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Original Research Paper

Analysis of constant-volume shear tests based on precise measurement of stresses in powder beds

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ABSTRACT

This study demonstrates a new constant-volume shear test configuration to analyze the stresses in powder beds and evaluate powder flowability. A novel cylindrical shear cell geometry and load cell arrangement allowed precise measurement of the normal stress acting on the shear planes of the powder beds. The stress transmission ratio between the top and shear planes decreased with increasing ratio of the powder bed height in the upper section of the shear cell to the shear cell diameter. This was due to friction between the powder bed and the side wall of the upper section of the shear tester. Using the measured values of the normal stress on the shear planes, the effects of the powder bed height and shear cell diameter were eliminated from the data. In addition, to evaluate the shear properties of the powder beds, the powder yield locus, consolidation yield locus, critical state line, shear cohesion, and void fraction were obtained from a single shear test. The powder yield locus data were used to obtain flow functions.

1. Introduction

In recent years, particle size reduction has become increasingly popular in various industries to improve the quality and performance of functional particles. However, small particles easily adhere and have low flowability, which causes problems related to powder handling in the development of new products and quality control of industrial processes. Appropriately evaluating powder flowability to resolve these issues remains challenging; many characteristic properties of particles, e.g., particle size distribution, particle density, particle shape, and specific surface area, affect the powder flow behavior in a complicated manner. Consequently, it is difficult to accurately predict the powder flowability even if all relevant characteristics can be quantified.

To quantitatively evaluate powder flowability, various methods and characteristic values have been proposed, e.g., the angle of repose, bulk density, compressibility, tensile strength, and shear strength; however, these values do not always lead to the same results. To comprehensively evaluate powder flowability, Carr [1] proposed a series of indices that correspond to different flow phenomena, i.e., the angle of repose, compressibility, angle of spatula, and cohesion or uniformity. This method is effective for evaluating the powder flowability under low stress. In addition, the avalanche method [2], vibratory feeder method [3], vibrating tube method [4,5], and vibration shear tube method [6] are effective for similar conditions as the applied forces are rather small.

On the other hand, for large stresses, the flowability depends on the magnitude of the applied stress. Hence, it is necessary to precisely measure such stresses and shear tests have been used for this purpose. Such test methods can be classified into several types depending on the structure of the shear cell, such as the Jenike cell [7,8] and rotational shear cell [9–11]. In addition, standards for the measurement and evaluation methods have been developed [12–15]. These shear tests have been employed in research in various industrial fields, e.g., the food industry, to measure the effect of moisture content [16,17], storage time [18], and particle shape [19,20], on the flowability, and in the pharmaceutical field for tableting [21] and prescription design [22]. The results of such shear tests are often used to design silos and hoppers [23] as a large amount of powder is naturally consolidated by gravity in such applications. In materials research, the flowability of nanoparticles has been analyzed [24].

Several developments have been made to both shear test equipment [25] and analytical methods [26,27], allowing use of the technique in expanded application areas. In the Jenike shear tester, the normal stress on the powder bed is determined by a weight placed on top of the powder and the normal stress on the horizontal cross-sectional area decreases due to the friction between the powder bed and the side wall of the shear cell. Therefore, the normal stress

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Nomenclature

A_P	horizontal cross-sectional area of powder bed (m^2)
A_L	area of side of powder bed in lower section of shear cell (m^2)
A_U	area of side of powder bed in upper section of shear cell (m^2)
C	shear cohesion (Pa)
D_C	inner diameter of shear cell (m)
F	force (N)
FF	flow function (Pa)
f_c	unconfined yield strength (Pa)
ff_c	$=\sigma_1/f_c$ (–)
g	acceleration due to gravity (m/s^2)
H_{PU}	powder bed height in upper section of shear cell (m)
k	constant in Eq. (6) (–)
ΔL_H	horizontal shear displacement (m)
M_B	mass of base (kg)
M_{BP}	mass of bottom plate (kg)
M_P	mass of powder (kg)
t	time (s)
D_{p50}	mass median diameter of powder (m)
γ_{TD}	stress transmission ratio between top and shear planes at steady-state shear, i.e., point D (–)
ε	void fraction (–)
ρ_b	bulk density (kg/m^3)
σ	normal stress (Pa)
σ_1	major principal stress given by the Mohr stress circle of steady state flow (Pa)
σ_g	geometric standard deviation of particle diameter (–)
τ	shear stress (Pa)
φ_{CSL}	angle of critical state line (°)

Subscripts

C	cell
E	point E (steady-state shear)
H	horizontal
L	lower
P	powder
S	shear plane
U	upper
V	vertical

on the shear plane is not equal to the value calculated simply from the weight and the cross-sectional area. In a previous study [28], we used a constant-volume shear tester and proposed a method for measuring vertical forces acting on both the bottom and top of the shear cell; however, the stresses in the powder beds were not studied in detail.

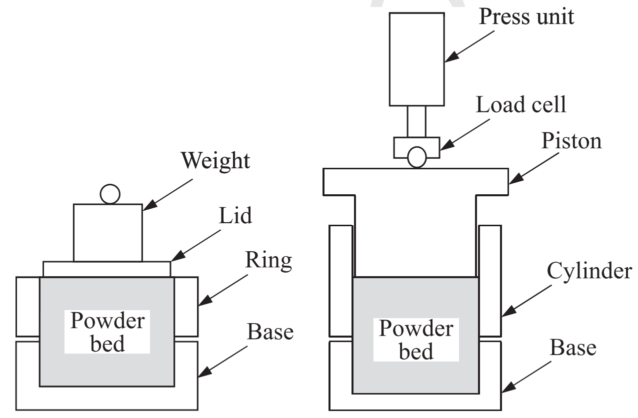
In the present study, the effect of powder bed height and shear cell diameter on the stresses was investigated and the validity of the constant-volume shear tests based on the normal stress on the shear plane was verified. In addition, the powder yield locus (PYL), consolidation yield locus (CYL), critical state line (CSL), shear cohesion, and void fraction were obtained under various conditions to evaluate the shear properties of the powder beds. Furthermore, the PYL data were used to obtain flow functions.

2. Materials and methods

2.1. Constant-volume shear test apparatus

Fig. 1 shows schematic diagrams of the two types of common shear test methods, i.e., the constant-load and constant-volume methods. The former uses a weight to apply a constant normal stress to the top plane of the powder bed, while the latter uses a mechanical press, where the vertical position of the top plane of the powder bed is fixed during the shear test.

Fig. 2 schematically illustrates the shear stress (τ) obtained from the constant-volume test as a function of the normal stress (σ) and the void fraction (ε) [29]. When shearing at a constant velocity starts from point D, the normal stress decreases and the shear stress increases; however, these stresses approach their respective constant values at point E, which indicates steady-state shear on the critical state line (CSL). After this point, by gradually lowering the base of the shear cell, where there is little change ($\leq 0.5\%$) in the void fraction of the powder bed, both the shear stress and normal stress decrease (moving along the curve from point E to point C). Therefore, by continuously measuring τ



(a) Constant-load method (b) Constant-volume method

Fig. 1. Schematic diagram showing two types of shear test methods. (a) Constant-load method. (b) Constant-volume method.

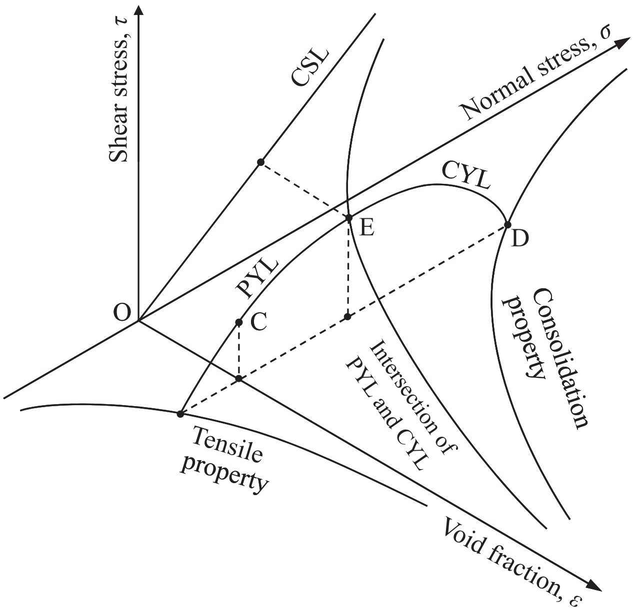


Fig. 2. A three-dimensional diagram showing the relationships between the mechanical properties of a powder bed.

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