EFFECTS OF SUBSTRATE GEOMETRY ON PERFORMANCE OF TWIN-FLUID ATOMIZER IN METAL POWDER PRODUCTION

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ABSTRACT Uniform and spherical metal powders have been widely used in many industrial applications. This paper investigates the effects of impingement of molten spray on the substrate to control of particle size and size distribution of the metal powder. The idea is to combine the classification process with atomization process in the metal powder production. Result shows that a significant reduction of the particle size occurred when the substrate was placed in the molten spray with different transmission ratio. The mean particle size was lowered to 8.78μm to 12.67μm as the transmission ratio was increased from 13.92% to 75.80%. The reduction in particle size was due to the effect of the blockage of the substrate. The particle size was further reduced to 6.72μm ~ 6.98μm when the disk-type substrate was placed in the spray flow field. It was found that the particle size with the disk type substrate because the transmission ratio of the disk type substrate was lower than that of the ring type substrate. The percentage of small particles (i.e., V15-) were higher than 60% and the percentages of V25-45 were lowered to 4.19% and 0.37% when the disk-type substrate was placed at Z=150mm and Z=200mm, respectively. It indicated that almost all of the particles were below 25μm under these conditions. Hence this technique can be used to control of the particle size in the production of the ultra-fine metal powder.

Keywords: Metal powder, Atomization, Impingement, Twin-fluid, Substrate

1. INTRODUCTION

Metal powders have been produced in large quantities by a variety of atomization techniques as referred to Cubberly et al. [1] and Lavermia et al. [2]. Particular methods are considered to produce metal powder for different metals, such as vibratory ball milling for aluminum, plasma arc spraying for tin, gas and water atomization for stannic. Rotating disk atomization (centrifugal atomization), vacuum atomization, and rotating electrode atomization are all applied in practice. Generally, people used water- and gas- atomization to produce metal powder. Controlling the gas flow and the pattern of the medium generally reduces efficiency. However, most atomizers are designed to allow the molten metal to fall freely and be controlled by the atomizing medium. Bradbury [3] reported that most used metal powders involve particles of sizes in the range of 175μm to 43μm. For special cases, particles must be superfine (<10μm). For example, metal powder injection molding described by German [4] requires particle sizes lower than 20μm. Liang [5] found that superfine metal powder can facilitate sintering materials up to 95% of the true density of a material with 3–8μm surface roughness.

Metal powder production using gas atomization techniques has become popular in recent years. In an effort to develop the linear atomizer for the spray forming application, Samuelsen et al [6] characterized the performance of a linear atomizer on the 3003 aluminum alloy. They found that Aluminum powder size, SMD, decreases from 125 mm to 103 mm as atomization pressure increases from 310 kpa to 379 kpa. Anderson [7] studied the atomization of Ni-base alloy and found that atomizing at the deep gas-aspiration pressures (at condition of wake-closure) in close coupled gas atomizers yields the finest powder. Ting [8] further studied the wake closure phenomenon of melt atomization. They found that the wake closure phenomenon (WCP) is highly sensitive to atomizer and melt pour jet geometry and pulsating atomization occurs. Stable wake-closure cannot be sustained during melt atomization. The melt filming process at above WCP gives rise to finer particle size distribution, lower melt flow rate, and higher GMR. Operating below WCP, the melt breakup mechanism could be similar to that of the free-fall atomization process. The most popular atomizers utilized for metal powder production in the literature were the external mixing type [6-9]. For example, Mates et al [9] investigated the performance of the external mixing atomizer for the production of tin powder. An annular HPGA (converging) atomizer and an annular UNAL (converging and diverging) atomizer were used to investigate the atomization performance. The pressure ratios up to 29–51 are required to achieve the desired atomization.

In an effort to improve the atomization efficiency on metal powder production, Wang et al. [10] first designed the atomizers with internal mixing mechanism. Results show that the performance of this atomizer is better than the conventional one with an external atomization. The ultra-fine powder (SMD<13μm) has been obtained under low pressure conditions and low gas-to-melt ratio at GLR=0.17 in the production of solder powder [11]. Wang et al. [12] further optimized the nozzle design and control parameters using Taguchi method. Results indicate that the accumulative volume of the solder powder within 0–15μm
is 56.9%. That is, more than half of the powder is within extra-fine range, indicating the better performance for the production of the metal powder.

The atomization processes for metal powder production mentioned above could be related to the mechanisms of liquid column instability, the liquid film instability and the impingement between the gas and melt, respectively. The efficiency of those processes depends on the relative velocity between the gas phase and melt.

Investigation on the impingement of the spray jet on the substrate has been the interests of many researchers due to its potential applications in industrial thermal control and material conditioning and processing. Angioletti et al. [13] attempted to improve the local heat transfer rates by impinging jets. They found that the vortex stretched and attempted to improve the local heat transfer rates by the relative velocity between the gas phase and melt.

It turns out that the velocity of normal component tends to become a larger vortex as it reaches the plate. They also found that the impact region is slightly offset with respect to the vertical position, due to the action of the stagnation region.

Atomization of molten metals into the metal spray becomes popular in recent development of the spray forming technology. Singer and Osprey [14-15] suggested that spray deposition was a new manufacturing process for metallurgy. The method has received considerable attention as it produces near-net-shape materials with uniform, rapidly solidified microstructure. Furthermore, superplastic property may be achieved by reducing the grain size for thermal mechanical processes (TMP). The grain size in most materials is less than 10 μm, but sometimes reaches 20 μm. Hence the finer atomization of the molten metal and its impact upon the solidification processes and the grain size is highly concerned.

In an effort to understand the deposition mechanisms of the spray forming material, Newbery et al. [16] investigated the impingement of the metal spray on the flat and angled substrates. Dynamic properties of gas and the metal spray of Fe-0.8wt.% C droplets during electric arc spraying was characterized by using particle image velocimetry (PIV). They found that flow behavior was dominated by the upward and then lateral flow of the numerous smaller droplets caused by splashing of superheated droplets on the substrate. At spray angles of 45° and greater, splash droplets are entrained exclusively in the ‘downhill’ flow of gas. When a topographic feature such a simple vertical step was introduced at the substrate, splash droplet behavior became complicated, with some splash droplets having trajectories that caused deposition on the vertical step wall.

Recently Wang et al. [17] developed a process for the production of metal powder as well as the spray forming material with impingement of spray to a substrate. The molten spray was first injected from the swirling chamber of the atomizer. It was then impinged upon the substrate to form the two phase impinging flow. The deposition rate of the molten spray on the substrate is controlled by the diameter of the substrate, the height of the substrate ring and the distance of the substrate from the outlet of the atomizer. This in turn determined the powder production rate of the spraying processes. Experimental results indicate that the deposition rate of the spray forming material decreases as the distance between the substrate and the atomizer increases. For example, the deposition rate decreases from 48% to 19% as the substrate is placed at a distance from 20 cm to 40 cm. On the other hand, the metal powder production rate and its particle size increases as the substrate is placed far away from the atomizer. The production of metal powder with mean particle size as low as 3 μm level has been achieved, a level which is not achievable by the conventional gas atomization processes. It is indeed the process deserved to pay more attention.

This paper intends to further investigate the control of particle size and size distribution by the impingement of the molten spray on the substrate with different geometries. The idea is to combine the atomization process with the classification process. As shown in Figure 1, the molten spray is first produced by a twin-fluid atomizer. It impinges on the substrate with different geometries. The particle size of the spray under different substrates will be characterized.

### 2. EXPERIMENTAL SETUP

The experimental setup of the atomization system is shown in Fig.2. The system consists of the melt crucible, the atomization unit, the cooling tower, the liquid nitrogen supply system, the nitrogen gas supply system, and the heating and flow control system. A 3160W heater conveys heat to the crucible. The melt and atomization gas are both pressurized by nitrogen gas. The cooling tower is filled with liquid nitrogen in order to cool and collect the metal powder. We also use thermal couples to measure the temperature of the crucible and the atomizer. The temperatures are adjusted to the setting values with a PID control system. The experimental procedures are listed as follows. (1) Heat up the eutectic metal (PbSn: 63.37%) in the crucible to a temperature 50 K over the melting point and so render it liquid. (2) Control the driving pressure of the melt and atomization gas to inject the metal spray to the cooling chamber. (3) Supply the liquid nitrogen to the cooling tower at a distance 60 cm from the atomizer to cool down the

![Fig.1 Schematic of the impingement of the molten spray on the substrate](image)
metal powder. (4) Collect the metal powder from the cooling tower. (5) Measure the particle size distribution with the RT-Sizer.

Fig. 2 Schematic of the experimental setup

The geometry of the substrate is shown as Figure 3, including the disk-type and ring-type designs. The outside diameter of the substrates D = 100mm. The inner diameter of the ring type substrate, d, varied from 40mm to 70mm, allowing different transmission of the molten spray to control the particle size of the metal powder collected in the down stream. The substrates were made of aluminum. They were attached to the atomizer at a distance, Z, from the nozzle outlet. The test matrix is shown in Table 1.

<table>
<thead>
<tr>
<th>Disk-Type</th>
<th>Ring-Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_L (bar)</td>
<td>P_G (bar)</td>
</tr>
<tr>
<td>3.5</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 1 Test Matrix

The spray drop size distribution is measured by a Malvern RT-Sizer, which uses the Fraunhofer diffraction technique. As shown in Figure 4, the laser beam is expanded to 5mm diameter in the transmitter and becomes diffracted when passing through the spray. The diffracted light is received by the photo detector through the Fourier lens and transferred to digital signal by the A/D converter. And finally, the software of the processor calculates the droplet size distribution. The spray size is measured at 100mm downstream of the discharge orifice. The spray was characterized by Sauter mean diameter, SMD. Test data were obtained by averaging results of five test runs. The maximum error of the spray measurement is ±5%.

3. RESULT AND DISCUSSION

Figure 5 illustrates the photo of the molten spray under test condition P_L = 3.5bar, P_G = 4.0bar during the spraying process. The spray cone angle was measured according the expansion angle shown in the photo. Result shows the spray cone angle is about 30° under test conditions P_G = 4.5 bar and P_L = 3.0 bar. The substrate was placed at the positions illustrated in Figure 6.
section area of the spray jet at position Z, $A_z$, can be defined as:

$$BR = \frac{A_{\text{sub}}}{A_z}$$  \hspace{1cm} (1)$$

Where $A_{\text{sub}}$ denotes the cross section area of the spray jet at the distance Z, $A_{\text{sub}}$ denotes the blockage area of the substrate to the spray jet. Hence the transmission ratio of the spray under the blockage of the substrate is defined as:

$$TR = \frac{A_z - A_{\text{sub}}}{A_z}$$  \hspace{1cm} (2)$$

Table 2 describes the calculation of TR at different positions under the blockage of the ring type substrates. The transmission ratio of the spray increased from 24.75% to 53.22% as the substrate was located at a distance Z from 150mm to 250mm for the ring type substrate with inner diameter $d=40$mm. The lowest transmission ratio took place when the substrate was placed at Z=200mm because the cross sectional area of the spray jet increased due to the flow expansion. Table 2 also showed that the transmission ratio increased as the inner diameter of the ring type substrate was increased. The purpose to vary the inner diameter of the substrate is to control the transmission of the spray through the substrate.

<table>
<thead>
<tr>
<th>Z</th>
<th>150mm</th>
<th>200mm</th>
<th>250mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>d=40mm</td>
<td>24.75%</td>
<td>13.92%</td>
<td>53.22%</td>
</tr>
<tr>
<td>d=50mm</td>
<td>38.67%</td>
<td>21.75%</td>
<td>58.23%</td>
</tr>
<tr>
<td>d=60mm</td>
<td>55.69%</td>
<td>31.33%</td>
<td>64.36%</td>
</tr>
<tr>
<td>d=70mm</td>
<td>75.80%</td>
<td>42.64%</td>
<td>71.60%</td>
</tr>
</tbody>
</table>

Table 2 Transmission ratio of the spray jet under the blockage of the ring type substrates

Figure 7 illustrates the dependence of the mean particle size on the transmission ratio of the spray jet across the substrate. As can be seen from the figure, the mean droplet size of the original spray without substrate was 13.78 μm. A significant reduction of the particle size occurred when the substrate was placed in the spray jet. It turned out that the mean particle size was lowered to 8.0μm with the low transmission ratio of the spray jet in the existence of the ring type substrate. Figure 7 also showed that the particle size increased from 8.78μm to 12.67μm as the transmission ratio was increased from 13.92% to 75.80%. It is clear that the reduction in particle size was due to the effect of the blockage of the substrate on the spray.

Furthermore, the effectiveness of the reduction in particle size by the blockage of the substrate depended on the position of the substrate. For example, when the substrate was placed at Z=200mm, the particle size of the spray increased from 8.78μm to 9.05μm as the transmission ratio was increased from 13.92% to 42.64%. The particle size increased because higher transmission rate through the ring-type substrate allowed more big droplets in the spray cone bypassed the substrate. Furthermore, the effectiveness of the blockage of the substrate decreased when the substrate was placed far away from the outlet of the atomizer. Hence the particle size of the spray increased from 9.2μm to 12.15μm as the transmission ratio was increased from 53.22% to 71.60% at Z=250mm.

This phenomenon could be explained with the solidification process of the spray droplets and deposition of the particles on the substrate. The higher deposition rate of the particles occurred as the substrate was placed near the outlet of the atomizer because the droplets were in the molten state with higher deposition ratio when they were impinged on the substrate. Moreover, the secondary atomization processes took place when the molten droplets were splashed on the substrate when it was placed near the atomizer. It turned out that many smaller particles were produced during the impinging process. On the other hand, the solidification processes took place as the droplets moved to the down stream. Hence the droplets was solidified and reflected from the substrate instead of deposition on the substrate in the down stream. Hence the deposition of the spray droplets on the substrate decreased.

The particle size increased from 6.72μm to 6.98μm when the disk type substrate was placed at Z = 150mm and 200mm, respectively. The particle size of this case was smaller than the case with ring type substrate because the transmission ratio of the disk type substrate was the lowest. The large particles of the spray were in the molten state and were deposited on the substrate when they impinged on the substrate. Moreover, the small particles generated from the splashing processes during the spray impingement on the substrate also affected the particle distribution.

Figure 8 further illustrated the dependence of Dv50 on the transmission ratio of the spray jet. Dv50 increased from 15.73μm to 17.43μm as the transmission ratio of the spray was increased from 24.75% to 75.80% at Z = 150mm. Similar result happened to the case at Z = 200mm. Dv50 was increased from 16.22μm to 17.06μm as the Transmission ratio was increased from 13.92% to 42.64%. Particle size was even higher when the substrate was placed
at $Z = 250\text{mm}$. $D_{v50}$ was increased from 16.52$\mu m$ to 18.06$\mu m$ when the substrate was placed at $Z = 250\text{mm}$. The Transmission ratio under this condition ranged from 53.22\% to 73.60\% which is approaching the limiting condition without substrate. It is concluded that the particle size can be controlled by adjusting the geometry of the substrate.

**Fig. 8 Dependence of $D_{v50}$ on the transmission ratio of the spray jet**

The above mechanisms can be further justified by the variation of the particle size distribution under different test conditions. The range of particle size distribution is normally defined by the standard deviation $\delta$ of the spray droplets shown as Equation-(3). The smaller value of $\delta$ indicated more uniform distribution of the particles.

$$\delta = \frac{D_{v84}}{D_{v50}}$$  \hspace{1cm} (3)

Figure 9 illustrates the dependence of size distribution on transmission ratio of the spray jet. The standard deviation $\delta$ of the original spray without substrate was 1.68. It was decreased to 1.58 and 1.62 as the substrates were placed at $Z=150\text{mm}$ $Z=250\text{mm}$, respectively. It indicated that the particles became more uniform by adjusting the position of the substrate. Moreover, the standard deviation $\delta$ of the spray was further reduced to 1.52 as the substrate was placed at $Z=200\text{mm}$. It turned out that both the particle size and the standard deviation of the spray were reduced when the substrate was placed at $Z =200\text{mm}$. Hence more uniform and smaller particles can be produced by placing the substrate at $Z=200\text{mm}$. It can be related to the spray pattern of solid cone or hollow cone in the spray jet. One may obtain the powder with finer particles by placing the disk-type substrate in the solid cone spray or placing the ring-type substrate in the hollow cone spray. Since the spray pattern depended on the design of the atomizers, one may control the uniformity of the spray particles by the disk- or ring-type substrates accordingly.

**Fig. 9 Dependence of size distribution on transmission ratio of the spray jet**

In an effort to see the percentage of the fine particles in the spray, Figure 10 further shows the dependence of $V_{15}$, on the transmission ratio of the spray jet. The symbol $V_{15}$ denoted the volumetric percentage of particle size below 15$\mu m$. $V_{15}$ of the original spray was 34.97\%. However, when the substrate was placed at $Z=150\text{mm}$, $V_{15}$ was 46.77\% with a transmission ratio of 24.75\%. $V_{0.15}$ reduced to 40\% as the transmission ratio was increased to 38.67\%. The same trend was observed when the substrate was placed at $Z=200\text{mm}$ and 250mm. The volumetric percentage of particle size below 15$\mu m$ decreased as the transmission ratio was increased. About half of the powder was in the ultra-fine range by adjusting the size and the position of the substrate. Hence this technique can be regarded as the controlling mechanism in the production of ultra-fine particles.

**Fig. 10 Dependence of $V_{15}$ on the transmission ratio of the spray jet**

Figure 11 further showed the dependence of volume percentage of particle size between 25$\mu m$ and 45$\mu m$(i.e. $V_{25-45}$) on transmission ratio At $Z=150\text{mm}$ The percentage of $V_{25-45}$ of the original spray without substrate is 27.43\%. The impingement of the spray on the substrate resulted in a decrease in the larger particles. Hence the percentage of $V_{25-45}$ reduced to 13.88\% ~ 23.23\% as the transmission ratio was increased from 24.75\% to 38.67\%. It indicated that part...
of the particles within 25~45μm had been deposited on the substrate. This also implied that the part of the spray particles were still in the molten state at Z= 200mm. When the inner diameter of the ring-type substrate was increased, the transmission ratio of the spray jet increased, allowing larger particles to pass through the substrate. Hence the percentage of V_{25,45} remained at an average of 22.4% as the transmission ratio was increased from 38.67% to 75.8%. It indicated that the effects of the substrate were declined as the substrate was placed in the further down stream. This can be attributed to the solidification process of the molten droplets in the down stream. The molten droplets became solidified from the outer region to the center region of the droplets by transferring heat to the gas phase. They became solid particles in the down stream. It turned out that the deposition process of the spray droplets on the substrate was replaced by reflection process during the impingement of the spray jet. Hence the filtration of bigger particles by deposition on the substrate became less effective in the down stream. It implied that the designer may control the particle size of the metal powder by proper adjustment of the transmission ratio of the substrate and the solidification process of the molten spray.

It is interesting to note that the volume percentage of particle size between 15μm and 25μm (i.e. V_{15,25}) was less sensitive to the variation in the transmission ratio as well as the position of the substrate, as shown by Figure 12. The percentage of V_{15,25} remained at 37~40% for the cases with and without substrate for the transmission ratio ranging from 20% to 70%. It implied that the dynamic behavior of the droplets in the median size range of 15μm and 25μm was insensitive to the existence of the substrate.

In an effort to compare the performance related to disk-type and the ring-type substrate, Figure 13 further illustrated the mean particle size of the spray jet with disk-type substrate. The particle size increased from SMD = 6.72μm at Z=150mm to SMD = 8.5μm at Z=250mm. The particle size in this case was smaller than the case with ring-type substrate (see Figure 7). This result can be explained by the higher blockage ratio of the case with disk-type substrate. However, the reduction in particle size with disk-type substrate seemed more effective even when the substrate was placed at the down stream positions. It may be attributed to the different flow structures associated with the substrate. The flow structure of the case with ring-type substrate could be defined by the combination of the jet flow in the central region and the wake flow in the outer region. On the other hand, the flow of the case with disk-type substrate was essentially the impinging flow structure. Hence the interactions between droplets and substrate were stronger in the case with disk-type substrate. The effects of droplets deposition and collision breakup processes were more significant especially when the temperature of the molten droplets was higher than the melting point. It would reduce the number of bigger droplets and produced a lot of smaller droplets in the spray jet.

The above mechanisms could be further explained by the particle size distributions as shown in Figure 14. The percentage of bigger particles were reduced and that of the smaller particles were increased when the disk-type substrate was placed at Z=150mm and Z=200mm. However, there were more big particles in the spray jet when the disk-type substrate was placed at Z=250mm. Hence the mean particle size was higher at this position.
As a result, the percentage of small particles (i.e., V15-) were higher than 60% when the substrate was placed at Z=150mm and Z=200mm (see Figure 15). The result also showed that the optimum position of the substrate was at Z=200mm as far as the production of ultra-fine powder is concerned. Figure 15 also showed that the percentages of V25-45 were 4.19% and 0.37% when the substrate was placed at Z=150mm and 200mm, respectively. It indicated that almost all of the particles were below 25 μm under these conditions.

On the other hand, the percentages of V25-45 was 17.55% when the substrate was placed at Z=250mm. It indicated that more big particles were obtained when the substrate was placed at Z=250mm. It was interesting to see that the percentage of median-sized particles, i.e., V15-25, remained almost constant at an average of 35.5 μm. Hence this technique can be used to control the particle size in the production of the ultra-fine metal powder.

4. CONCLUSION

Significant reduction of the particle size in metal production has been achieved by the impingement of the molten spray jet upon the substrate. The mean particle size was lowered to 8.0 μm with a low transmission ratio of the spray jet in the existence of the ring type substrate. The particle size increased from 8.78 μm to 12.67 μm as the transmission ratio was increased from 13.92% to 75.80%. The reduction in particle size was due to the effect of the blockage of the substrate on the spray. The particle size increased from 6.72 μm to 6.98 μm when the disk-type substrate was placed at Z=150mm and 200mm, respectively. The particle size of this case was smaller than the case with ring type substrate because the transmission ratio of the disk type substrate was lower. The percentage of small particles (i.e., V15-) were higher than 60% and the percentages of V25-45 were 4.19% and 0.37% when the disk-type substrate was placed at Z=150mm and Z=200mm, respectively. It indicated that almost all of the particles were below 25 μm under these conditions. Hence this technique is very effective in controlling the particle size in the production of the ultra-fine metal powder.

5. ACKNOWLEDGEMENT

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6. NOMENCLATURE

- PG: atomization gas pressure (bar)
- PL: liquid injection pressure (bar)
- SMD: Sauter mean diameter (μm)
- Z: distance from the substrate to nozzle
- d: inner diameter of the ring-type substrate
- D: outside diameter of substrate
- TR: transmission ratio of ring-type substrate

7. REFERENCE

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