MECHANICS OF POWDER MATERIAL COMPACTION

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Abstract: The connection consolidation theory with contemporary compaction mechanics is considered. The main principles for powder compaction theory formulated are analyzed. A connection is established between the identity principle and the hypothesis of the existence of a representative element, and one possible way of determining its dimensions is demonstrated. The main attention is devoted to the hypothesis of continuity and the results of compaction mechanics, which are obtained based on it. A connection is noted between consolidation theory and the concept of the mean-square viscous stresses. Problems are indicated that may easily be resolved by means of the concept of mean-square viscous stress. The relative solution of the problem of evaluating density distribution is noted. Problems are discussed for powder breaking directly during compaction in a rigid die.

Ideas formulated in creating powder compaction theory have been transformed into compaction mechanics. The impetus for this was the rapid development of problems accumulated in a number of branches of engineering connected primarily with producing articles of complex shape and use of the so-called difficult-to-deform powders in order to prepare structural materials.

The requirement became evident in the middle of the 1970s for formulating a concept of the behavior of compacted powders and compressed porous materials, which on one hand would make it possible to monitor property formation during compaction, and on the other to facilitate minimization of scrap, in particular to prevent the appearance of delaminating cracks. It appeared to be entirely natural that this type of concept should emerge from discrete-contact ideas about powder behavior.

On the other hand production problems required a rational model of the process formulated in the spirit of theory for treating metals under pressure. It was assumed that this model would make it possible to describe the behavior of compacted materials with different external effects. Theories of this type appeared in the 1970s and 80s and a new direction was formulated, i.e., compaction mechanics.

The most widespread models for this direction were formulated in terms customary for continuum theory, and they are different versions of ductility theory with internal variables (porosity, solid-phase strain accumulation, cohesion characteristics).

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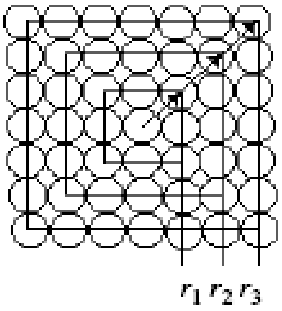

Fig. 1. Determination of the average packing density of particles.

However, it should be noted that in contrast to traditional forming compaction mechanics uses ideas about the mechanics of microinhomogeneous bodies. Analysis for an elementary cell and averaging operations are used alongside experimental methods for identifying model parameters. Due to this the majority of compaction models contain information about powder particles, their properties, deformation and rheological characteristics of the solid (nonporous) phase. In fact there is a successive connection of compaction mechanics with ideas introduced into powder metallurgy.

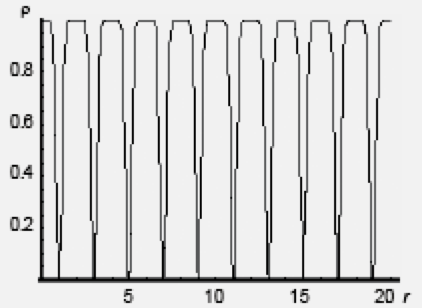

Fig. 2. Distribution of local density along a beam issuing from a central particle.

In us early work we introduced for consideration and used actively the idea of a two-phase porouspowder material. Here the supporting phase is a carcass of particles that during consolidation are transformed into the matrix of a porous body. We devoted particular attention to the mechanism of the transfer of external stresses from the die to individual particles. In the course of careful and fundamental analysis he arrived at the idea of a contact cross section as a key link governing the global mechanical response of a powder − pores system.

Connected with us idea is obtaining quantitative relationships between macroscopic and local characteristics of powder-porous bodies in the consolidation theory. Within the concept of a contact cross section a particular role is played by forces (in the case of mechanical action) or current (in analyzing electric conductivity) distributed through this cross section. Reference of them to the area of the cross section determines stresses that are connected with its structure. On the other hand, by the overall projection of particles the non-porous part of the cross section and forces connected with it are calculated.

Thus a relationship is established approximately between macroscopic elasticity modulus and conductivity, and also the corresponding particle material characteristics. The ideas have been developed in the concept of mean-square stresses and strain rates where force characteristics of a powder carcass have been transformed into averaged energy fields.

A feature of this approach is the fact that averaged fields may be worked out independently both on the basis of analyzing the state of a carcass and also proceeding from macroscopic considerations. Equating the values of specific deformation energy calculated by different methods leads to an expressions for averaged force characteristics. The universality of this approach is provided by the fact that in calculating the effective mechanical characteristics attention is not drawn to individual components of the force vector in fixed areas, but to the overall stress tensor operating within a microvolume. This approach is also sensitive to the topology of contact cross sections since the structure of the pore space is considered in calculating effective properties. In both the concept of a contact cross section and in that of mean-square stresses and strain rates there are a marked assumption that some microvolumes exist characterizing compact properties.

The problem of their existence is closely connected with the principles of identity and self-regulation. The assumption that the properties of a compact are similar to those of a powder particle was treated more broadly by understanding that an elementary carrier of compact properties is not an individual powder particle, but some hyperparticle.

Naturally a question arises of the dimensions of this hyperparticle and about how many particles it contains. The answer to this question may be obtained in determining the average powder bulk density. The customary determination connected with dividing the mass by the volume of poured material is appropriate in the case when the amount of particles is quite large and their addition to a charge does not lead to a change in its density. If we consider the region of a charge comparable in volume with powder particles, their density becomes sensitive to the number of particles. This is illustrated by the procedure of determining the average bulk density for a model of dense cubic packing(Fig. 1).

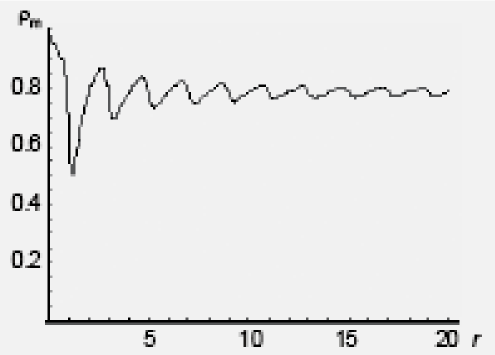

Fig. 3. Distribution of average density along a beam issuing from the central particle.

If a specific particle is fixed at the packing center (Fig. 1) and a beam is passed through it, then the change in local density along the beam is shown by the curve presented in Fig. 2. Now the particle at the centre is surrounded by a sequence of cubes for each of which it is possible to determine density as the quotient of the total mass of particles in a cube to its volume. The value obtained will be a function of the distance of the tip of a cube to its center. Here the density of each of the cubes is determined by the equation:

$$\rho = \frac{\int_V \rho_{local} dV}{V} \tag{1}$$

Here it is assumed that the local density is described by the curve presented in Fig. 2, whereas V is a uniformly increasing function of distance from the central particle. The calculation is facilitated by approximation of this curve with a periodic function that may be integrated in explicit form.

As a result of this for a sequence of the cubes described a density distribution is obtained for each of them in relation to distance from the central particle (Fig. 3). It is easy to understand that resulting distribution describes a quasi-oscillating function whose amplitude decreases with distance from the central particle. Here the nature of the decrease may be estimated proceeding from the form of the function $\rho_{local} = f(r)$. Similarly it possible to establish that distance from the central particle at which the averaged density is unchanged. Naturally it is necessary to consider the error of density determination. Knowing this dimension it is also possible to establish the number of particles within a given volume.

This dimension may be ascribed to the hyperparticle for which the identity principle is valid. The methodological importance of the identity principle combined with a procedure for determining the hyperparticle size involves the fact that for powder-porous bodies it is possible to use the continuity (continuum) hypothesis also first formulated. The procedure described above indicates the scale within which the continuum hypothesis is valid.

In fact on the basis of the continuum hypothesis it appeared possible from a single position to illuminate many problems formulated in powder compaction theory. Here a key role was played by the idea of a powderporous body flow potential. In many versions of continuum theory for powder compaction and the ductility of porous bodies this potential is determined phenomenologically, i.e. on the basis of treating the results of experiments with different deformation schemes.

However such approach did not introduce into the corresponding models of the required information about the properties of particles and pore space topology. Being based on analyzing the rate of energy dissipation within a hyperparticle of powder material it makes it possible to connect it with the macroscopic dissipation rate containing invariants of the macroscopic deformation rate. In the simplest case, when energy dissipation in the powder phase is associated only with particle deformation, it is possible to connect the flow potential with porosity, rheological, and deformation characteristics of powder particles.

The latter take account of movement kinetics for die elements and external friction. Thus, mathematical models emerging from formulation of the flow potential are able to monitor density distribution. Currently this monitoring is accomplished by numerical methods using special program packages.

Comparison of calculated and experimental results indicates good conformity. Here it should be borne in mind that as a rule these packages are readily readjusted: simple substitution of both kinematic conditions and material functions of the model responsible for powder properties is feasible.

Apparently the problem of density distribution, and more accurately the problem of control this distribution by selecting suitable movement kinematics for die tools and lubrication of the die and punch surfaces may be considered as practically resolved. Today it is possible to consider this achievement as the most effective result of compaction mechanics.

The problem of compact breaking is normally associated with the problem of density distribution. We are particularly talking about the fact that by this term we understand both breaking of unsintered compacts outside a die under conditions of application of external loads, and also breaking of compacts in a die under the action of the compaction force. The first of these phenomena may be resolved in principle at the macroscopic level by choice of a suitable deformation model and limiting criterion.

Of course the problem remains of connecting material parameters of a macromodel with the adhesion characteristics of powders, particle shape, and their formability. However, results obtained in this field make it possible to hope for answering this question in the foreseeable future. Another situation is with problem of breaking during compaction in a rigid die. In this case there is a set of problems connected with forming delamination cracks and overcompaction.

These phenomena are observed with the action of compressive stresses in the absence of a free surface. From this it follows that the normal approaches based on using well-known failure criteria appear to be inadequate. Nonetheless, the greatest number of supporters favors an approach based on combined formulation of the ellipsoidal flow potential and Drukker-Prager conditions for failure.

Appearance of these cracks is connected with local instability of deformation and formation of shear bands [18]. On the whole this assumption gives qualitatively believable results: a relationship between compaction and shape change rates, and also the orientation of delamination cracks are probable. However, difficulties of a mathematical nature remain: localized bands in a very narrow range of instability cannot be detected by known numerical methods. We should also talk about another situation: in order to reveal this effect models are used containing only one parameter, i.e. density.

Apparently another weakening parameter should be introduced into the model. A possible parameter may be the relative proportion of the contact cross section. However, it remains unclear how this parameter may be represented at the macroscopic level. In spite of the fact that the problems of delaminating cracks and overcompaction are far from final solution, compaction mechanics may be considered as a reliable means of monitoring consolidation in the compaction and deformation stages of porous billets.

Models and ideas formulated are used in related fields, i.e. damage accumulation theory, soil and rock mechanics, viscous failure mechanics. It should be noted that currently it is used most beneficially in the countries of Western Europe, Japan, and the USA where different aspects of compaction mechanics are a subject of research in a number of well-known international programs.

However, in acknowledging the leading specialists in these countries a marked contribution to formation of this field of knowledge has been made by scientists from the previous Soviet Union that up to the end of the 1980s held a leading position in the subject.

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