From the production point of view boriding is one of the most studied processes of chemicothermal treatment of materials [1-3]. At the same time it is known that this type of coating reveals a significant instability of properties in service. The conflict in test results may be related to the action of not previously taken into consideration structural parameters of the coatings, for example, to preferential orientation of boride grains by crystallographic directions. This assumption becomes more substantiated if it is taken into consideration that formation in boride grains of [001] crystallographic texture leads to the occurrence in the coatings of a well-expressed anisotropy of the thermophysical properties [1]. The influence of texture on the strength properties of boride coatings has not been investigated until now.

The purpose of this work was to study the influence of the morphological and crystallographic texture on the strength properties and stressed condition and therefore supporting capacity of boride coatings applied by known methods [1-6] on iron—carbon alloys.

Structure and Properties of the Coatings. The phase composition and crystallographic texture of the coatings were studied on a DRON-2.0 diffractometer by recording from the surface of flat specimens in the radiation of an iron anode with a manganese filter. The pole density \( P_{hk} \) determined using the Harris method served as the quantitative characteristic of texture. It characterizes the ratio of the number of crystals for which the \([hk]\) axis of texture which is a normal to the \([uvw]\) plane coincides with the normal to the surface of the specimen to the number of crystals of the same orientation in a texture-free specimen [7]. The chemical analysis of the coatings was determined on a Camscan scanning electron microscope equipped with the system of a Link 860 energy dispersion X-ray microanalyzer.

As the result of impregnation two-phase (FeB, Fe₂B) coatings consisting of columnar (acicular) crystals elongated in the surface direction were obtained on the surface of the specimens (Fig. 1a, b). With the exception of borided specimens obtained in a mixture of B₄C with additions of oxygen-containing activators (CuSO₄, KMnO₄) the structure of the remaining investigated coatings did not differ from the well-studied and systematized structural types in which FeB phase is present on the surface in the form of a continuous layer or individual needles (Table 1). Boriding in a mixture of B₄C with oxygen-containing activators leads to formation of a new and previously unstudied coating in which FeB phase propagates as a layer to some \((10 \mu m)\) distance from the surface within the Fe₂B layer (Fig. 1c). It has been established (Table 1) that together with the horizontal cracks normally recorded in the presence of residual compressive forces formed after boriding [1, 8] there are also cracks normal to the surface (Fig. 1a-c) which, as is known, occur under the action of residual tensile stresses.

X-ray diffraction investigation results showed (Table 1) that a characteristic structural feature of the coatings studied is the presence in the boride layers of axial crystallographic texture. It has been established that in contrast to the Fe₂B layer axially textured in the [001] direction, three types of textures, [001], [111], and [111] + [001], are observed in the FeB layer. The results obtained agree well with the data given in [1]. It was found that the preferential orientation of the FeB and Fe₂B phases is formed not only in liquid boriding, as was previously assumed [1], but also as the result of impregnation in B₄C-base solid powder media with additions of metals and oxygen-containing activators in which the coatings are formed with significant development of the liquid-phase mechanism of external mass exchange of boron with boric boron anhydride [3]. However, in contrast to [1], the author of this article has shown that the degree of texture \( P_{hk} \) of the boride phases may increase not only in the forward direction from the surface into the depth of coatings but also in the opposite when the perfection of the axial texture in the FeB layer is higher than in the Fe₂B layer. It is characteristic that cracks normal to the surface appear in those layers in which the perfection of the [001] axial texture is higher (Table...
Fig. 1. Microstructure of coatings obtained as the result of boriding at 930-980°C of 45 (a, b) and U8 (c) steels in powder mixtures of B₄C + 10 wt.% Ti (a), B₄C + 5 wt.% Mn (b), and B₄C + 3 wt.% CuSO₄·5H₂O + 3 wt.% KMnO₄ (c). a) 400×, b) 500×, c) 700×.

1). In this case the opening and density of normal cracks increases with an increase in the degree of texture of the layers (Fig. 1a, b). The investigation results provide a basis for assuming that appearance in the FeB and Fe₂B layers of axial crystallographic texture with an [001] axis leads to a reduction in the supporting capacity of the coatings.

**Evaluation of the Strength of Structurally Nonuniform Boride Coatings.** In accordance with [9] the strength properties of boride coatings were evaluated with use of qualitative and quantitative criteria of brittle fracture. The force criterion of fracture toughness \( K_{lc} \) was determined from the extent of brittle cracks occurring at the tips of an indentor impression [10, 11] taking into consideration features of the applicability of this method to thin surface layers nonuniform in composition and structure with an initial field of residual stresses [9, 12]. The tests were made in indentation of a standard Vickers pyramid on a PMT-3 tester in the 0.2-2.7 N range of loads. Not less than 30 impressions were applied under each load. To calculate the microhardness the "whole" impressions of the indentor were used. The characteristics of strength, microhardness and fracture toughness, were determined under conditions under which use of loads providing reaching of a constant ratio of elastic and plastic under the indentor [13] and, as a consequence, constant values of \( H_p \) and \( K_{lc} \) was specified.

The anisotropy of properties observed in the coatings may be not only a reflection of the crystallographic and morphological anisotropy or nonuniformity of the composition of the material but also the consequence of the influence of residual stresses acting along the surface. To verify this assumption the fracture toughness was measured across the cross section of the same coating in which the residual stresses were measured by conducting successive heat treatment of the steel base. The residual stresses were determined by the mechanical method from the deformation of the borided specimen measured during electrolytic etching of one side of it [14]. It was established that regardless of the orientation of the brittle cracks \( K_{lc} \) is invariant within the limits of each layer in relation to the residual stresses acting in the coating (Fig. 2). Such a result unexpected at first glance is apparently related to the fact that the extent of the brittle cracks occurring in the allowable range of loads is less than the linear dimensions of the boride grains. Obviously the values of \( K_{lc} \) recorded under these conditions characterize the fracture toughness of the individual grains but do not reflect the fracture resistance of the whole coating as an elastic continuum as a whole.

From the method point of view the fact that in the particular case in which a crack does not intersect a grain boundary the criteria of brittle fracture determined are not sensitive to the action of residual stresses is important. From this it follows that the orientation relationship of fracture resistance observed in tests of boride layers is caused by the influence of their structural nonuniformity. For evaluation of the brittle strength of boride coatings it is desirable to use the critical stress intensity factors presented in the form of the function \( K_{lc}(\varphi) \), where \( \varphi \) is the coordinate angle between the direction of crack propagation and the surface.

Taking into consideration the observed features of the structure of coatings the experimental values of the function \( K_{lc}(\varphi) \) in the boride layers correspond to the directions for which the angle \( \varphi \) is 0 and \( \pi/2 \). Quantitative measurements showed that with an expressed anisotropy of the form of the columnar grains in crystallographically textureless coatings an orientation relationship of the brittle strength characterized by the following relationship of the extreme values of frac-