EFFECTS OF RESIDUAL POROSITY ON THE PROPERTIES OF TUNGSTEN CARBIDE – COBALT HARD ALLOYS

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The effects of porosity on the properties of single-phase sintered materials have already been investigated by a number of authors. Ryshkewitch, working with polycrystalline alumina and zirconia specimens, obtained the following, nowadays well-known formula for the relationship between porosity and compressive strength [1, 2]:

$$S = S_0 e^{-bP}, \tag{1}$$

where S is the strength of a porous material, S_0 the strength of the same material in the nonporous condition, b a constant, and P the porosity expressed as a fraction of unity, i.e., the ratio of the pore volume to the whole volume of the material.

In [3, 4], it is shown that Ryshkewitch's equation also describes satisfactorily the porosity dependence of the tensile strength, hardness, elongation, and impact strength of various sintered materials (both ceramic and metallic). The variation of the thermal and electrical conductivities of sintered materials with porosity was investigated by Kingery [5], who found that increases in porosity produced almost proportional decreases in the conductivities. These findings apply to single-phase materials of appreciable porosity (up to 50-70 vol. %), produced by solid-phase sintering.

WC–Co hard alloys are distinguished from such materials by their high density, which is a result of sintering in the presence of a liquid phase. Their residual porosity is very low, as a rule less than 0.5 vol. %. Yet experience shows that the volume and size of the pores in hard alloys have a marked effect on their properties. Anderson [6] notes that residual porosity in WC–Co alloys substantially decreases their transverse rupture strength (from 340 to 290 kg/mm^2 for a WC–Co alloy with 10% of cobalt). At the same time, porosity has a pronounced deleterious effect on the homogeneity of alloys. Similar data, actually revealing an even stronger effect of porosity (a 20-25% decrease in transverse rupture strength), are cited by Japanese investigators [7, 8]. Loshak [9] found that, for standard WC–Co alloys, transverse rupture strength was reduced by 15%, and fatigue life by a factor of about nine compared with nonporous alloys.

The present work was undertaken with the aim of conducting a systematic investigation into the effects of porosity upon the properties of hard alloys and establishing relevant quantitative relationships, since published investigations along these lines are lacking. A WC–Co alloy with a cobalt content of 8 wt. % (VK8 alloy) was chosen for investigation. Specimens were produced having different porosities and pore sizes – fine (less than 50 μ) and large (more than 50 μ). This was effected by adding a pore-forming agent – potassium chloride – to the WC–Co mixture. This compound has a boiling point (1406°C) lying within the sintering temperature range of VK8 alloy and can therefore be expected to be completely removed in the last stage of densification during sintering, leaving its traces in the form of pores. This proved in fact to be the case: Metallographic examinations and spectral and x-ray structural analyses revealed that the sintered alloys investigated were entirely free from potassium. Alloys of different pore sizes were obtained by varying the method of addition of potassium chloride to the hard-alloy mixture.

Porosity was determined as the ratio of the total area of pores of ≥10-μ size in a microsection (×100) to the whole area of the microsection. All the specimens investigated were subjected to this examination.

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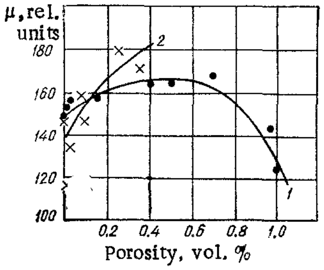


Fig. 1. Variation of magnetic permeability of VK8 alloy with volume content of fine (1) and large pores (2).

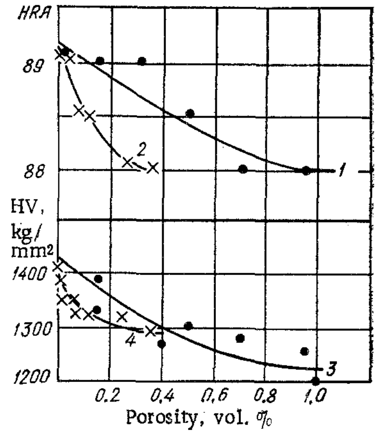
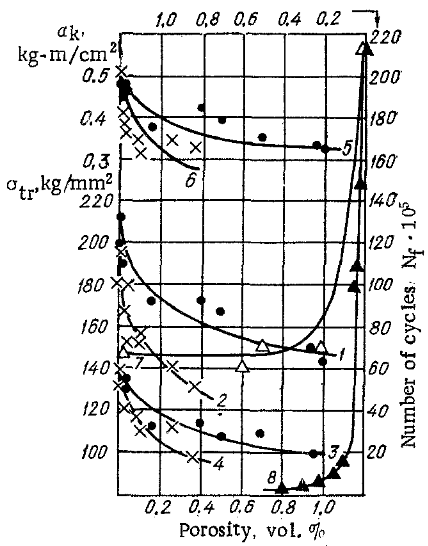


Fig. 2. Variation of Rockwell hardness HRA (1, 2) and Vickers hardness HV (3, 4) of VK8 alloy with volume content of fine (1, 3) and large pores (2, 4).



In each series of tests, use was made of control specimens of zero or nearly zero porosity, which were prepared by a special technique from the given batch of charge material. Tests were carried out on two-phase specimens having a fairly even distribution of carbide grains and approximately the same mean carbide grain size (1.9-2.1 μ).

The density, electrical resistivity, and normal elastic modulus values obtained were found to be virtually unaffected by the pore content of specimens and independent of pore size.

With increase in porosity, the magnetic permeability of the material (Fig. 1) grew, while its Rockwell and Vickers hardness (Fig. 2), transverse rupture strength (three-point bending scheme) at room and elevated temperatures, impact strength, fatigue life in symmetrical cyclic bending (Fig. 3), and arbitrary life coefficient in the turning of gray cast iron (Fig. 4) decreased exponentially for both pore size groups (fine and large).

With increase in porosity, both the fatigue life, determined under cyclic loading conditions, and the transverse rupture strength, determined under static loading conditions, decreased, the former more sharply than the latter. At a porosity of 0.1 vol. % (large pores), σ_{tr} decreased by about 20% and the fatigue life by a factor of 10; with fine pores, σ_{tr} diminished on the average by 10% and the fatigue life by about half.

The variation of the yield (0.1% proof) stress and compressive strength (Fig. 5) was essentially similar to the variation of the other properties, as described above. However, the fall in compressive strength with increase in porosity was much less pronounced than the fall in transverse rupture strength, even in the range of small pore volumes. A still greater difference was that the absolute values of yield stress and strength were larger for the alloys with large pores than for the alloys containing only fine pores.

DISCUSSION OF RESULTS

The apparent independence of the density, electrical resistivity, and modulus of normal elasticity of VK8 alloy from porosity over the pore volume range from zero to 1 vol. % is evidently attributable to insufficient sensitivity of the standard methods of measurement of these magnitudes at the very low porosities investigated.

The magnetic permeability of the alloy is more sensitive in this respect than its other magnetic characteristics (for example, coercive force). It is known that coercive force can be expected to grow with increase in the volume content of nonmagnetic inclusions and with decrease in their size [10]. As the variation of magnetic permeability is as a rule opposite to that of coercive force, the magnetic permeability of the alloy was found to grow

Fig. 3. Variation of transverse rupture strength σ_{tr} at room temperature (1, 2) and 800°C (3, 4), impact strength a_k (5, 6) and fatigue life N_f (7, 8) of VK8 alloy with volume content of fine (1, 3, 5, 7) and large pores (2, 4, 6, 8).

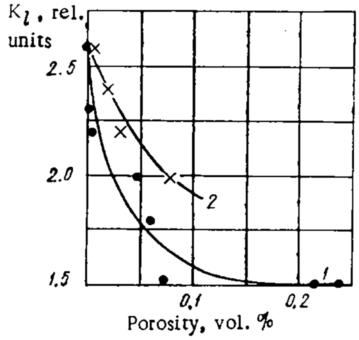


Fig. 4. Variation of arbitrary life coefficient of VK8 alloy in turning of cast iron with volume content of fine (1) and large pores (2).

with increase in pore size. It is not yet possible to explain why the magnetic permeability grew with increase in pore volume content (Fig. 1). It is quite probable, however, that the pore shape factor played an important part in this phenomenon.

The exponential character of the curves in Figs. 2-5 is undoubtedly linked with stress concentration in pores, resulting in the initiation of cracks following the application of a comparatively light external load [5]. As the number of pores per unit volume and hence their volume fraction grow, it becomes increasingly probable that a pore having the most dangerous shape and occupying the most dangerous position will appear in the material. Such a pore will lead to maximum stress concentration and initiate a crack. It is reasonable to assume that the probability of such a dangerous pore, characterized by maximum stress concentration, being found in the material is an exponential function of the amount of pores per unit volume, i.e.,

$$\gamma = \alpha e^{\beta N}; \tag{2}$$

$$\gamma = \alpha e^{\beta P}, \tag{3}$$

where γ is the probability, α and β are constants, N is the pore concentration, and P is the porosity, which leads to Ryshkewitch's equation [1].

As impact strength is a function of both ultimate strength and plasticity, it is quite understandable that, with the very small change in plasticity observed for the material investigated, the impact strength curve is similar in shape to the ultimate strength curve (Fig. 3). The hardness of the material, too, falls exponentially with increase in porosity (Fig. 2), since hardness is, of course, proportional to yield stress.

That the mechanical property vs porosity curves for VK8 alloy have an exponential character is confirmed by the fact that plots of the room- and elevated-temperature transverse rupture strengths of the alloy constructed in semilogarithmic coordinates are straight lines (Fig. 6). The useful life of a VK8 alloy tool in the turning of cast iron becomes shorter with increase in porosity (Fig. 4). This is mainly due to the reduction in hardness, but the reduction in strength must also play a part, since tool wear involves the breaking out of fine particles (crumbling) from the cutting edge of a hard alloy tool. Since both the hardness and the strength of the alloy decrease exponentially, its machining life curve, too, has an exponential character.

The changes in transverse rupture strength and fatigue life were particularly marked for the material with large pores, which was linked with the latter's shape. Metallographic examinations revealed that,

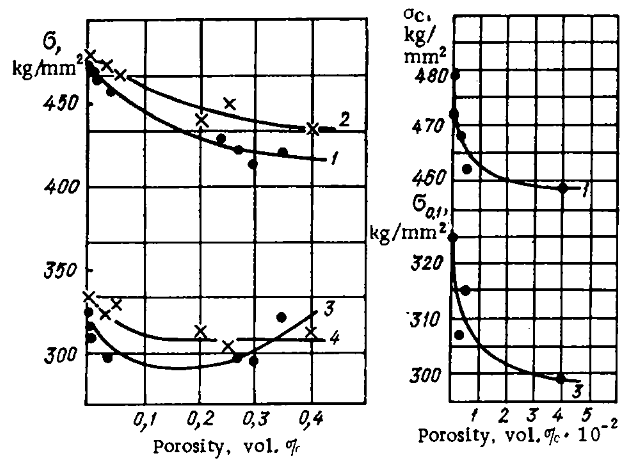


Fig. 5. Variation of compressive strength σ_c (1, 2) and 0.1% proof stress $\sigma_{0.1}$ (3, 4) of VK8 alloy with volume content of fine (1, 3) and large pores (2, 4).

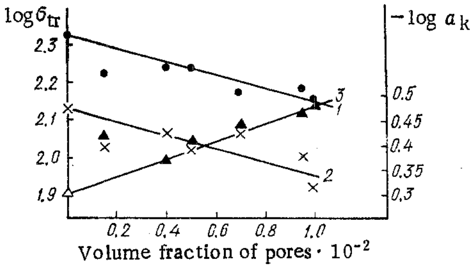


Fig. 6. Variation of transverse rupture strength of VK8 alloy at room temperature (1) and 800°C (2) and its impact strength (3) with volume fraction of pores, plotted in semilogarithmic coordinates.

unlike the small pores, which were spherical, the large pores were of irregular elongated shapes and acted as "internal notches," bringing about an increase in the value of coefficient of stress concentration.

A somewhat different picture was observed in compression, where higher values of yield stress and ultimate strength at the same porosity were recorded for the alloy with large pores. This was, of course due to the fact that the resistance of plastic deformation of WC−Co alloys is less in compression than in transverse bending, so that their brittle rupture in the former case is preceded by appreciable plastic deformation. It may be assumed that here the coefficient of stress concentration is much less than in macroscopically purely brittle materials [11], as a result of which the deterioration of mechanical properties with increase in porosity is less pronounced. In this case, the factor of pore concentration, i.e., the number of pores per unit volume, becomes dominant. This factor is favorable in the case of large pores, since, at any given porosity, the number of pores is then less.

Now hardness is as a rule proportional to yield stress, and because of this the material with large pores might have been expected to exhibit higher hardness. However, this was not the case, possibly because of the appearance of brittle cracks in the corners of diamond indentations at the usual loads employed in hardness determinations, as a result of which plastic deformation ceased to be the decisive factor. However, more work is necessary to elucidate this point.

CONCLUSIONS

1. The transverse rupture strength, fatigue life in cyclic bending, ultimate strength and yield stress in compression, hardness, and impact strength of VK8 hard alloy decrease with increase in porosity. The decrease is exponential, i.e., manifests itself particularly strongly in the range of low porosities. The relationship discovered, which is satisfactorily described by Ryshkewitch's formula, is due to the fact that the probability of appearance of maximum (dangerous) stress concentration varies exponentially as a function of the number of pores per unit volume.

2. A particularly marked decrease in transverse rupture strength, impact strength, and fatigue life is exhibited by VK8 alloy with large pores (> 50 μ). Such an alloy is characterized by higher values of yield stress and ultimate strength in compression. With both large and fine pores, the decrease in these characteristics is less pronounced than the decrease in transverse rupture strength, impact strength, and fatigue life in cantilever type cyclic bending.

3. The useful life of a VK8 alloy tool in the turning of cast iron also decreases exponentially with increase in porosity owing to the fall in hardness and strength.

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