

## COMPOSITE MATERIALS

# Lower Limit Size of Pores in Metals under Sintering

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**Abstract**—The results of the derivation of an analytical expression for determining the lower limit (critical) pore sizes in the material are presented. It is shown that the material cannot contain pores with a size below a certain critical value.

**Keywords:** pore size, surface tension, gas pressure, sintering, strength

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## INTRODUCTION

Diffusion mass transfer and dislocation mass transfer occur in the process of thermomechanical treatment of materials. This leads to a decrease in pore size and an increase in the density of the material. These processes also occur when there is no external pressing pressure and internal gas pressure in the pores of the material [1], and their driving force is a decrease in the free energy of the material due to a decrease in the free surface area as a result of the action of surface tension forces. The effect of external compressive pressure leads to an even greater decrease in porosity.

The results of investigations of the shape of an isolated pore, the stress-strain state of the material around the pore, and the features of the distribution of vacancies, which is caused by the stress field, are considered in detail in [2, 3], where it was shown that the distribution of stresses around the isolated pore and their magnitude substantially determine the features and kinetics of mass transfer associated with healing of the pore. An expression for the minimum pore radius possible in a material when there is no external pressure is given in [1].

The purpose of this work is to determine the lower limit size of pores existing in the material under external pressure, which corresponds to the conditions of hot isostatic pressing (HIP) used in industry to reduce the porosity of materials and increase their strength properties.

## RESULTS AND DISCUSSION

The solution to the problem of the stress-strain state of a material near a spherical cavity with radius  $R$

with an internal pressure  $P_i$  subjected to external pressure  $P_0$  in an infinite medium belongs to G. Lamé [4, 5].

The distribution of radial  $\sigma_r$  and tangential  $\sigma_t$  stresses around a spherical cavity with radius  $R$  is determined by the expressions

$$\sigma_r = -P_i \frac{R^3}{r^3} + P_0 \frac{(R^3 - r^3)}{r^3}, \quad (1)$$

$$\sigma_t = P_i \frac{R^3}{2r^3} - P_0 \frac{(2r^3 + R^3)}{2r^3}, \quad (2)$$

where  $r$  is the distance from the center of the pore.

If there is no internal pressure in the material with a spherical pore and the external pressure does not act, then the stresses in the material are not equal to zero, since there is a Laplace pressure  $P_L$  acting in the direction from the material to the pore and equal to

$$P_L = \frac{2\alpha}{R}, \quad (3)$$

where  $\alpha$  is the surface tension of the material. This pressure contributes to the formation of the stress-strain state of the material. In this case, the action of the internal pressure  $P_i$  can be represented as the sum of the gas pressure inside the pore  $P_G$  and the Laplace pressure

The stresses are maximal on the pore surface at  $r = R$  and are equal to

$$\sigma_r = P_L - P_G, \quad (4)$$

$$\sigma_t = -\frac{P_L - P_G}{2} - \frac{3P_0}{2}. \quad (5)$$

**Table 1.** Properties and critical radius of pores for some metals at room temperature [6–10]

Material	$\alpha$ , N/m [6–10]	$\sigma_{0.2}$ , MPa [6]	$R_{cr}$ , nm ( $P_0 = 0$ )	$R_{cr}$ , nm ( $P_0 = 100$ MPa)
Iron	1.90	170	34	285
Chromium	2.20	190	35	165
Titanium	1.70	300	17	34
Cobalt (annealed)	1.97	300	20	39
Copper (cold-hardened)	1.75	380	14	23
Molybdenum (annealed)	2.60	570	14	19
Nickel (deformed)	1.82	686	8	10
Tungsten	2.80	760	11	14

Then, the principal normal stresses acting on the areas where there are no tangential stresses are

$$\sigma_1 = \sigma_r = P_L - P_G, \quad (6)$$

$$\sigma_2 = \sigma_3 = \sigma_r = -\frac{P_L - P_G}{2} - \frac{3P_0}{2}. \quad (7)$$

Plastic deformation of the material around the pore will begin when a certain critical stress value is reached.

In the context of the theory of strength, there are several hypotheses according to which the material

begins to deform if the acting equivalent stress  $\sigma_{eq}$  exceeds some acceptable value  $[\sigma]$ . The energy theory of strength (the theory of the highest specific potential energy of deformation) proceeds from the assumption that the amount of potential energy of deformation accumulated at the moment of the onset of material plasticity is the same both in a complex stress state and under simple tension. The fourth energy hypothesis of strength is consistent with experimental data for ductile materials. According to the fourth energy hypothesis [5], the strength condition has the form

$$\sigma_{eq} = \sqrt{1/2[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \leq [\sigma]. \quad (8)$$

Equations (6)–(8) show that the equivalent stress  $\sigma_{eq}$  is

$$\sigma_{eq} = \frac{3(P_L - P_G + P_0)}{2}. \quad (9)$$

The yield strength of the material  $\sigma_{0.2}$  can be taken as the allowable stress  $[\sigma]$ , and then, if the equivalent stress  $\sigma_{eq}$  is equal to the yield strength, plastic deformation will begin and the material will flow into the pore, and the pore will collapse. Therefore, Eqs. (3) and (9) make it possible to derive an analytical expression for the lower limit (critical) pore size  $R_{cr}$

$$R_{cr} = \frac{6\alpha}{2\sigma_{0.2} + 3P_G - 3P_0}. \quad (10)$$

Table 1 shows the calculated values of the critical pore radius for some metals at room temperature for the case where the internal gas pressure  $P_G = 0$  (pressing and sintering in vacuum) and the external pressure  $P_0 = 100$  MPa (isostatic pressing).

The yield strength decreases with increasing temperature, which leads to an increase in the critical pore size, while the action of internal pressure reduces the critical pore size. An increase in external pressure leads to the fact that large pores begin to collapse, that is, the critical pore size increases.

The results of optical microscopy of a thin section of a magnetically hard alloy Fe–26Cr–16Co–2Mo–2W–0.5Si sintered at 1420°C are presented in [11]. Pores with a lower limit size of  $\sim 1$   $\mu\text{m}$  are visible in photomicrographs. Studies of the same alloy with a scanning electron microscope show that the lower limit pore size is  $\sim 0.6$   $\mu\text{m}$ . An evaluation for the alloy ZhS32U–VI confirmed by experiments on the restoration of the fine structure is conducted in [12]. It shows that small pores  $\sim 0.25$   $\mu\text{m}$  in size, remaining in the castings after their compaction, dissolve by the diffusion mechanism in a time of  $\sim 100$  s. Our evaluation of the critical pore size for pure nickel is  $R_{cr} = 42$  nm ( $\alpha = 1.82$  N/m,  $\sigma_{0.2} = 280$  MPa,  $T = 1200^\circ\text{C}$  [13], and  $P_0 = 100$  MPa).

The results make it possible to conclude that lower limit pore size in porous materials is limited by the critical value  $R_{cr}$ , which can be evaluated from expression (10).

## CONCLUSIONS

It is shown that the decrease in pore size due to plastic deformation of the material occurs as a result of the action of surface tension and external pressure. An analytical expression for the lower limit size of pores existing in the material is obtained by comparing the

principal effective stresses with the yield strength of the material.

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