Sintered parts made of ductile materials constitute the main class of powder metallurgy products. Depending on the type of service for which they are intended, such materials must fulfill different requirements. In some cases porosity is desirable and necessary (bearings, filters, and sound-absorbing elements), while in others it is undesirable but unavoidable (residual porosity in constructional parts). Porosity decreases strength and, as a rule and to an even greater extent, ductility. Where sintered materials of special properties are to be produced (for bearings, filters, and other components), a compromise is often necessary and a lower level of mechanical properties is accepted, although an attempt is always made to minimize the loss of strength and ductility. Materials combining any required properties with maximum attainable strength and ductility can be expected to exhibit the highest resistance to wear, corrosion, and oxidation and to have the longest useful life.

In order to be able to exercise control over the properties of sintered parts by varying processing conditions, it is necessary first of all to know the strength and ductility limits attained in materials at any given porosity. This problem is closely linked with a number of other requirements. A clear understanding is necessary of the specific nature of the strength and ductility of a porous solid. A quantitative relationship must be established between strength, ductility, and several other fundamental characteristics. Invariant relations must be found between strength and ductility. Knowledge of all these relationships is necessary also if maximum benefit is to be derived from experimental data obtained in investigations and in the control of processes of manufacture of sintered ductile materials.

Earlier researches [1-6] have established the following basic characteristics of a porous solid:

\[
\begin{align*}
\alpha &= -d\omega/d\beta = \vartheta \omega / d\vartheta, \quad \alpha/\vartheta = \vartheta \omega / d\vartheta; \\
\omega &= -d\beta = (\alpha/\vartheta^2) \vartheta d\vartheta, \quad \vartheta = \int_0^\vartheta = \alpha d\vartheta, \quad \vartheta = \vartheta \omega,
\end{align*}
\]

where \( \vartheta \) is the relative density, \( \beta = 1/\vartheta \) is the relative volume, \( \alpha \) and \( \alpha/\vartheta \) are the contact (critical) sections expressed, respectively, as the fractions of the whole volume of the body \( \alpha \) or of the volume of its solid phase \( \alpha/\vartheta \) (\( \alpha/\vartheta \) is also the area of interparticle contact expressed as a function of the particle surface area), and \( \varphi \) and \( \omega \) are the volumes of the material of the particles displaced during consolidation into narrower contact zones (i.e., the volumes of these contact zones), expressed, respectively, as fractions of the volume of the whole body \( \varphi \) or of the volume of its solid phase \( \omega \).

The characteristics \( \alpha \) and \( \alpha/\vartheta \) represent also the sizes of the critical zone expressed as fractions of the volume of the whole body \( \alpha \) or of the volume of its solid phase \( \alpha/\vartheta \). Transfer of the stresses of consolidation and elastic deformation of the body being consolidated takes place solely in the critical zone. The whole irreversible deformation of consolidation and the work done in this deformation are localized entirely in the displaced volume of material [3-6]. The characteristic \( \omega \) is the most convenient for describing the process of formation of this volume, and the characteristic \( \varphi = \omega \vartheta \) the most convenient for describing the condition of the porous body during the formation of contact zones.

The formation of the critical sections and zone is a cumulative process. The quantity \( \alpha \) grows from the beginning of the shaping operation, steadily increasing with rise in shaping pressure, continues to grow during sintering, increasing with rise in temperature and increase in holding time, and as a rule reaches its highest value at the final instant of

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The growth and formation of contacts during consolidation are accompanied by local disturbances and decreases in their sizes. Nevertheless, the growth of the contact section (and critical zone) induced by these two processes usually proceeds uninterruptedly.

However, the final size of the critical sections and zone is not merely an end result of the whole previous history of its growth. It in turn determines the behavior and properties of the consolidated body not only in the past but also in the present, i.e., at the instant of testing of its properties. Because of this, to determine the final size of the contact section it is usually sufficient to know only the \( \alpha = F(\theta) \) relationship for the final stage of sintering. The quantity \( \alpha \) can always be determined (with accuracy to about 5\%) by tests which do not affect its value [5, 7], e.g.,

\[
\alpha = E/E_c = (\rho_c/\rho)^2/\theta = (\lambda_c/\lambda)^2/\theta = (\nu_c/v)^2/\theta,
\]

where \( E, \rho, \lambda, \) and \( v \) are, respectively, the elastic modulus, electrical resistivity, and electrical conductivity of the porous body and the velocity of sound in this body, and \( E_c, \rho_c, \lambda_c, \) and \( v_c \) are the corresponding characteristics for the nonporous body.

The volumes of the narrower, usually discrete contact zones of particle material in which the whole irreversible consolidation deformation is localized, \( \omega \) and \( \varphi = \theta \omega \), also grow during all the processes. But in this "displaced" volume of material, which has grown until the last instant of sintering [3-5], in turn, is fully localized the plastic deformation experienced by sintered specimens during tensile testing. As will be shown below, in this case, too, it is sufficient to know the variation of \( \omega \) and \( \varphi \) as functions of \( \theta \) in the final stage of sintering, and again these quantities can always be determined (also with an accuracy of about 5\%) by carrying out tests which do not alter their values.

In [8] a family of equations for the power relationship between contact section and relative density was derived to characterize the processes of ordinary sintering. This approach was subsequently adopted in a number of other investigations [6, 9]. From the generalized equations (1) and (2) it follows that this family is characterized by a power-type dependence on density also for the other characteristics under consideration:

\[
\alpha = \theta^m, \quad \alpha_I = \theta^2, \quad \alpha_{III} = \theta^3; \quad \alpha/\theta = \theta^{m-1} = \theta^n,
\]

\[
(\alpha/\theta)_I = \theta, \quad (\alpha/\theta)_{III} = \theta^2;
\]

\[
d(\alpha/\theta) = d\theta^n = n\theta^{n-1}d\theta, \quad \omega = \theta^{m-1}/(m - 1) = \theta^n/n = (\alpha/\theta)/n;
\]

\[
\omega_I = \theta, \quad \omega_{III} = \theta^2/2, \quad dw = d(\alpha/\theta)/n = \theta^{n-1}d\theta,
\]

\[
\varphi = \theta^m/(m - 1) = \alpha/(m - 1) = -(dw/d\theta)/n;
\]

\[
\varphi_I = \theta^2, \quad \varphi_{III} = \theta^3/2, \quad m \geq 2, \quad m_I = 2, \quad m_{III} = 3;
\]

\[
n = m - 1, \quad n \geq 1, \quad n_I = 1, \quad n_{III} = 2,
\]

where, at any instant of consolidation at \( \theta = \text{const} \), \( m \) and \( n \) are the same for all characteristics of a given body.

At \( m = m_I = 2 \) and \( n = n_I = 1 \) the properties (including strength and ductility) of sintered bodies at a given density have their maximum values (bodies of the first type [5, 6]). The symbols representing the characteristics of these bodies have the subscript I. Exponents \( m = m_{III} = 3 \) and \( n = n_{III} = 2 \) are typical of sintered bodies whose characteristics have their highest values at a given completely open porosity (bodies of the second type). The properties of bodies of the second type are denoted in Eqs. (4)-(8) by symbols with the subscript II. Values of \( 3 > m > 2 \) and \( 2 > n > 1 \) are characteristic of bodies of intermediate types, having both open and closed porosities. The properties of these bodies are superior to those of bodies of the second type but inferior to those of bodies of the first type. Values of \( m > 3 \) and \( n > 2 \) are characteristic of bodies of inferior properties.

Let us demonstrate that the family of equations obtained applies generally to the sintering of powder bodies. An increment of specific work done during the consolidation of a body being sintered is described by the equation [5, 6]