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INFLUENCE OF THERMO-OXIDATION AND VIBRATION STRENGTHENING METHODS ON THE FRACTURE RESISTANCE OF HARD ALLOYS

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This article examines the influence of thermo-oxidative and vibration strengthening methods on the resistance of hard alloys to brittle fracture. Cemented carbides based on tungsten carbide with a cobalt binder (WC-Co) are widely used in mining, drilling, and cutting tools operating under conditions of high loads and dynamic impacts. Under such operating conditions, the reliability and durability of hard-alloy tools depend not only on hardness and wear resistance but also on the ability of the material to resist crack initiation and propagation.

The theoretical basis of the research is the Griffith–Orowan brittle fracture theory, which relates the strength of brittle materials to the effective surface energy and the critical length of defects present in the material. Particular attention is given to the role of the cobalt binder phase in the fracture mechanism of WC–Co alloys. It is assumed that the main contribution to the fracture energy is associated with the plastic deformation of the cobalt phase located near the crack tip. Consequently, changes in the structural state of the binder phase during post-sintering treatments may significantly influence the mechanical properties of the alloy.

The experimental results demonstrate that both thermo-oxidative and vibration treatments lead to an increase in the strength characteristics of WC–Co alloys. The strengthening effect is mainly associated with structural and mechanical changes occurring in the cobalt binder phase, which increases the ability of the material to absorb deformation energy near the crack tip.

The obtained results confirm the effectiveness of combined strengthening technologies for improving the reliability and durability of hard-alloy tools. These findings may be useful for optimizing technological processes in the production of cemented carbide components intended for operation under severe loading conditions.

Keywords: *hard alloys, cemented carbides, tungsten carbide–cobalt alloys (WC–Co), thermo-oxidative treatment, vibration processing, strengthening methods, brittle fracture, fracture resistance, crack propagation, mechanical properties.*

Eq. 8. Fig. 2. Table. 2. Ref. 18.

1. Problem formulation

Hard alloys based on tungsten carbide with a cobalt binder (WC–Co) are widely used in mining, drilling, and cutting tools operating under severe loading conditions. Such tools are subjected to complex stresses, including high static and dynamic loads, impact forces, and abrasive wear. Under these conditions, the reliability and durability of hard-alloy components depend not only on their hardness and wear resistance but also on their ability to resist brittle fracture. However, cemented carbides are characterized by relatively low fracture toughness, which increases the risk of crack initiation and propagation during operation.

When designing hard-alloy tools intended for operation over a wide range of loading rates and applied forces, it is necessary to consider a complex combination of physical and mechanical properties of the material. At the same time, it is often impossible to simultaneously achieve maximum values of all required characteristics. For example, alloys with higher hardness and wear resistance usually demonstrate increased brittleness, while alloys with improved strength and fracture resistance may exhibit reduced hardness. Therefore, the selection of a particular grade of hard alloy for a specific application is usually associated with

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a compromise between these properties.

One of the possible approaches to improving the operational reliability of hard alloys is the use of strengthening technologies applied after the sintering stage. Among such methods, thermo-oxidative treatment and vibration processing are of particular interest. These methods can influence the structural state of the material, especially the cobalt binder phase, and thereby modify the mechanical properties of the alloy. However, the mechanisms by which these treatments affect fracture resistance and crack propagation behavior remain insufficiently studied.

In particular, it is important to determine how thermo-oxidative and vibration treatments influence key parameters of fracture mechanics, such as effective surface energy, bending strength, and resistance to crack growth. A deeper understanding of these relationships would make it possible to optimize strengthening technologies and improve the performance of hard-alloy tools operating under severe conditions.

Therefore, the problem addressed in this study is the investigation of the influence of thermo-oxidative and vibration strengthening methods on the resistance of hard alloys to brittle fracture and the determination of the mechanisms responsible for the improvement of their mechanical properties.

2. Analysis of recent research and publications

Hard alloys based on tungsten carbide with a cobalt binder (WC–Co) are widely used in modern engineering due to their high hardness, wear resistance, and thermal stability. These materials are extensively applied in mining, drilling, and cutting tools operating under severe mechanical and thermal conditions. However, despite their high hardness, cemented carbides are characterized by relatively low fracture toughness, which increases the risk of brittle fracture during operation. Therefore, many scientific studies focus on improving the balance between hardness, strength, and resistance to crack propagation in these materials.

Recent research has shown that the mechanical properties of WC–Co alloys are strongly influenced by their microstructure, including the size of tungsten carbide grains, the distribution of the cobalt binder phase, and the characteristics of phase boundaries. In particular, coherent WC/Co phase boundaries can increase fracture toughness because they impede the propagation of microcracks and promote crack-tip blunting within the ductile cobalt phase. Such microstructural features improve the ability of the material to resist crack growth under mechanical loading.

Another important research direction concerns the modification of cemented carbides through various post-sintering strengthening technologies. Experimental studies demonstrate that additional treatments, such as cryogenic processing or thermobaric synthesis, can significantly improve mechanical properties by refining the microstructure, increasing compressive residual stresses, or modifying the phase composition of the cobalt binder. These structural changes contribute to increased hardness, wear resistance, and fracture toughness of WC–Co composites.

Modern investigations also analyze the mechanisms of crack initiation and propagation in cemented carbides under cyclic and dynamic loading conditions. Studies of fatigue crack growth in WC–Co materials show that the development of cracks is closely related to the size and distribution of defects, grain boundaries, and the plastic deformation capability of the binder phase. Understanding these mechanisms is essential for improving the reliability and durability of hard-alloy components used in industrial tools.

Despite the significant number of studies devoted to improving the mechanical properties of cemented carbides, many aspects of strengthening technologies remain insufficiently investigated. In particular, limited attention has been paid to the combined influence of thermo-oxidative treatment and vibration processing on the fracture resistance of WC–Co alloys. A detailed study of these methods and their effect on crack propagation resistance is therefore important for developing more effective strengthening technologies for hard-alloy tools operating under severe loading conditions.

3. The purpose of the article

The purpose of this article is to investigate the influence of thermo-oxidative and vibration strengthening methods on the resistance of tungsten carbide–cobalt (WC–Co) hard alloys to brittle fracture. The study aims to determine how these technological treatments affect the mechanical properties, effective surface energy, and crack propagation resistance of the material, as well as to identify the mechanisms responsible for the improvement of fracture toughness in cemented carbides.

4. Results and discussion

When designing a hard alloy tool, for example, a mining cutting and drilling tool, intended for work in a wide range of loading speeds and applied forces, it is necessary to take into account a number of indicators of the physical and mechanical properties of alloys. However, not all the main characteristics can be high at the same time, therefore, when choosing a brand of hard alloy, based on the expected operating conditions of the tool, one always has to make a compromise decision: either give up hardness, and hence wear resistance, but choose an alloy with greater dynamic strength, or incorporate a harder but brittle alloy and thereby increase the danger. In this regard, it is of practical interest to clarify the influence of hardening methods on the resistance of hard alloys to brittle fracture, since it is known [1] that during deformation hardening, the plastic properties of the material deteriorate and its brittleness increases.

by Griffiths , is based on equation (1.1)

$$\delta_1 = \left[\frac{2E_{\gamma_{\text{еф}}}}{(1-\mu)^2\pi l_{\text{кр}}}\right]^{1/2} \qquad (1)$$

where $\delta_1$the stress normal to the plane of a two-dimensional crack, with a length of E is Young's modulus; μ- Poisson's ratio; $\gamma_{\text{еф}}$ –effective surface energy, which means the work of creating a unit area of a new fracture surface; $l_{\text{кр}}$ – the critical half-length of the defect in the material (the width of the defect is negligibly small).

The quantity $\gamma_{\text{еф}}$ consists mainly of the true surface energy of the substance $\gamma$and the work P of plastic deformation of a small volume of the sample adjacent to the moving crack tip.

$$\gamma_{\text{еф}} = \gamma + \text{P} \qquad (2)$$

In brittle fracture of metals, for example, in Orovan's experiments on brittle fracture of low-carbon steel at low temperature [2, 3], the work of plastic deformation of the layer adjacent to the fracture surface is two to three orders of magnitude greater than the surface energy of the metal, as a result of which the value can be neglected γ. Then equation (1.2) has the form

$$\delta_1 = \left[\frac{2EP}{(1-\mu)^2\pi l_{\text{кр}}}\right]^{1/2}\text{P} \qquad (3)$$

This equation is commonly called the Griffiths-Orovan equation .

The value of the effective surface energy $\gamma_{\text{ефф}}$ obtained by various methods, is currently known for a significant number of "brittle" materials, including hard alloys [4-8]. The main condition for applying the Griffiths-Orowan criterion to hard alloys WC- Co is the brittle nature of fracture during bending and stretching, i.e. the absence of noticeable macroscopic plastic deformation before fracture. This condition is satisfied by alloys with a cobalt content of slightly more than 15% (by mass) and with an average carbide grain size of slightly more than 5 μm [7]. For these alloys, an empirical equation (1.4) was obtained, which relates the tensile strength to the cobalt content in the alloy C

$$\delta^2 = \text{AEcP} \qquad (4)$$

Where $\delta$is the tensile strength during transverse bending; A-constant.

The alignment (3.22) was experimentally [8, 9] by establishing a linear relationship between ${\delta^2}_a$ and the derivative of Es. The constant A obtained from such graphs had a value of 0.03-0.04.

A number of assumptions were made when deriving the equations:

1. The destructive crack propagates along the grain boundaries in the cobalt phase, and the latter is plastically deformed in a thin layer adjacent to the fracture surface, due to which $\gamma_{\text{eфф}}$ in equation (1.3) is equal to the work of local plastic deformation of cobalt P. This assumption was made after [11], where it was shown by quantitative photography using an electron microscope that during bending fracture of fine-grained WC-Co alloys, the crack passes almost only along the boundaries of WC- Co and the cobalt phase.

2. Work γ_{ef} is proportional to the cobalt content in the metal

$$\gamma_{ef} = \alpha * \text{CoP} \qquad (5)$$

The constant αmeans the work of plastic deformation that occurs per one percent of cobalt.

3. The critical crack length $I_{\text{кр}}$ from equations (3.21) and (3.19) does not depend on the cobalt content Co.

Points 2 and 3 were checked in [9]. In particular, it was found that the assumptions made are correct, and the value $I_{\text{кр}}$ is 13 μm for alloys containing 6-15% (by mass) and with an average carbide grain size d = 2 μm. The value of the constant was obtained to be 50 MPa and equation (1.4) took the form:

$$\delta_a^2 = 5\text{E}f_{Co}\text{P} \qquad (6)$$

This equation agrees well with experimental data.

According to works [108, 109], for coarse-grained alloys the following equation is valid:

$$\delta_a^2 = AEc + K\mathrm{P} \qquad (7)$$

where A is a quantity that depends from cobalt content , but increasing from increase average size carbide grains up to d = 5 μm, at d = 5 μm the value of K = 633104 n/m.

As shown by the data [9], at the size carbide grains, approximately more than 2 microns, the crack passes not only along the cobalt , but also along the carbide phase , and from increase grain size is getting bigger Therefore , the growth boundaries strength in coarse-grained alloys work - related destruction carbide grains. As established [9], the contribution of carbide phase to common. The strength of coarse-grained WC alloy 6% Co is approximately 13% for coarse-grained WC alloy - 15% for 10%. Length critical crack $I_{\text{кр}}$for the carbide phase, 9 μm was obtained. Since the strength, toughness and critical crack length of the carbide phase are less than the same parameters of the binder phase, a crack that has arisen in the carbide phase will propagate relatively easily along this phase. phase and will lead to the destruction of the alloy regardless of from content properties connective phases . In fact, the destruction alloys, including coarse- grained , controlled mainly by content and properties phases binding . This is due to the fact that cracks that arose long before the alloy breaks down in the carbide phase at a distance , proportional to the grain size " rest " in the cobalt layers , viscosity which , as already noted , are two orders of magnitude more than Value viscosity WC. Indeed, if $\gamma_{\text{ефф}}$carbide is 10 J/m² [9], then for alloys with 6 and 15% CO, in which the crack passes through the bonding phase, bypassing the carbide grains, $\gamma_{\text{ефф}}$it is 60 and 150 J/m², respectively. These data indicate that if, as a result of further sintering processing, change value $\gamma_{\text{ефф}}$, then this will be caused by qualitative transformations in the cobalt phase. Having determined $\gamma_{\text{ефф}}$independently for each type of processing, it is possible, firstly, to predict the strength of the alloy and the real behavior of structures made of hard alloys in operational conditions. conditions and, secondly , to clarify mechanism gain . For this purpose , in the method [4], according to the definition $\gamma_{\text{ефф}}$, deep cuts are provided (H - H = 0.2-0.4 mm; H- thickness sample ; - depth section).

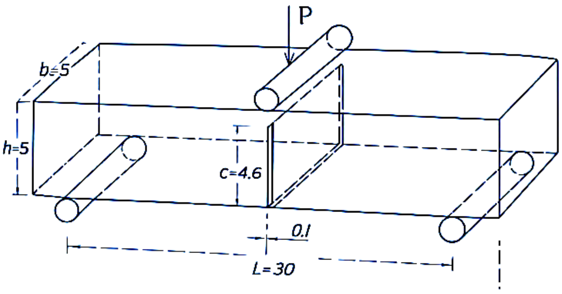

Fig. 1. Sample loading diagram

Under the conditions of stored elastic energy of the sample, crack propagation in surface layers strengthened by various methods is spent. It should be noted that the paper presents the results of the analysis of various methods for determining $\gamma_{\text{ефф}}$WC-C alloys: analytical method, "yield" method, unloading work method. The tests were carried out on samples of different shapes under different loading conditions (three-point bending, double cantilever, double torsion, impact tensile).

It has been established that alloys obtained by different methods but having the same microstructural parameters have the same values $\gamma_{\text{ефф}}$

For the research, samples of the VK 8B alloy were prepared from the same batch of raw materials (one batch of WC and one batch of Co), and on the same equipment. The obtained samples, thus, had the same composition of the binder phase. It is quite likely that the numerical value of the coefficient A obtained in the experiments will depend only on the subsequent post-sintering treatments.

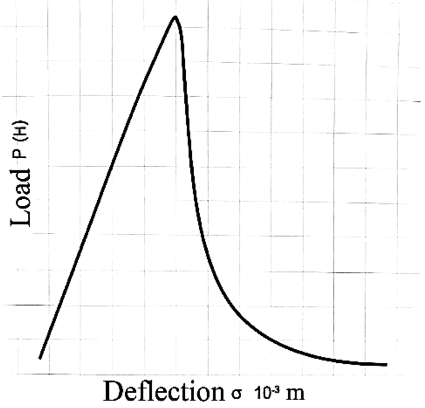

Fig.2 Diagram nagruzka-deflection

Table 1

Hardening technology methods on the strength properties of the VK 8B alloy (average size of carbide grains d = 4.5 μm)

Type of processing	γ_{ef} , J /m²	σ_{zg} , MPa	$\alpha \cdot 10^5$ J /m²	l, μm	K_{1C} , MPa	A, MPa
Party No. 1						
Initial state	188	179	0.35	24	15	65
Thermal oxidation	276	212	0.47	24	21.6	91
Vibration treatment	278	229	0.71	21	22.5	105
Thermal oxidation and vibration treatment	345	238	0.76	23	27	114
Party No. 2						
Initial state	130	156	0.37	21	9.9	49
Thermal oxidation	145	188	0.86	16	11	72
Vibration treatment	150	226	1.47	12	11.4	99
Thermal oxidation and vibration treatment	218	249	the samples did not collapse	14	16.5	124

Table 1.1 shows the data of experimental definition, α and calculation I_{KD}. A and Ks for VK 8V alloys. Parameter K,s is the resistance to crack propagation or the critical value of the stress intensity at the moment of crack growth initiation. According to [112] K,s was calculated according to the dependence

$$K_{1C} = \frac{2\gamma_{ef}E}{(1-\nu^2)}P \tag{8}$$

As can be seen from Table 1.1, TO in combination with VO results in all cases to simultaneous increase main indicators mechanical properties of the alloy, which indicates a high degree strengthening and simultaneous increasing resistance to spread cracks . At the same time, different options processing samples from baked tungsten carbide did not lead to changes (Table 1.2).

Table 2

Influence of hardening technology methods on the value of effective surface energy γ_{ef} and strength characteristics of sintered tungsten carbide samples

Type of processing	γ_{ef} , J /m²	σ_{zg} , MPa	$\alpha \cdot 10^5$ J /m²	d, μm
Initial state	16	840	1.51	14.58
Thermal oxidation	13	860	1.38	14.55
Vibration treatment	18	920	1.36	9.6
Thermal oxidation and vibration treatment	16	890	1.26	10.2

The presented data may confirm the previously put forward assumption that the strengthening effect of alloys is largely associated with changes in the cobalt phase.

5. Conclusion

The conducted research investigated the influence of thermo-oxidative and vibration strengthening methods on the resistance of tungsten carbide–cobalt (WC–Co) hard alloys to brittle fracture. The results show that the application of these technological treatments leads to a noticeable improvement in the mechanical characteristics of cemented carbides, particularly in terms of bending strength and resistance to crack propagation.

Experimental studies demonstrated that both thermo-oxidative treatment and vibration processing contribute to an increase in the effective surface energy and fracture toughness of the material. The strengthening effect is primarily associated with structural changes occurring in the cobalt binder phase, which plays a decisive role in the fracture mechanism of WC–Co alloys. The cobalt phase absorbs a significant portion of the deformation energy near the crack tip, which increases the material's resistance to brittle fracture.

The results also indicate that the combined application of thermo-oxidative and vibration treatments provides the most significant strengthening effect. This combination leads to a simultaneous increase in key mechanical parameters and improves the ability of the alloy to resist crack initiation and propagation under mechanical loading.

Thus, the use of combined strengthening technologies can be considered an effective approach for improving the reliability and durability of hard-alloy tools operating under severe service conditions. The obtained results may be useful for optimizing technological processes in the production and post-treatment of cemented carbides intended for mining, drilling, and cutting applications.

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ВПЛИВ МЕТОДІВ ТЕРМООКИСНЮВАЛЬНОГО ТА ВІБРАЦІЙНОГО ЗМІЦНЕННЯ НА ОПІР КРИХКОМУ РУЙНУВАННЮ ТВЕРДИХ СПЛАВІВ

У статті досліджено вплив методів термоокиснювального та вібраційного зміцнення на опір твердих сплавів крихкому руйнуванню. Тверді сплави на основі карбіду вольфраму з кобальтовою зв'язкою (WC-Co) широко застосовують у гірничодобувному, буровому та різальному інструменті, що працює в умовах високих навантажень і динамічних ударів. За таких умов експлуатації надійність і довговічність твердосплавного інструменту залежать не лише від твердості та зносостійкості, а й від здатності матеріалу чинити опір зародженню та поширенню тріщин. Тому дослідження методів зміцнення, які дають змогу підвищити тріщиностійкість за збереження високої твердості, має важливе практичне значення.

Теоретичною основою дослідження є теорія крихкого руйнування Гріффітса–Орована, яка пов'язує міцність крихких матеріалів з ефективною поверхневою енергією та критичною довжиною дефектів, наявних у матеріалі. Особливу увагу приділено ролі кобальтової зв'язки в механізмі руйнування сплавів WC–Co. Припускається, що основний внесок в енергію руйнування пов'язаний із пластичною деформацією кобальтової фази, розташованої поблизу вершини тріщини. Відповідно, зміни структурного стану фази-зв'язки під час обробок після спікання можуть істотно впливати на механічні властивості сплаву.

Експериментальні дослідження виконано на зразках твердого сплаву ВК8В, виготовлених з однієї партії порошків карбіду вольфраму та кобальту, щоб забезпечити однаковий хімічний склад і мікроструктурні параметри. Досліджено вплив різних зміцнювальних обробок — термоокиснювальної обробки, вібраційної обробки та їх комбінованого застосування — на механічні характеристики сплаву. Основними проаналізованими параметрами були межа міцності при згині, ефективна поверхнева енергія, тріщиностійкість та інші показники, пов'язані з механікою руйнування.

Експериментальні результати свідчать, що як термоокиснювальна, так і вібраційна обробка приводять до підвищення міцнісних характеристик сплавів WC–Co. Комбіноване застосування цих методів забезпечує найістотніше підвищення опору руйнуванню та поширенню тріщин. Ефект зміцнення головним чином пов'язаний зі структурними та механічними змінами, що відбуваються у кобальтовій фазі-зв'язці, внаслідок чого зростає здатність матеріалу поглинати енергію деформації поблизу вершини тріщини.

Отримані результати підтверджують ефективність комбінованих технологій зміцнення для підвищення надійності та довговічності твердосплавного інструменту. Ці висновки можуть бути корисними для оптимізації технологічних процесів під час виготовлення твердосплавних деталей, призначених для роботи в умовах важкого навантаження.

Ключові слова: *тверді сплави, цементовані карбіди, сплави карбід вольфраму – кобальт (WC– Co), термоокиснювальна обробка, вібраційна обробка, методи зміцнення, крихке руйнування, тріщиностійкість, поширення тріщин, механічні властивості.*

Ф. 8. Рис. 2. Табл. 2. Літ. 18.

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