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Criterion of gas and solid dual-phase flow atomization crash in molten metal

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Abstract: A self-invented atomization process, in which molten metal is atomized into powder by a high-velocity gas stream carrying solid particles as the atomization medium, was introduced. The characteristics of powders prepared by common gas atomization and dual-phase flow atomization under similar conditions were compared. The experimental results show that the dual-phase flow-atomized powders have average particle sizes that are one-half that of the common gas-atomized particles; additionally, they possess a finer microstructure and higher cooling rate under the same atomization gas pressure and the same gas flow. The Weber number in the crash criteria of liquid atomization is adopted to measure the crash ability of the atomization media. The Weber number of the dual-phase flow atomization medium is the sum of that of the gas and the solid particles. Furthermore, the critical equation of the crash model in dual-phase flow atomization is established, and the main regularities associated with this process were analyzed.

Key words: atomization; metal powder; gas and solid dual-phase flow; Weber number

1 Introduction

Two-fluid atomization of molten metal, in which molten metal is directly crashed into droplets by a high-velocity gas stream and then is rapidly solidified into powders, is one of the most important methods for the preparation of powders [1,2]. For many years, either to improve the efficiency of the atomization process or to obtain an ideal powder with a finer size or narrow size distribution, a significant deal of research has been performed by many scholars on improving the atomizing nozzle structure, the atomization medium pressure, spray status and patterns and other aspects of the molten metal. As a result, a variety of two-fluid atomization processes have been developed [3−5]. Among these, gas and solid dual-phase flow atomization, as presented by CHEN et al [6], is a breakthrough in the traditional method of taking a single liquid or gas as the atomizing medium, where the molten metal or alloy is atomized into powders by a high-velocity gas stream carrying solid particles as the atomization medium. Accordingly, research shows that the atomization efficiency is significantly improved and that the particle size distribution of the powder is more restricted [7,8].

The experimental results show that certain process regularities are associated with gas and solid dual-phase flow atomization. For example, with increasing the atomizing gas pressure, the powder atomization size is reduced more significantly under single gas atomization. At the same gas flow rate and pressure, there is an optimum relative content of solid particles, which yields the minimum size of atomized powder particles.

To reveal the basic concepts of gas and solid dual-phase flow atomization and to explore the crash mechanism, the ratio of the Weber number of atomization medium inertia force and the surface tension of molten metal is used as the crash criterion of liquid atomization in this study; the number has been adopted to measure the crash ability of the atomization media. Here, we define the Weber number of gas and solid dual-phase flow to be the sum of that of the gas and that of solid particles, according to the fact that molten metal is in the critical crash condition when it suffers the common effects of percussive force, aerodynamic force and surface tension of its own solid particle form. When the three forces are in balance, the crash model of a droplet in dual-phase flow is used; accordingly, the critical equation of the crash model in dual-phase flow atomization is established and provides a reference for

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our theoretical study to further explore the interaction of the gas and solid phases in dual-phase flow.

2 Experimental

The experimental set-up used for the gas and solid dual-phase flow atomization is shown in Fig. 1. The flow process is illustrated in Fig. 2. The experimental process is as follows: when the atomization metal or alloy is smelted in an intermediate frequency furnace or resistance furnace, the degree of superheating is 150−200 °C. The use of dry salt (NaCl) particles, particles of Fe powders or the same composition with atomized metal powder is adopted in the form of solid medium particles, which are used by the atomization process; these particles are then loaded in the send-tanks (a powder storage tank) in advance. During the powder atomization process, a high-velocity gas stream is produced by compressed air or through the high pressure of a N_2 bottle 1. The gas is fed through the gas delivery pipeline and passes the send-tank at 5, forming a high-pressure gas and solid dual-phase flow with the solid powder at 6 in the tank. The mixture then erupts from a circumferential weld through level-running piping to nozzle 8 in the atomizer (spray gun) and then is poured into the tundish at 9. The mixture is manufactured into powder by atomizing the molten metal, which is the excurrent from the catheter; the powder is cooled by cooling water, which erupts from the water ring at 10; the powder falls into the water in the bottom of the atomizing chamber at 11. The atomizing gas pressure is adjusted by reducing the valve setting at 3, where the pressure value is read by the indicator on the reducing valve. Additionally, the gas pressure in the nitrogen cylinder is read by barometer 2, and the initial pressure of the nitrogen cylinder adopted by this experiment is 12 MPa.

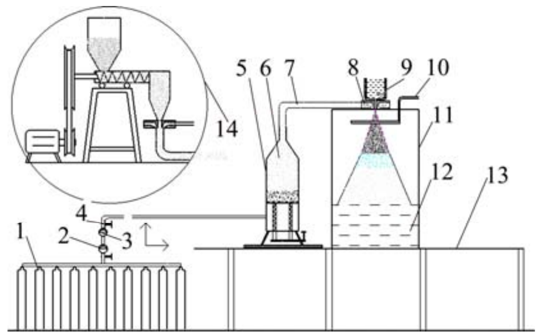

Fig. 1 Gas and solid dual-phase flow atomization experimental set-up (1—High-pressure bottle; 2—Air pressure calibration; 3—Reducing valve; 4—Air valve; 5,14—Solid particle emission tanks (5 and 14 are interchangeable); 6—Solid particle; 7—Gas and solid dual-phase flow; 8—Atomizer; 9—Crucible; 10—Cooling water pipe; 11—Atomizing chamber; 12—Cooling water; 13—Platform)

3 Results and discussion

3.1 Effect of atomization gas pressure on powder size

A 6−6−3 bronze alloy was selected as the research object, and the processing parameters were as follows. The diameter of the liquid stream was selected at 4.5 mm, and a soluble salt was adopted as the solid particle. The flow rate was controlled at approximately 53 g/s, and the gas pressures were 0.6, 0.8 and 1.0 MPa. The distribution of the average particle size of the powders obtained is shown in Table 1.

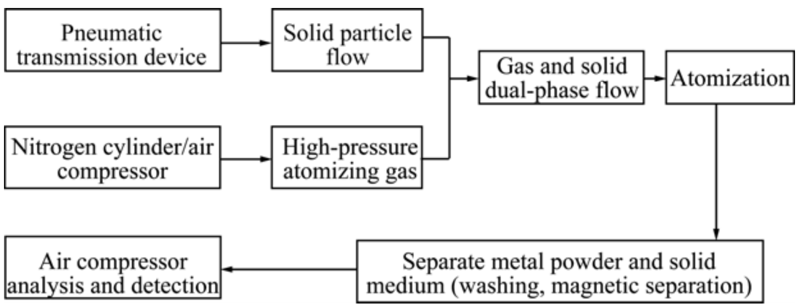

Fig. 2 Flow process of gas and solid dual-phase flow atomization

Table 1 Average particle size resulting from dual-phase flow atomization and ordinary gas atomization of 6−6−3 bronze alloy under different gas pressures

Average salt flow rate/ ($g \cdot s^{-1}$)	Diameter of molten metal/ mm	Gas pressure/MPa	Average particle size/μm	
			Salt atomization	Gas atomization
53	4.5	0.6	81.4	150.5
		0.8	70.9	136.2
		1.0	56.3	118.4

Table 1 shows that the average particle size of the powders gained from the gas and solid dual-phase flow atomization process is reduced with increasing gas pressure, and the distribution range of the particle size is more focused. Specifically, with each additional 0.1 MPa increase in gas pressure, the median diameter $d(50)$ is decreased by approximately 8−10 μm. Other experimental results, such as atomizing Al−40%Si (in mass fraction) and a 304 stainless steel, are similar.

3.2 Relationship between solid phase medium flow rate and powder characteristics

The flow rate of the solid particles is a very important parameter in gas and solid dual-phase flow atomization. When performing gas atomization, the mass flow rate of gas affects the particle size of the powder; in contrast, in the dual-phase flow atomizing process, the mass flow rate of the solid medium significantly influences the resulting powder. To study the relationship between the flow rate of the solid particle and the properties of the powder, the Al−30%Si alloy, technical-pure Zn, stainless steel and bronze 6−6−3 alloy were selected. The atomizing gas pressure was 0.8 MPa, and the flow rate of the gas was 3.3 m^3/min. The experimental results are shown in Table 2.

It can be seen from the experimental results that the particle size of the powder made by solid atomization first decreases with increasing flow rate of the solid particles. When the flow rate of the particles increases to a certain value, upon further increasing the flow rate of the salt, the particles will increase in size gradually. Ultimately, there is an optimal ratio of the flow rates. The experimental data reveal that the optimal relationship between the flow rate of the solid particles and the flow rate of the molten metal generally follows the 1:1 rule.

Micrographs obtained by scanning electron microscopy analysis of atomized powders produced under different processing conditions are shown in Fig. 3, reflecting the fact that the particle size resulting from dual-phase flow atomization is approximately half that produced by ordinary gas atomization. At the same time, as the surface tension of the molten metal is increased

Table 2 Average particle size of metal powder under different salt flow rates

Sample	Diameter of catheter/mm	Flow rate of molten metal/(g·s^{-1})	Flow rate of solid particle/(g·s^{-1})	Median diameter $d(50)$/μm	Ratio of flow rate of solid particles and flow rate of molten metal
Stainless steel	3.5	42	92	102	2.19
			58	62	1.38
			44	74	1.05
			36	92	0.86
			0	130	0
Zn	4.2	90	225	147	2.50
			140	72	1.56
			80	66	0.89
			40	90	0.44
			0	107	0
6−6−3 bronze	4.5	106	120	96	1.13
			110	65	1.03
			100	62	0.94
			90	49	0.84
			60	66	0.57
			40	79	0.38
			20	81	0.19
			0	82	0
Al−30%Si	6.0	141	225	150	1.60
			140	70	0.99
			80	85	0.57
			40	120	0.28
			0	155	0

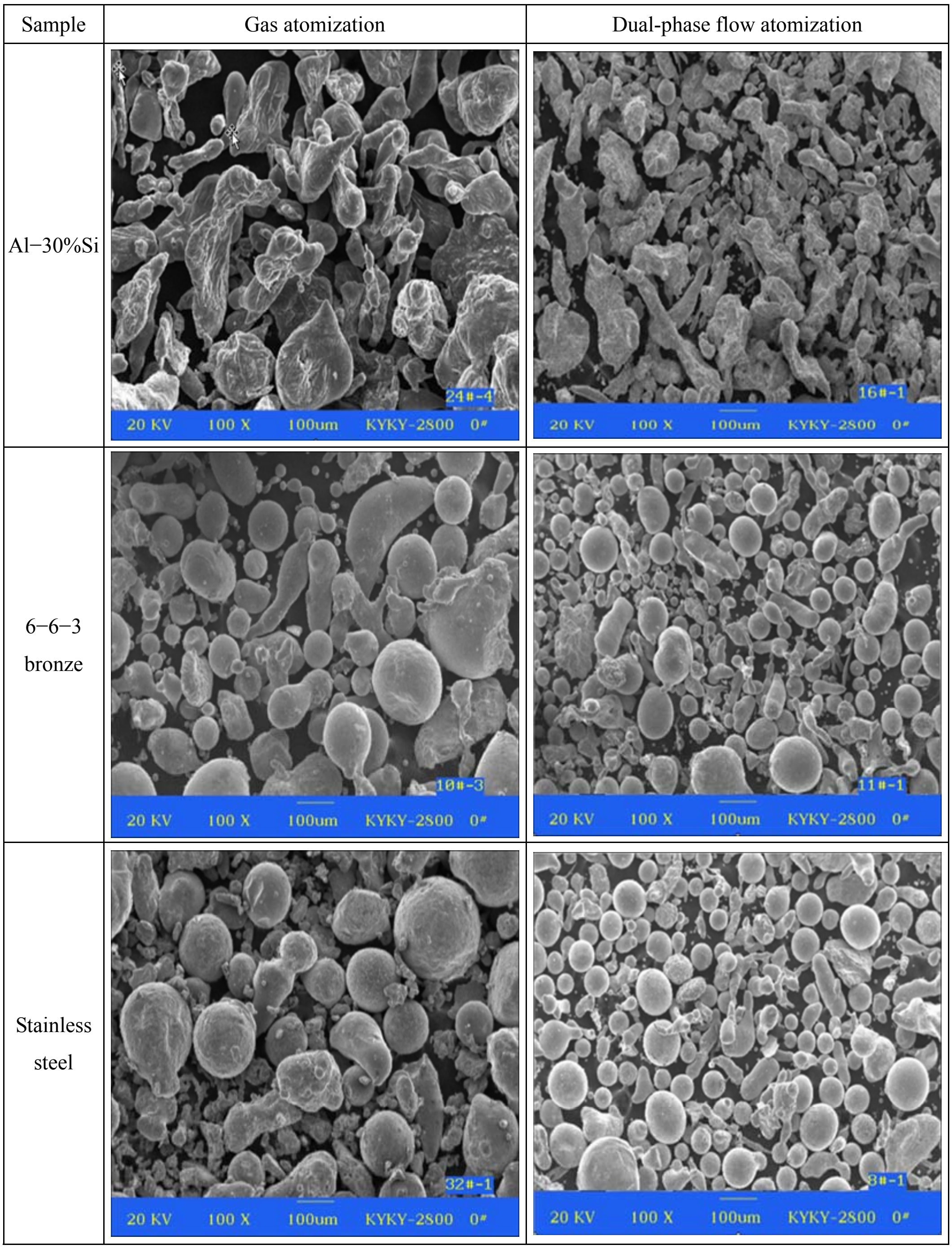

Fig. 3 Powder morphologies of alloys fabricated under different atomization processes

(the surface tension of Al−30%Si is 670 N/m, and the distributions of 6−6−3 bronze and stainless steel are 1100 and 1500 N/m, respectively), the powders become more spherical.

4 Foundation for crash criterion

When the molten metal moves with a comparatively higher velocity in the gas or other molten metal, the molten metal will disperse into fine droplets, generating the atomizing phenomenon. The basic mechanism of molten metal atomization is the instability of the free surface of the molten metal. The stability of the molten metal mainly depends on the primary acting force in the flow fields [9,10], because the surface tension is the main force present and must be considered in the molten metal atomization process, under all circumstances [11]. Hence, the Weber number is introduced as an important molten metal atomization parameter.

$$We = \frac{\rho L U^2}{\sigma_L} \tag{1}$$

where L is the reference length or reference particle size of the molten metal, U is the reference velocity, ρ is the reference density of the fluid or atomizing medium, and σ_L is the surface tension of the molten metal. For two-fluid atomization, the reference velocity is usually the relative velocity of the atomizing gas and molten metal droplets.

When the value of We is larger than a certain critical value, We_{crit}, split and crush are generated in the molten metal droplet. Therefore, when studying the atomization of molten metal, the Weber number is used as the molten metal stability criterion, called the fracture dimensionless number, namely, when the Weber number of the atomizing medium is larger than a critical value, the molten metal is crushed by atomization [11]. Namely, the critical condition of the atomizing gas is given by

$$We > We_{crit} \tag{2}$$

In the following, after the important molten metal atomization parameters, the We is used as the dimensionless number of fracture. Then, the concept of the solid particle flow Weber number is introduced, and the Weber number of the gas and solid dual-phase flow is derived. Additionally, the critical condition of fracture of the gas and solid dual-phase flow atomizing process is established. Lastly, a comparison of the Weber number of the gas and solid dual-phase flow and the gas flow single phase Weber number is derived, and then, the processing set-up of dual-phase flow atomization is further explored.

4.1 Aerodynamic force effect

First, only the aerodynamic force is considered for the situation of droplet fracture. Because the viscosity of the molten metal is smaller, a molten metal droplet K is mainly affected by aerodynamic force and surface tension during atomization. When the aerodynamic and surface tension forces are balanced, i.e.,

$$\frac{1}{2} C_{DK} \rho_a (u_a - u_K)^2 \pi r_K^2 = 2\pi r_K \sigma_K \tag{3}$$

The molten metal droplet is in the critical point of fracture at this moment, and the critical Weber number derived from this is given by

$$We_{crit} = \frac{2 r_K \rho_a (u_a - u_K)^2}{\sigma_K} = \frac{8}{C_{DK}} \tag{4}$$

where C_{DK} is the drag coefficient of the molten metal droplet K, r_K is the radius of the molten metal droplet K, ρ_a is the gas density, μ_a is the velocity, σ_K is the surface tension of the molten metal droplet K, and μ_K is the velocity of the molten metal droplet K.

Formula (3) is derived according to the use of spherical particles; however, in reality, the particles often deform and fracture. Hence, the Weber number is modified according to the experiment, i.e.,

$$We_{crit} = \xi \frac{8}{C_{DK}} \tag{5}$$

where ξ is the modifying factor that represents the degree of sphericity of the particle, ξ=1/2. Thus, it is impossible for the critical value to be a fixed number but instead is distributed within a range of values. The experimental results show that, at low Weber numbers, molten metal droplets are spherical according to the surface tension function. When the value of We reaches 4, the molten metal droplets begin to deform, and when the value of We is sufficiently large, the droplet completely fractures. Namely, when $We > We_{crit}$, complete fracture of the droplet begins.

4.2 Particle impact of droplets

When a dual-phase flow atomizing medium particle P collides with the molten metal droplets, the loss of kinetic energy in the particle P is defined as

$$\Delta E_P = \frac{1}{2} \cdot \rho_P \cdot \frac{4}{3} \pi r_P^3 \left(u_P - u'_P\right)^2 \tag{6}$$

where u'_P is the instantaneous velocity of particle P after a dual-phase flow atomizing medium particle P collides with the molten metal droplets and the surface energy change of the particles injected in the droplets,

$$\Delta E_1 = -4\pi r_P^2 \sigma_K \cos\theta \tag{7}$$

where θ is the wetting angle between the particle and the molten metal. Additionally, when $\Delta E_P - \Delta E_1 \geq 0$, the atomizing medium particle P can penetrate the molten metal droplet K or is captured by the molten metal droplet K. The conditions under which the particle passes through the droplet and causes it to fracture are that the particle must meet the following empirical formula obtained from the least squares method:

$$1 - 0.246 Re_{PK}^{0.407} L_{PK}^{-0.096} \varDelta_{KP}^{-0.278} < 0 \tag{8}$$

where Re_{PK} is the Reynolds number when the dual-phase flow atomizing medium particle P moves into a large molten metal droplet K, L_{PK} is the Laplace number, which represents the stability of droplet K, and $\varDelta_{KP}$ is the ratio of the molten metal droplet K radius to the solid particle P radius. Apparently, when the contents share the relationship formula (8), the dual-phase flow atomizing medium particle P penetrates through the large molten metal droplet K, and because the viscosity of the molten metal is larger, a linear column (wire) of metal is knocked out after penetrating particle P, causing the instability of the metal wire surface, breaking it down into small droplets.

4.3 Criterion of common effects by aerodynamic force and impact force of particles

Under the conditions of gas and solid dual-phase flow atomization, the droplets develop from the common functions of the aerodynamic force and impact force of the particles and surface tension. When the three forces are balanced, the droplet reaches the critical point of fracture. When particle P collides with droplet K, the momentum of the particle changes. The effects of the force of collision within a given unit of time on the droplets can be developed based on the law of momentum,

$$F_{PK}=C_{KP}\rho_P(u_P-u_K) \tag{9}$$

Therefore, incorporating the aerodynamic force presented in formula (3), the equilibrium equation of force in a droplet at the critical point is

$$\frac{1}{2}C_{\mathrm{D}K}\rho_{\mathrm{a}}(u_{\mathrm{a}}-u_K)^2\pi r_K^2+C_{KP}\rho_P(u_P-u_K)=2\pi r_K\sigma_K \tag{10}$$

where C_{KP} is the total volume of solid particle P that collides with the molten metal droplet K. After both sides of equation (10) are divided by $1/4\pi C_{\mathrm{D}K}r_K\sigma_K$, and when the equation is combined with Eq. (4), the following equation is obtained.

$$We_{\mathrm{a}}+\frac{4C_{KP}\rho_P(u_P-u_K)}{\pi C_{\mathrm{D}K}r_K\sigma_K}=\frac{8}{C_{\mathrm{D}K}} \tag{11}$$

where

$$We_{\mathrm{a}}=\frac{2r_K\rho_{\mathrm{a}}(u_{\mathrm{a}}-u_K)^2}{\sigma_K} \tag{12}$$

In reference to formula (4), the gas Weber number of the atomizing medium is We_{a}. Then, the second term of the left side in formula (11) can be taken as We_P, i.e.,

$$We_P=\frac{4C_{KP}\rho_P(u_P-u_K)}{\pi C_{\mathrm{D}K}r_K\sigma_K} \tag{13}$$

Next, define

$$We_{\mathrm{a}P}=We_{\mathrm{a}}+We_P \tag{14}$$

as the Weber number, which is commonly affected by aerodynamic force and the impact force of solid particles. We call this the criterion of gas and solid dual-phase flow.

Considering that droplet K is affected by deformation before it fractures and then multiplying by the modifying factor ξ on the right side of the formula above, we can define $8\xi/C_{\mathrm{D}K}$ as the critical Weber number, i.e.,

$$We_{\mathrm{crit}}=\xi\frac{8}{C_{\mathrm{D}K}} \tag{15}$$

According to the critical condition formula (2), when

$$We_{\mathrm{a}P}>We_{\mathrm{crit}} \tag{16}$$

complete fracture occurs in the droplet. Formula (16) is the critical condition for solid atomizing fracture.

Briefly, equations (2), (5), (9), (10)−(16) are basic conditions that gas and solid dual-phase flow atomization follow. Formula (13) shows that, compared with the ordinary gas atomization Weber number We_{a}, the dual-phase flow atomization Webber number $We_{\mathrm{a}P}$ increases item We_P. Under the same condition, compared with the atomization of ordinary gas, dual-phase flow atomization has a higher Webber number and crash capability.

Stainless steel powder is used as an example in the following, and the conditions of the effects of the dual-phase flow atomization processing parameters on particles of the powder that uses salt as the solid particle are discussed in detail.

5 Discussion

The following parameters are observed for the calculation below. Nitrogen is used as the atomizing gas, and salt is the solid particle used to atomize the stainless steel. The catheter aperture is 4.5 mm and the molten metal flow rate is 42 g/s. The known density of nitrogen is 1.2 kg/m^3, the surface tension of stainless steel is 1.88 N/m, the velocity u_K of the molten metal flow from the catheter is very low relative to the velocity of air, and the Weber number is approximately equal to 0 in the calculation [12,13]. Additionally, according to Ref. [11], the atomization initial diameter of the droplet is approximately 200−300 μm; then, the Weber number of a stainless steel droplet in a nitrogen gas stream is

$$We_{\mathrm{a}}=\frac{2r_K\rho_{\mathrm{a}}(u_{\mathrm{a}}-u_K)^2}{\sigma_K}=(12.7\sim19.1)\times10^{-5}u_{\mathrm{a}}^2$$

The Weber number of the salt particles is

$$We_P=\frac{4C_{KP}\rho(u_P-u_K)}{\pi C_{\mathrm{D}K}r_K\sigma_K}=\frac{4Nm_P(u_P-u_K)}{\pi C_{\mathrm{D}K}r_K\sigma_K}$$

where $C_{\mathrm{D}K}$ is the drag coefficient of droplet K in gas, because the Reynolds number of droplet K in the gas ranges from 10^3 to 10^5 , $C_{\mathrm{D}K}\approx0.46$ can be found by the criteria of the drag coefficient curve; m_P is a quality of the single salt particle. For the average particle size of 200 μm, m_P=1.13×10^{-5} g·N is the average number of salt particles that collide with the initial individual droplets of stainless steel when converging in the collision zone of the atomizing focus area [14,15].

In the process of salt atomizing, the diameter of the salt particle flow and liquid flow converging collision zone approximately equals the diameter of the catheter, the value of which is 4.5 mm. The height of the converging collision zone is approximately equal to the width of the circumferential flow, the value of which is 3 mm. Hence, the area of the cylindrical side formed by salt stream is 42.4 mm^2. As seen from Fig. 4 stream flows 42.4 mm^2 (Fig. 4).

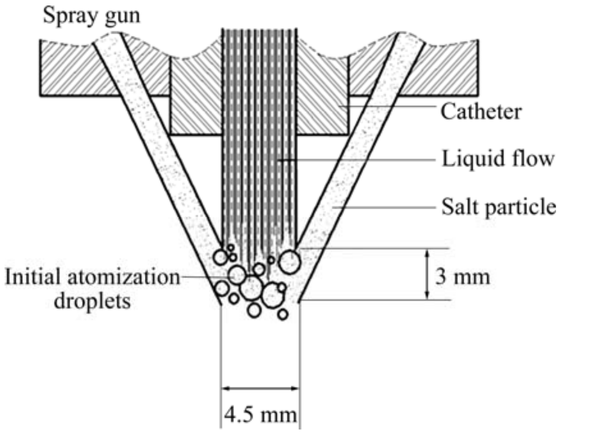

Fig. 4 Schematic diagram of salt particle collision with initial droplet

When the salt flow rate is known, the sprayed salt particle number N_P in unit of time can be calculated according to the flow rate of the solid particle and the average quantity of this particle number, N_P, is divided by the area of the cylindrical side. Additionally, the salt particle number injected per square millimeter in units of time (ρ_N) can be obtained. For example, when the flow rate of salt is 50 g/s, a value of ρ_N=1.05×105 mm^{-2}/s is calculated.

For the initial atomizing droplet, the diameter of which is in the range from 200 to 300 mm, and the effective area S_d of which is 6.28×10^{-2}–1.42×10^{-1} mm^2. The velocity of the molten meta flow can be calculated approximately as 0.65 m/s based on the use of molten metal with a rate of 80 g/s and the catheter with an aperture measuring 4.5 mm. This calculation is performed by ignoring the effects of acceleration due to gravity and relies on the atomization of the initial droplets passing through the salt particle converging collision zone at the speed of 0.65 m/s, which requires 4.6×10^{-3} s.

It can be estimated that approximately $N=\rho_N S_d t\approx$ 30−68 salt particles collide with a single initial droplet by substituting in the particle Weber number formula. Next, it can be calculated that, when the flow rate of the salt particles is 50 g/s, the Weber number of the particle is equal to $We_P=(3.33\sim11.65)\times10^{-3}u_P$.

For any flow rate ($\dot{m}$) of salt, the Weber number of the solid particle is $1/50\dot{m}(3.33\sim11.65)\times10^{-3}u_P$.

Therefore, the Weber number of the dual-phase flow is

$$We_{aP}=We_a+We_P=(12.7\sim19.1)\times10^{-5}u_a^2+\frac{1}{50}\dot{m}\cdot(3.33\sim11.65)\times10^{-3}u_P$$

According to the formula above, the Weber number of the gas flow and dual-phase flow can be calculated during the process of solid salt atomization under different gas flow velocities and particle flow velocities, and the gas flow velocity and particle flow velocity can be determined based on the atomizing process parameters of the flow conditions of a solid medium (the pressure of the atomizing gas). Through calculation, different particle flows (a constant atomizing gas pressure) and the Weber number of the gas and solid dual-phase flow under different atomizing gas pressures (constant particle flow) and the Weber number of gas atomization under the same conditions are drawn in Figs. 5 and 6.

Figure 5 shows the changing relation of the gas Weber number of ordinary gas atomization and the Weber number of dual-phase flow atomization under dual-phase flow atomizing and the flow rate of the solid medium under the pressure condition of 0.8 MPa. From Fig. 5, when the flow rate of the solid medium increases, the Weber number of the dual-phase flow atomization first increases and then decreases, which manifests the effect of atomization as an initial increase followed by a weakening when the flow rate of the solid medium continues to increase. When the flow rate of the salt is approximately 60 g/s, the effect of atomization is optimal and the finest stainless steel powder is prepared, which is consistent with the experimental results. Figure 6 shows how the Weber number of gas atomization changes with variation of the atomizing gas pressure, as well as how the Weber number of the solid atomizing process under the same conditions as gas atomization when the flow rate of the solid medium is 50 g/s. As can be seen from Fig. 6, the Weber number for the atomization of

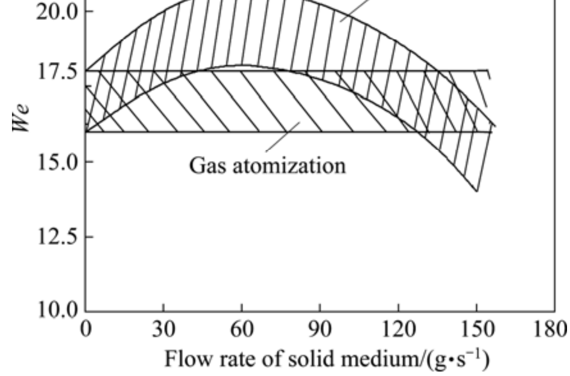

Fig. 5 Relationship between Weber number and flow rate of solid medium

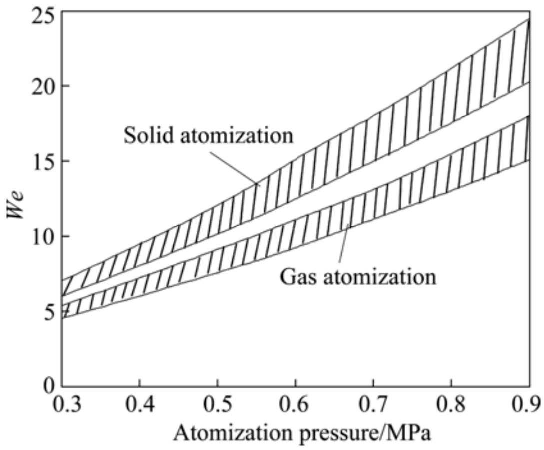

Fig. 6 Relationship between Weber number and atomizing gas pressure

ordinary gas and the atomization of the solid increased with increasing atomizing gas pressure, and the extent of increase in the atomizing solid was larger than that of the atomizing ordinary gas, which manifested that the increased extent of dual-phase flow atomizing was better than gas atomizing, which is consistent with the experimental results. Therefore, some aspects of the experimental process can be explained by the changing relationship of the Weber number.

6 Conclusions

1) The dual-phase flow-atomized powders have characteristic of an average particle size that is one-half that of the common gas-atomized particles, yielding a finer microstructure and higher cooling rates under the same atomization gas pressure and the same gas flow.

2) The particle size of the powder made by dual-phase flow atomization initially decreased when increasing the flow rate of the solid particles. When the flow rate of the particles increases to a certain value, further increase in the flow rate of salt causes the particle size to increase gradually. Additionally, there is an optimal ratio of the flow rates.

3) The Weber number in the crash criteria of liquid atomization has been adopted to measure the crash ability of the atomization media. The Weber number of the dual-phase flow atomization medium is the sum of that of the gas and solid particle phases, allowing the critical equation of the crash model in dual-phase flow atomization to be established.

4) It is impossible for the critical value to be a fixed number but instead is distributed within a range: at low Weber number, the molten metal droplets are spherical under the surface tension function. Then, when the value of We reaches 4, the deformation of molten metal droplets begins, and when the value of We is sufficiently large, the droplet achieves complete fracture. Namely, when $We>We_{crit}$, complete fracture begins to develop in the droplet.

5) Compared with the Weber number of ordinary gas atomization We_a, the dual-phase flow atomization Webber number We_{aP} increases item We_P. Under the same conditions, compared with the atomization of ordinary gas, dual-phase flow atomization has a higher Webber number and crash ability.

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金属液流的气固两相流雾化破碎准则

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摘　要：介绍了一种自行发明的新的雾化方法。该方法是采用含有固体介质的高速气流即气固两相流对液体金属或合金进行雾化而制备粉末的一种方法，对比研究了同等条件下普通气体雾化与两相流雾化制备粉末的特征，研究了固体雾化过程中主要工艺参数对固体雾化粉末特征的影响规律。结果表明，两相流雾化制得粉末的平均粒度约为普通气体雾化所得粉末的二分之一，而且粒度分布更集中，粉末的冷却速度比普通气体雾化高一个数量级，粉末微观组织更细小；采用液体雾化破碎准则韦伯数以衡量雾化介质的破碎能力，得出两相流雾化介质的韦伯数为气体韦伯数和颗粒流韦伯数之和，建立了两相流雾化破碎的临界方程，并以此讨论了主要工艺规律。

关键词：雾化；金属粉末；气固两相流；韦伯数

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