is not concerned with the mechanical and geometrical features of the cooling channels and the input and output mechanisms of the cooling water, which can normally be designed independent of the atomisation conditions. This article is concerned with the selection of cooling water flow rates for different atomising conditions.

Fig. 2 shows a schematic diagram of an atomiser that is water cooled underneath. The liquid metal impinging on the atomiser will solidify and form a solid layer of the metal, if the heat extraction by the cooling water exceeds the superheat of the liquid metal. In production, a thin solid layer in the range of 0.1–2 mm is desirable. Too thick a layer leads to reduced material yields, worsened atomisation conditions, and increased proneness to instability. If the solid metal layer is too thin, however, any fluctuation in the liquid metal flow may remelt it, damaging the protection against the direct contact between the liquid metal and the atomiser.

The cooling process of the liquid metal is complex because of the involvement of fluid flow, phase transformation, conduction, radiation and the geometrical complexity. To obtain a first order estimation, however, it is sufficient to consider the heat flow as a one-dimensional steady problem. The heat transfer from the liquid metal to the cooling water can be considered as the dominant mechanism. Once a steady state is established, the liquid metal flow on the atomiser does not solidify. The temperature of the liquid film at the interface with the top surface of the solid layer is maintained at the melting point of the metal. The temperature of the liquid film at its top surface is likely to remain at the pouring temperature. The heat loss can be estimated as half of the superheat and equal to the heat carried away by the cooling water, i.e.:

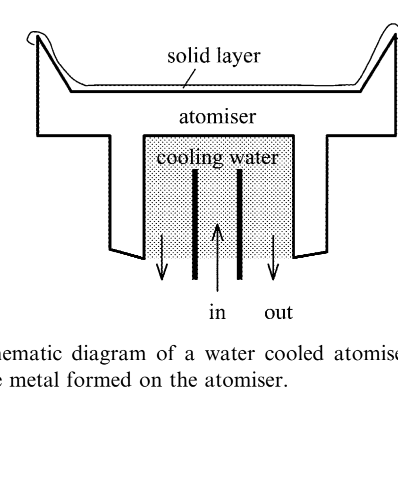

Fig. 2. Schematic diagram of a water cooled atomiser with a solid layer of the metal formed on the atomiser.

$$0.5\rho cQ(T_p - T_m) = \rho_w c_w F(T_w - T_o), \tag{15}$$

where c is the specific heat of the liquid metal, T_p is the pouring temperature of the liquid metal, T_m is the melting point of the liquid metal, ρ_w is the density of water, c_w is the specific heat of water, F is the volume flow rate of the cooling water, T_w is the maximum temperature of cooling water, or the temperature of the atomiser at the interface with the cooling water, and T_o is the temperature of the cooling water before entering the cooling channel.

In normal conditions of efficient cooling, the maximum temperature of the cooling water should be kept 20 °C below the boiling point. The difference between T_w and T_o is roughly 50–60 °C. The volume flow rate of the cooling water can therefore be estimated by:

$$F \approx \frac{0.01\rho cQ(T_p - T_m)}{\rho_w c_w} \tag{16}$$

In steady-state atomisation, the heat is extracted at a constant heat flux through the solid metal layer and the atomiser. The heat flux is equal to the heat loss of the liquid metal divided by the area of the cross section where the heat passes through. The cross sectional area of the heat flux, A, can be regarded as the area of the top surface of the cooling channel as shown in Fig. 2. According to the heat conduction law for a one-dimensional steady-state problem, there is:

$$\frac{0.5\rho cQ(T_p - T_m)}{A} = \kappa_m \frac{T_m - T_i}{t_m} = \kappa_a \frac{T_i - T_w}{t_a}, \tag{17}$$

where κ_m is the thermal conductivity of the solid metal, T_i is the temperature at the interface between the solid layer and the atomiser, t_m is the thickness of the solid layer, κ_a is the thermal conductivity of the atomiser, and t_a is the thickness of the atomiser in the cooling region. Eq. (17) gives:

$$T_i = T_w + \frac{0.5\rho cQ(T_p - T_m)t_a}{\kappa_a A} \tag{18}$$

and

$$t_m = \frac{\kappa_m A(T_m - T_w)}{0.5\rho cQ(T_p - T_m)} - \frac{\kappa_m}{\kappa_a} t_a. \tag{19}$$

The two parameters calculated by Eqs. (18) and (19) provide indicative information on whether the cooling system would work properly. The temperature at the bottom of the solid layer, T_i, should be lower than the melting point of the atomiser material by a margin of at least 100 °C. If T_i, as calculated by Eq. (18), is too high, the thickness of the atomiser in the cooling region, t_a, should be reduced to bring the atomiser temperature down. The thickness of solid metal layer should normally fall within 0.1–2 mm. If t_m, as calculated by Eq. (19), is greater than 2 mm, the thickness of the atomiser in the cooling region, t_a, should be increased, or alternatively the flow rate of the cooling water is reduced. If t_m is smaller than 0.1 mm, the thickness of the atomiser in the cooling region, t_a, should be decreased, or alternatively the flow rate of the cooling water is increased. In any case where either atomiser thickness or water flow rate is changed, assessment of the water cooling system should be carried out again.

6. Conclusions

In designing a centrifugal atomiser, an electric motor with a high working rotation speed and sufficient power should be selected first. The maximum radius of the atomiser is determined by the power and material constraints and the minimum radius is determined by the hydraulic jump radius. A cup atomiser with the slope angle of the cup wall in the region of 60–70° would result in a good spreading of the liquid film on the atomiser and thus small spray droplets. The flow rate of the cooling water can be estimated from the pouring conditions of the liquid metal and the suitability of the design of the cooling system can be assessed by examining the heat flow in the solid metal layer and in the atomiser.

References

[1] Masters K. Spray drying handbook. 5th ed. Essex: Longman Scientific & Technical; 1991.

[2] Singer ARE, Kisakurek SE. Centrifugal deposition of aluminium strip. Metals Tech 1976;3:565–70.

[3] Rickinson BA, Kirk FA, Davies DRA. CSD – a novel process for particle metallurgy products. Powder Metall 1981;24:1–6.

[4] Anderson R. Powder metallurgy at Pratt and Whitney. Int J Powder Metall 1990;26:171–9.

[5] Angers R. Centrifugal atomization: influence of process parameters on size distribution. In: Capus JM, German RM, editors. Powder production and spray forming: advances in powder metallurgy and particulate materials. Princeton: Metal Powder Industries Federation; 1992. p. 79–88.

[6] Osborne MG, Anderson IE, Funke KS, Verhoeven JD. Centrifugal atomization into a rotating quench bath. In: Capus JM, German RM, editors. Powder production and spray forming: advances in powder metallurgy and particulate materials. Princeton: Metal Powder Industries Federation; 1992. p. 89–103.

[7] Sears JW, Itoh G, Loretto MH. Spray forming of Ti-aluminide-based alloys. In: Froes FH, Caplan I, editors. Titanium '92: science and technology, vol. 2. Warrendale: Minerals, Metals & Materials Society; 1993. p. 987–1002.

[8] Yule AJ, Dunkley JJ. Atomization of melts for powder production and spray deposition. Oxford: Clarendon Press; 1994.

[9] Dowson AL, Duggan MA, Zhao YY, Jacobs MH, Young JM. Microstructure and thermo-mechanical processing response of spray formed Ti alloys produced by centrifugal spray deposition. In: Cadle TM, Narasimhan KS, editors. Advances in powder metallurgy & particulate materials, vol. 3. Princeton: Metal Powder Industries Federation; 1996. p. 9/67–78.

[10] Zhao YY, Dowson AL, Johnson TP, Young JM, Jacobs MH. Prediction of liquid metal velocities on a rotating disk in spray forming by centrifugal spray deposition. In: Cadle TM, Narasimhan KS, editors. Advances in powder metallurgy & particulate

materials, vol. 3. Princeton: Metal Powder Industries Federation; 2001. p. 9/79–89.
[11] Zhao YY, Dowson AL, Jacobs MH. Modelling liquid flow after a hydraulic jump on a rotating disk prior to centrifugal atomization. Modelling Simul Mater Sci Eng 2000;8:55–65.
[12] Zhao YY. Analysis of flow development in centrifugal atomisation Part I: film thickness of a fully spreading melt. Modelling Simul Mater Sci Eng 2004;12:959–71.
[13] Zhao YY. Analysis of flow development in centrifugal atomisation Part II: disintegration of a non-fully spreading melt. Modelling Simul Mater Sci Eng 2004;12:973–83.
[14] Xie JW, Zhao YY, Dunkley JJ. Effects of processing conditions on powder particle size and morphology in centrifugal atomisation of tin. Powder Metall 2004;47:168–72.
[15] Bueche FJ. Introduction to physics for scientists and engineers. Tokyo: McGraw-Hill Kogakusha Ltd; 1975.
[16] Parnes R. Solid mechanics in engineering. Chichester (NJ): Wiley; 2001.
[17] Zhao YY, Jacobs MH, Dowson AL. Liquid flow on a rotating disk prior to centrifugal atomization and spray deposition. Metall Mater Trans B 1998;29:1357–69.