Powder Technology 318 (2017) 62–67

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Particle size distribution of tin powder produced by centrifugal atomisation using rotating cups

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ARTICLE INFO

Article history:
Received 13 February 2017
Received in revised form 11 May 2017
Accepted 21 May 2017
Available online 22 May 2017

Keywords:
Centrifugal atomisation
Powder
Particle size distribution
Atomiser

ABSTRACT

Centrifugal atomisation is a low-cost technology for producing metal powders, but its wide applications are hampered by its limited capability of producing fine powders and there is insufficient research on the particle size distributions of centrifugally produced powders. This paper studies the effects of the atomiser geometry and the key process parameters on the particle size distribution of tin powders produced by centrifugal atomisation. The results showed that the particle sizes of the as-produced powders follow lognormal distribution. The median particle size for all atomisers decreases with increasing atomiser rotation speed and with decreasing melt flow rate, due to reduced film thickness of the melt before disintegration. The cup atomiser with a wall angle of 67.5° produced the finest powders, because of a significant improvement of dynamic wetting between the melt and the atomiser. The particle size distributions of all the powder samples have a similar lognormal bell shape with the geometric standard deviations between 1.6 and 2.5. Narrow particle size distributions can be achieved by reducing the variability of any of the processing parameters affecting the particle size.

1. Introduction

Centrifugal atomisation has been used for producing metal powders for several decades [1]. Its main advantages as an industrial scale technology are low production cost and high productivity for producing powders of relatively large particles. Recent applications include uranium fuel powders [2,3] and solder powders [4,5]. However, centrifugal atomisation is not as widely used in industry as the gas and water atomisation techniques, because of its limited capability of processing high-melting-point metals and producing fine powders. Several technical challenges in the design of centrifugal atomisers need to be overcome [6]. Firstly, a very high rotation speed is required to generate centrifugal forces great enough to break up the liquid metal into droplets in the desirable size range of 20–50 μm. This high rotation speed is often practically difficult to achieve due to the lack of robust high speed motors free of vibration problems. Secondly, the atomiser must be able to withstand the elevated temperature of the liquid metal for long periods of time and therefore needs to be water-cooled for most liquid metals. From the design and operational point of view, water cooling of a rapidly moving part is undesirable. Thirdly, a bulky chamber is required for the solidification of the high-velocity liquid metal droplets. Tian et al. [7] have recently designed and built a centrifugal atomiser to address these issues. They used an externally mounted router motor that was magnetically coupled to the atomiser to provide a rotational speed up to 24,000 rpm and used a rotating quench bath filled with oil to provide efficient cooling of the liquid droplets. However, further technical development and scientific understanding of the centrifugal atomisation process are still necessary before it becomes a more competitive metal production process.

Hinze and Milborn [8] studied atomisation of liquids from a rotating cup and identified three modes of liquid disintegration: direct droplet formation (DDF), ligament disintegration (LD), and film disintegration (FD). In the DDF regime, the droplet sizes of some metals may be estimated theoretically from the atomising conditions [9]. The droplet size distributions become increasingly poly-disperse as the disintegration mechanism moves to the LD and FD regimes. Under the atomisation conditions normally used in the metal powder production, the disintegration mechanism is either LD or a combination of DDF, LD and FD [10]. Zhao [11] attributed the occurrence of the three atomisation modes to incomplete wetting between the liquid metal and the atomiser and developed an analytical model to illustrate the effects of process conditions on the transition from one disintegration regime to another. Better wettability between the liquid metal and the atomiser leads to a thinner continuous film before its disintegration into ligaments and subsequently droplets, and therefore results in finer droplets.

Several quantitative models have been developed to calculate the liquid velocity and film thickness on centrifugal atomisers [12,13] and the droplet size formed in the DDF [14], LD [15] and FD [16] regimes. These models assume simple atomiser geometries and perfect wetting conditions and often require numerical solutions. Although they offer some valuable insights into the atomisation process, their applications are limited. This is mainly because the flow conditions on a practical

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http://dx.doi.org/10.1016/j.powtec.2017.05.038
0032-5910/

centrifugal atomiser are complicated by hydraulic jump [12,17], skull formation [10,12,18] and coating material [19,20]. The particle size distribution of centrifugally atomised powders has to be determined experimentally.

The effects of process conditions on the particle size of centrifugal atomised powders are well documented in the literature. The particle sizes normally follow a lognormal distribution, and lower melt flow rate, higher atomiser rotation speed and larger atomiser diameter result in smaller powder particles [10,21]. Various types of atomisers, including flat discs, vaned wheels, inverted bowls and cups, have been used [22]. Although atomisers with complex design and shape offered no significant benefits under certain atomising conditions compared with a simple flat disc [23], cup shaped atomisers often produced finer powders than flat discs [5,10,24,25]. Cup atomisers can improve the wetting between the liquid and the atomiser. They also make it easier to obtain a symmetrical feed of melt, especially at high melt flow rates. For many applications, cup atomisers are the best choice. However, the research on atomiser design is still inadequate and inconclusive, largely because it is difficult to isolate the effect of atomiser design from so many other factors that may affect the performance of atomisation. The effect of cup designs, e.g., cup wall angle, on the characteristics of the particle size distribution, including median and spread, is not fully understood.

This paper carries out an experimental study on the particle size distribution of centrifugally atomised tin powders using cup-shaped atomisers with different cup wall slope angles. The effects of the key process parameters, i.e., atomiser rotation speed and melt flow rate, on the particle size distribution are studied. The spread of the particle size ranges are characterised and the key parameter determining the particle size is discussed.

2. Experimental

The centrifugal atomisation apparatus and the operational procedures used for the experiments was described in detail in the previous paper [10]. The atomisers used in the study were cylindrical steel cups with a diameter of 8 cm. Each cup had a flat bottom and a sloped conical wall at the circumferential edge. A series of cups with different wall slope angles of 45°, 67.5° and 90°, as shown schematically in Fig. 1, were used. They were all pre-tinned in order to maximise the wetting with the melt during atomisation. In each experiment, commercially pure tin was first melted in a furnace at a temperature of 550° to ensure a high superheat. The melt was then poured into a tundish with an exchangeable bottom nozzle. The melt flow rate was determined by measuring the mass of the melt in the tundish and the time required for its discharge through the nozzle under gravity. The cylindrical nozzles had diameters of 2, 3 and 4 mm, corresponding to melt flow rates of approximately 65, 150 or 220 kg/h, respectively. The melt flowed through the nozzle under gravity onto the centre of the rapidly rotating cup, positioned 1 cm below the nozzle, and was broken up by the cup into a horizontal spray of droplets. A part of the spray was allowed to fly into a powder collection chamber, which was long enough to ensure that the vast majority of the droplets solidified during flight to form solid particles. The as-produced powder sample (Fig. 2) was finally collected and subsequently analysed by a series of sieves.

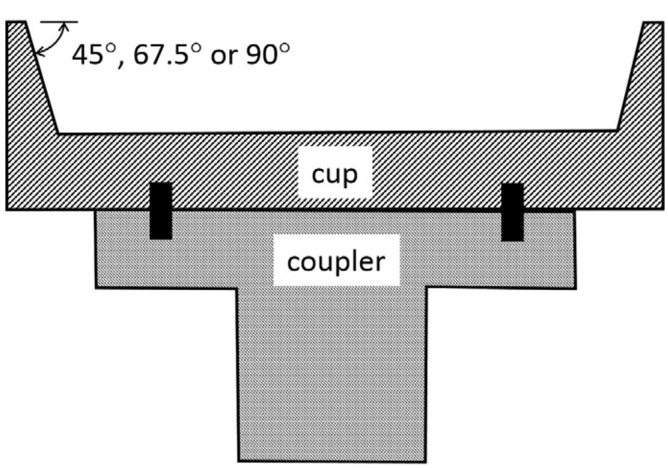

Fig. 1. Schematic diagram of the atomising cups.

3. Results and discussion

Figs. 3–5 show the lognormal plots of the accumulative weight percentage of the particles under a specific particle size versus the particle size for the powder samples produced using 45°, 67.5° and 90° atomising cups, respectively, with different atomiser rotation speeds and melt flow rates. All the plots are linear in the lognormal scale, with the coefficients of determination $R^2 > 0.94$.

The results show that the particle sizes of the powders produced by centrifugal atomisation using cups follow the lognormal distribution. As flat disc atomisers also produced powders with lognormal distributions [10], it is demonstrated that lognormal distribution applies to all centrifugally atomised powders, regardless of the atomiser used. A log normal distribution results if the variable is the product of a large number of independent variables. This is clearly true in centrifugal atomisation, where the particle size is affected by many independent variables or processing parameters, including the physical properties and flow rate of the melt, the geometry, surface condition and rotation speed of the atomiser. Each of these variables can fluctuate due to changes in the processing conditions, e.g., melt temperature, atomiser vibration and other operating variations.

Fig. 6 shows how the median (or geometric mean) particle size of the powder samples produced using a flat disc [10] and cups varies with atomiser rotation speed and melt flow rate. The values of the median particle size, D_{50}, which corresponds to the accumulative weight percentage of 50%, were obtained from the fitted lines in Figs. 3-5. Some clear trends can be observed from the results. For all atomisers, the median particle size decreases with atomiser rotation speed for any given melt flow rate. The median particle size generally increases with melt flow rate, but the magnitude of the effect of melt flow rate depends on the atomiser rotation speed. At a low rotation speed of 6000 rpm, an increase in melt flow rate results in a significant increase in the median particle size. At higher rotation speeds, increasing melt flow rate produces a less significant effect on the particle size. For each rotation speed, there seems to be a critical melt flow rate below

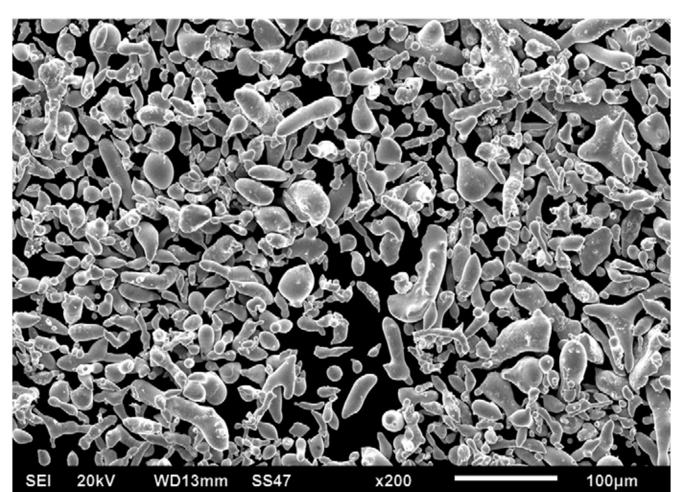

Fig. 2. SEM photograph of a typical tin powder, produced using the 67.5° cup with a rotation speed of 12,000 rpm and a melt flow rate of 65 kg/h.