Advanced Powder Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Advanced Powder Technology

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

Original Research Paper

# Novel powder packing theory with bimodal particle size distribution-application in superalloy

Xianjue Ye [a], Yunping Li [b,c,*], Yanling Ai [a], Yan Nie [d]

[a] School of Materials Science and Engineering, Central South University, Changsha 410083, China
[b] State Key Lab for Powder Metallurgy, Central South University, Changsha 410083, China
[c] High Temperature Materials Research Institute, Central South University, Changsha 410083, China
[d] Yuanmeng Precision Technology (Shenzhen) Institute, Shenzhen, China

ARTICLE INFO

*Article history:*
Received 19 March 2018
Received in revised form 6 June 2018
Accepted 11 June 2018
Available online xxxx

*Keywords:*
Powder metallurgy
Superalloy
Packing density theory
Sintering

ABSTRACT

Powder packing behavior plays an important role in determining sintering ability of powder and the resultant performance of materials. In this study, a novel powder packing theory with bimodal particle size distribution is proposed by considering the loosening effect, wall effect and wedging effect. This theory is applied in PM nickel base superalloy by using mixture of coarse particles and fine particles. Microstructures of alloy sintered by vacuum hot pressing (HP) are observed by optical microscope (OM) and electron backscatter diffraction (EBSD). The prediction result by this theory is in good agreement with the experimental results. The enhanced sintering ability of powder containing appropriate fractions of coarse particle and fine particle is ascribed to the filling of fine particles to the voids between coarse particles, which enhanced the density of sample after sintering. Tensile behavior and the fracture morphology of alloys with various particle distributions are analyzed in details, suggesting the higher reliability of the present theory.



## 1. Introduction

Powder metallurgy (PM) is a technique of making materials or components from metallic powders. PM processes can avoid or reduce the metal removal processes, thereby drastically reducing the yield losses in manufacture and often resulting in lower costs. PM can also produce a variety of unique metals such as copper, tungsten, molybdenum, and superalloys [1–10] etc., which are impossible to obtain from casting or forming in other ways. PM nickel-base superalloys for application as gas turbine discs exhibit superior mechanical properties than that from the conventional processes [11–15]. The required specifications for mechanical properties of gas turbine discs are a good combination of both high strength and high creep resistance at high temperatures. However, a serious problem existing in PM superalloy is the residual pores, which are hard to eliminate during sintering and significantly lower the mechanical properties of final products. In addition, the creep resistance of alloy is closely dependent on the grain size: the steady state creep rate at high temperatures, $\dot{\varepsilon}_s$ becomes lower with increasing grain size [16–18]. For PM superalloy, the carbide- and oxide-dominant previous particle boundary (PPB) is an important factor inhibiting the grain growth during sintering. In order to enhance the creep resistance, coarse powder containing large grains is more suitable for PM Ni-based superalloy. However, due to the low specific surface area as well as the low packing density of coarse powder, the microstructure after sintering is generally characterized by a large number of defects such as voids as a result of low sintering ability of powder [11,12] (Fig. 1).

The powder sintering ability is closely related to its packing density, which is, therefore, necessary to be predicted to optimize the particle size distribution of powder before sintering. This is especially important in PM nickel base superalloy, where microstructure containing both large grain size and fine grain size is required to meet the high creep resistance and high mechanical property. In addition, despite the numerous efforts in both the theory and experimental results of powder packing density theories, their accuracy is still not so high as to be used extensively [19–28]. Some empirical packing models were built based on experimental results [19–24]. With the increasing computer processing capability, some packing models were established based on the computer simulations, which have been applied to optimize the mono-particle size powder [25,26], resulting in the powder with

* Corresponding author at: State Key Lab for Powder Metallurgy, Central South University, Changsha 410083, China.
*E-mail address:* lyping@csu.edu.cn (Y. Li).

https://doi.org/10.1016/j.apt.2018.06.012
0921-8831/

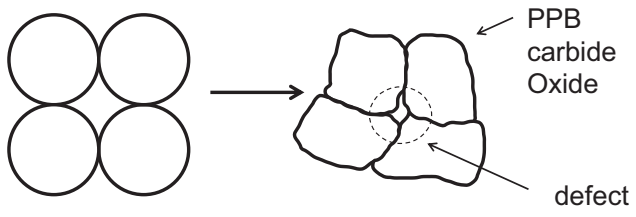


**Fig. 1.** Schematic illustration of traditional sintering process.

a slight spread of particle size [27] or with log-normal size distributions [28]. These empirical models, derived from the experimental data or computer simulations, are useful in many engineering applications. However, they do not well give detailed explanations on the interactions among the particles, leading to large error in prediction. Various theoretical particle packing models considering the interactions among particles have been summarized systematically [29]. Recently, more advanced packing theories considering both loosening effect and wall effect are proposed [30–34] and are compared with other theories by Jones et al. [35]. Although these theories are helpful to better understand the micro interactions among particles, there are still large deviations between the theoretical and experimental results. A 3-parameter particle packing model was also developed by Kwan et al. [36] by taking account into the wedging effect. However, this model does not connect tightly with the theoretical function and just adds a third-order term to the former linear function. The third parameter relating to the wedging effect in this theory is hard to be used in practice.

Therefore, in present research, a packing theory of powder with a bi-model particle size distribution is proposed to solve this problem for the first time (Fig. 1). The powder consists of both coarse particles and fine particles, while the fine particles are used to fill in the voids between coarse particles to improve the sintering ability of powder. The results demonstrate a good consistence with the experimental results.

## 2. Packing theory with bimodal particle size distribution of powder

In the conventional particle packing theories, two effects (Fig. 2), loosening effect and wall effect, are generally used to calculate the packing density of powder, and show relatively higher reliability in prediction [30–34,36]. When the coarse particles are dominant while the fine particles are larger than the spaces between coarse particles, fine particles are hard to fill into the spaces among the large particles and will affect the arrangement of coarse particles. This is called loosening effect, where this disturbance on the arrangement of coarse particles by fine particles leads to a lower packing density, leading to lower sintering ability of powder. When the fine particles are dominant and the size of the coarse particles is much larger than the fine particles, the surface of the coarse particle seems like a wall to fine particles. The voids caused by the 'wall' between coarse particles and fine particles are larger than the voids between fine particles. This so-called wall effect, the interaction between coarse particles and fine particles, also decreases the packing density.

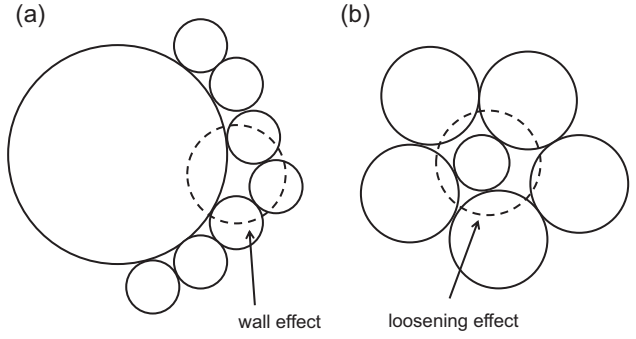


**Fig. 2.** (a) The schematic illustration of wall effect when the fine particles are dominant and (b) the loosening effect when the coarse particles are dominant.

The powder used in the present model is the mixture of spherical particles with binary size distribution. Packing densities of both fine and coarse particles are represented as $\alpha_1$ and $\alpha_2$, respectively. If $\phi_i$ is the partial volume fraction of a given particle (fine particle or coarse particle), the packing density $\rho$ of powder after mixture can be written as

$$\rho = \sum_{i=1}^{n} \phi_i \quad (i = 1 \text{ for fine particle, and 2 for coarse particle}) \tag{1}$$

Fractions of coarse or fine particles are denoted by $\omega_i$,

$$\omega_i = \frac{\phi_i}{\rho} \tag{2}$$

Hence,

$$\sum_{i=1}^{n} \omega_i = 1 \tag{3}$$

When fine particles are dominant, the space occupied by coarse particles can be defined as $\phi_2$, so the space left for fine particles is $1 - \phi_2$. Assuming no interactions between coarse particles and fine particles, the packing density is given by

$$\rho = \phi_2 + \alpha_1(1 - \phi_2) \tag{4}$$

When the fine particles are dominant, by considering the wall effect, the packing density of the powder (denoted by $\rho_1$) may be obtained from [32]:

$$\rho_1 = \alpha_1 + (1 - \alpha_1)g\phi_2 \tag{5}$$

where $g$ is a constant related to the wall effect determined by $g = 1 - r_1/r_2$ [32]. When size ratio of fine particles and coarse particles tends to zero ($r_1/r_2 \to 0$), fine particles are too small to cause the Wall Effect. So $g$ equals to 1 in order to make Eq. (4) and Eq. (5) consistent. When the size of coarse particles is equal to the size of fine particles ($r_1/r_2 = 1$), $\rho_1$ is equal to $\alpha_1$ since only fine particles are calculated. So $g$ equals to 0.

When coarse particles are dominant, the packing density without interactions is given by

$$\rho = \alpha_2 + \phi_1 \tag{6}$$

Considering the loosening effect when the coarse particles are dominant, the packing density of the binary mix (denoted by $\rho_2$) may be obtained from the following equation [32]:

$$\rho_2 = \alpha_2 + f \cdot \phi_1 \tag{7}$$

where $f$ is a constant related to the loosening effect. Parameter $f$ is similar to $g$. $f$ equals to 1 when $r_1/r_2 \to 0$ and equals to 0 when $r_1/r_2 = 1$.

The packing theory shown above will generate two packing density curves along the particle size constitution: one for the situation that coarse particles are dominant and the other for situation that fine particles are dominant. In actual applications, it is hard to determine which situation is predominant when fractions of both coarse and fine particles are close. An easier way is to evaluate the values of both$\rho_1$ and $\rho_2$ and to take the situation with

Please cite this article in press as: X. Ye et al., Novel powder packing theory with bimodal particle size distribution-application in superalloy, Advanced Powder Technology (2018), https://doi.org/10.1016/j.apt.2018.06.012