Powder Technology 336 (2018) 406–414

Contents lists available at ScienceDirect

Powder Technology

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

A novel model of calculating particle sizes in plasma rotating electrode process for superalloys

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ARTICLE INFO

Article history:
Received 13 December 2017
Received in revised form 22 April 2018
Accepted 2 June 2018
Available online xxxx

Keywords:
Superalloy
PREP
Particle size distribution
Rosin-Rammler distribution
Surface tension

ABSTRACT

A novel PSD (particle size distribution) model to calculate the powder yields of plasma rotating electrode process (PREP) of nickel base superalloys powders was studied. The results showed that the meshing data of the nickel base superalloys powders like EP741NP and Inconel718 produced by PREP fitted the calculation of the novel PSD model well. The results also showed that not only rotating speed but also melting rate had significant influence on the fine powder yield in the centrifugal atomization system. The general PREP nickel base alloy powders showed characteristics of a bimodal Rosin-Rammler distribution mixed by the ligament disintegrating and direct drop formation. The fractions of the both mechanisms and the process factors of spraying were discussed. This fitting can help the engineers make the target powder yield increase by adjusting the process parameters.

1. Introduction

Nickel base superalloy is a series of materials with excellent performances at high temperature, which is applied in the conditions of airplane gas turbines [1]. Nowadays, the widely used Ni-base or Ni-Fe base superalloys (for example Inconel718) applied in higher temperature conditions are added a larger fraction of niobium or tantalum for precipitation of the second phases, which support high hardenability [2]. Complex contents make it difficult to control segregation in casting. In order to reduce the defects of macro segregation and macro shrinkage [3] of casting, near-net-shape process like hot isostatic pressing (HIP) [4] is used, which is the most used powder forming process of the superalloys. EP741NP, the superalloy developed for powder forming, has been reported to be one of the most advanced Ni-base superalloys used in Russian fighters [5].

The superalloys are also suitable for 3D Printing. It has been mentioned that the general superalloys like Inconel718 can be laser-printed from powders with high density and low macro defects [6, 7].

The superalloys spherical powders used for HIP and 3D printing should have applicable size ranges, high flowability, lower impurity and extremely lower micro defects (porosity) [8, 9]. In general, the widely applied spraying methods for producing high purity spherical metal powders are divided into the gas atomization (GA) and the centrifugal atomization [10, 11]. Method of electrode induction melting gas atomization (EIGA) [12] is the mainly used gas atomization process, and the most widely used centrifugal atomization method nowadays is the plasma rotating electrode process (PREP) [13]. For HIP products, generally, PREP powders are more preferred because powders sprayed by centrifugal force have higher roundness degree without gas-formed inner holes, and these defects strongly damage the fatigue performance [13, 14]. However, compared with the GA methods, the fine powder yield of the commercial PREP method is slightly lower than GA methods [15].

It is reported that there are at least 3 different spraying models existing in the centrifugal atomization, including direct drop formation (DDF), ligament disintegration (LD), and film disintegration (FD) [16]. The typical applied equation for calculating the mean diameter of the sprayed powders is based on the view that the drop separates from the molten pool boundary immediately when getting enough centrifugal force against the liquid surface tension itself [16], which is suitable for DDF [17]. For LD particles, the average diameter prediction had been proved, added with viscosity, in Weber's theory [18]. But these models are not easy to compare with the DDF equation until Kamiya and Kayano [19] give a simple semi-empirical law to describe the average diameter of unique LD models for low viscosity liquid.

However, there is few research on the powder yield calculation of the mixed spraying model of DDF and LD, which is useful for the cost control of the PREP. It should concern not only the mean diameter, but also the yield of a selected size range.

This paper aims to derive an applicable particle size distribution (PSD) model of the PREP superalloy powders via different spray model factors, especially the powder yield of a random size range. The model can support/fit a PSD calculating result before atomization

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https://doi.org/10.1016/j.powtec.2018.06.002
0032-5910/

under the selected conditions. The tested PSD results and the PSD calculations of the EP741NP/Inconel718 powders produced by PREP were discussed. The model fitted the results well under the conditions that the rotating speeds ranging from 14,000–20,000 rpm.

2. Experiments and principle

2.1. Atomization mechanism of the PREP

The atomization model for PREP is based on the centrifugal models, which was deeply discussed by the high speed camera and exported 3 elemental spray models: DDF, LD and FD [16, 17], as shown in Fig. 1. A statistical equation to approximately determine the actual spray model can be expressed as the Hinze-Milborn number, *Hi* [16, 20]:

$$Hi = \frac{\mu^{0.17} Q \rho^{0.71} \omega^{0.6}}{\gamma^{0.88} D^{0.68}} \tag{1}$$

This equation is suitable for the atomization of metals [20]. In the Eq. (1), the Hi is a dimensionless parameter, the μ (Pa·s) is the viscosity of the liquid metal, the Q ($m^3 \cdot s^{-1}$) is the melting rate, the ρ ($kg \cdot m^{-3}$) is the density, the ω ($rad \cdot s^{-1}$) is the rotating speed, the γ ($N \cdot m^{-1}$) is the surface tension of the liquid metal, and the D (m) is the diameter of the rotating bar.

In the Eq. (1), if $Hi < 0.07$, the main spray model is DDF; if $0.07 < Hi < 1.33$, the main spray model is LD; if $Hi > 1.33$, the main spray model is FD. The commercial PREP often uses the rotating speed of <15,000 rpm, electrode diameter between <75 mm, and melting rate lower than 3×10^{-6} m^3 s^{-1} [16, 21] (affected by the max heat power and the nature of the material), thus, the deduced main spray model by Eq. (1) is DDF, LD or the mixture of DDF and LD for the majority of common alloys.

For DDF model the average diameter (similar with the peak diameter, d_{peak}, or d_{50} while the distribution is unimodal) can be calculated as Eq. (2) [16, 17], under the boundary condition that a drop on the rotating boundary of the molten pool has enough inertial power of centrifugal force to oppose the liquid surface tension [16, 17].

$$d_{DDF} = \frac{1}{\omega}\sqrt{\frac{12\eta\gamma}{\rho D}} \tag{2}$$

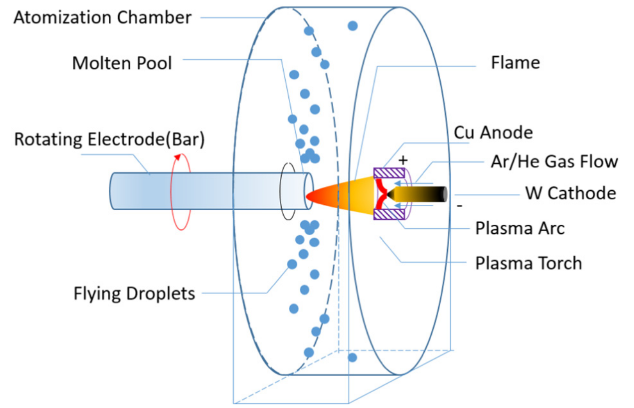

Fig. 2. A typical schematic diagram of non-transferred arc PREP (plasma rotating electrode process) atomizer. A rotating bar is molten by the high temperature gas heated by the plasma arc in the torch, and the droplets are formed by the centrifugal force of the high angular speed.

In Eq. (2), d_{DDF} (m) is the average diameter under complete DDF model, η is a dimensionless correct factor (about 1) to fix the error between calculated and tested DDF main particle diameter. Other parameters are same with chapters above.

For LD diameter, the average particle diameter can be calculated by the Kamiya and Kayano law for low viscosity liquid (<20 mPa·s, applicable for most metals) [19, 22]:

$$d_{LD} = 2.0D\sqrt{\frac{\gamma}{\rho\omega^2 D^3}} \tag{3}$$

In Eq. (3), d_{LD} (m) is the average diameter under complete LD model, other parameters are same with the chapters above.

2.2. Experiments

The structure of the used PREP atomizer is shown on Fig. 2. This atomizer (PREP2000), supported by Sino-Euro Materials Technologies of Xi'an Co. Ltd., used a plasma torch (non-transferred arc) as the heat source.

As shown on Fig. 3, when spraying, the chamber was filled with Ar/He mix gas, the rotating electrode (bar) melted by high temperature

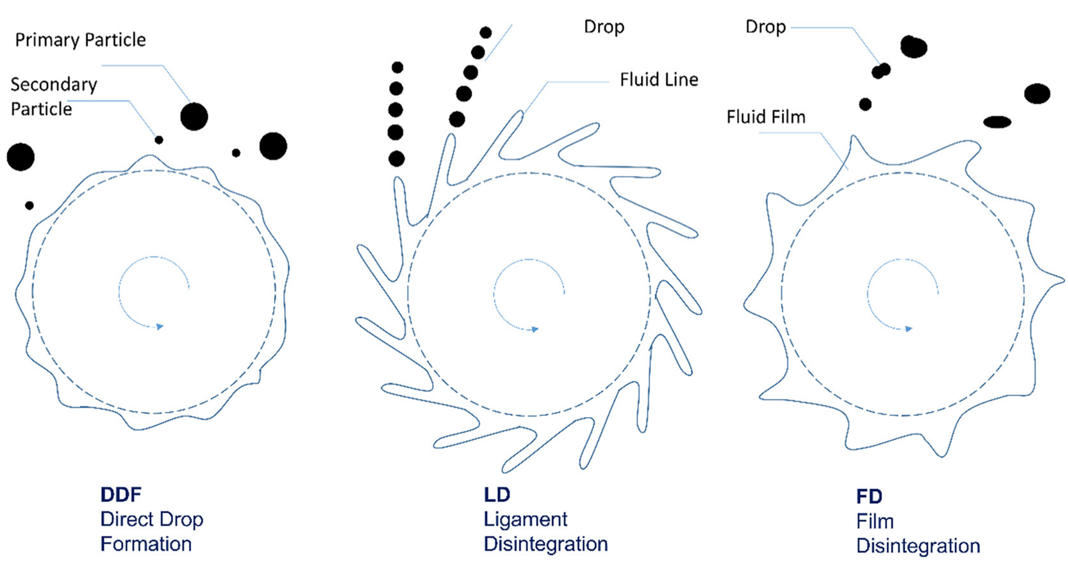

Fig. 1. The typical centrifugal spray models of DDF (direct drop formation), LD (ligament disintegrating) and FD (film disintegrating).