Multistage Process Control of Submicro- and Nanocrystalline Multiphase Structure Formation in Hard Alloy Materials Treated by Electron Beam[1]

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Abstract – Scientific and technological principals of process control of submicro- and nanocrystalline multiphase structure formation in hard alloy materials during electron beam treatment allowing to increase their lifetime under cutting conditions of metal are considered. On the basis of the physical materials science approach to structure-phase transformations in all stages of technological process of submicro- and nanostructural systems obtaining the fundamental correlations between phase composition, a defect substructure, production technology and exploitation characteristics of an final product are revealed. The main parameters allowing to control the formation of submicro- and nanostructural states in all stages of technological process of hard alloy cutting tool production are determined.

1. Introduction

At the present time, the most widely used alloys in manufacturing industry are hard alloys based on tungsten carbide (WC-type hard alloys) and tungsten carbide with titanium carbide (TC-type hard alloys) whose properties are rather thoroughly studied [1]. Tungsten carbide, forming the base of the solid phase of the above alloys, has features a good wettability with a liquid binder, a high elastic modulus, and plasticity even at room temperature. At the same time, tungsten carbide has a number of shortcomings such as low scaling and wear resistances, low resistance to dimpling during cutting of steels, and low temperature of the beginning of adhesive contact with the treated material. Moreover, early in the 80s of the last century, the deficiency of tungsten carbide considerably increased, requiring its saving and use only in those industries where its replacement is almost impossible. Thus, the necessity arises of changing over from tungsten and cobalt carbide as hard alloy constituents to new systems based on more readily available elements (so-called tungsten-free hard alloys) [2, 3].

Tungsten-free hard alloys are rather cheap cutting tool materials. The extension of technological capabilities of hard alloy production and the development of powder metallurgy and materials science as a whole have made possible new group of alloys based on refractory Ti compounds – W-free hard alloys.

These alloys have peculiar features that allow their effective substitution for scarce hard tungsten-cobalt alloys. However, a full replacement of WC alloys has not been designed to date, since tungsten-free hard alloys do not have in full measure the required properties.

At the present time, studies aimed at improving the properties of this material are conducted in various ways, e.g., by changing the structure of hard alloys, by fully or partially replacing the carbide component of alloys with new hard components, and by modifying the structure and the phase composition of the binder material. Experience suggests that in most of cases, the greatest effect in improving the exploitation properties of metals, alloys, cermet and ceramic materials is attained through combining different modification methods with resort to radically new techniques of the formation and control of the structure and properties of products.

The objective of this work is to analyze the mechanisms of structural transformations and changes in the mechanical characteristics of a hard alloy based on tungsten carbide at different stages of its formation.

2. Experimental procedure

In the study, we analyzed the changes in the structure and in the properties of a hard alloy based on titanium carbide at the following stages of its formation:

1. Formation of the carbide phase. We examined and compared the structure and the properties of titanium carbide powders obtained by reactive sintering and by the carbothermal method.

2. Grinding of the powders of both types, which essentially changes the dispersivity and the structural characteristics of the titanium carbide powders.

3. Sintering of the hard alloy to obtain a cermet composite. The changes in the structure and phase composition of the hard alloy material at different stages of its synthesis were analyzed by scanning and

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transmission electron microscopy and by X-ray diffraction analysis. The properties of the hard-alloy material were studied by measurements of the nano- and microhardness, full-scale cutting and turning tests of the carbon steel.

3. Results and discussion

3.1. Stage of the carbide phase formation

The powders obtained by reactive sintering have much narrow X-ray lines than the initial powders obtained by the carbothermal method. High-temperature carbidization assists in producing powders with a more perfect crystalline structure and mosaic blocks about two times larger than those in the carbothermal powders.

It is seen from the results that the initial powders and the intermediate materials participating in the production of the alloys by two technologies differ in the width of the X-ray lines.

3.2. Treatment of the synthesized powder

The peculiarity of vibration grinding is fatigue fracture of the treated material due to a high frequency and relatively small impact momentum of grinding bodies. As a result, the elastic energy in the grinded material is gradually stored, and this at a certain threshold leads to fracture of particles. It is found that as the time of vibration grinding is increased, the block size decreases equally for the <111> and <100> directions. Examination of the crystal sizes is indicative of their isotropy in different directions.

Grinding significantly changes the dispersivity and the structural characteristics of the titanium carbide powders. The width of X-ray lines increases rapidly, particularly for the powders obtained by reactive sintering. Harmonic analysis of the TiC powders after grinding reveals significant refinement of mosaic block and an increase in lattice microdistortions.

It should be noted that the refinement of mosaic blocks and deformation of the crystalline lattice proceed faster in the sintered powders, resulting in a more defect structure of the TiC powders after grinding.

3.3. Sintering of the hard alloy

Sintering of the powders was realized with and without hot pressing. Two sintering methods were employed: sintering by direct conduction of the current and by liquid-phase sintering in a vacuum furnace.

Metallographic examination of the system 80% carbothermal TiC – 20% NiTi shows that on induction heating, a characteristic carbide frame is formed. The carbide grain distribution is nonuniform. Both carbide and binder clusters are found. At the points of grain contacts, without binding phase, pores are observed.

In the case of hot pressing with direct conduction of the current, a quite different structure is formed. The carbides are nonuniform in size, but rather uniformly distributed in the matrix. Virtually all carbides are surrounded by the binding phase.

On liquid-phase sintering in a vacuum furnace, the structure of the composite material features uniform distribution in the matrix and pores are found. The temperature level of recrystallization of brittle materials like titanium carbide depends on the prehistory and on the heredity of a technological process of hard alloy production. More brittle reactively sintered TiC powders feature larger distortions of the crystalline lattice and quick return of the width of X-ray lines with increasing the annealing temperature. On sintering, the line width (420) of the TiC phase decreases, being indicative of the growth of perfection of the crystalline lattice of this phase under thermal action. The considerable narrowing of the line is noticeable even on low-temperature sintering of the TiC–NiTi and TiC–NiCr powders. The process is most intense in high-temperature alloys, with the result that the sharp distinction between the defect structures of the TiC powders observed after grinding decreases markedly. However, while at the stage of preliminary sintering the difference in the carbide phase structure in the alloys fabricated by the different methods is retained, the final sintering levels it almost entirely.

On sintering the alloys, the width of the line (420) of the carbide phase decreases, being indicative of the growth of perfection of the crystalline lattice of this phase.

Electrosintering with lower rates results in surface diffusion and spreading at the particle contacts observed in ordinary sintering. It is found experimentally that the contribution of the contact resistance between the particles is more significant in longer grinding of TiC–NiTi and the influence of this factor is observed for an appreciable length of time. Short-time electrosintering precludes undesirable reactions between the grinding-activated powders and the air gases such that parts made of this powder can be sintered in air.

The mechanical properties and the structure of the hard alloy are significantly affected by the percentage of the binding phase in the alloy. Therefore, it is necessary to determine the dependences of the phase composition and the structural and mechanical properties on the binder content.

The alloys of all compositions under study contain two structural constituents: carbide grains and a binding phase distributed between them. Grains of the solid phase are highly nonuniform in size. Increasing the binder content in the alloys results in a break of the grain aggregates, coarse grains dominate, and the average grain size increases. The dependence of the binder size on the binder content allows the conclusion that increasing the mass. Persents of the binding phase leads to breaking of the carbide frame and then to surroundings of the carbide grains.

The porosity of the alloy increases but it is no grater than 0.7% according to the RF and ASTM standards and, therefore, there is no decrease in hardness.

The imperfection of the alloy structure is obvious. The structure remains to be coarse-grained, since it is formed at a comparatively high sintering temperature. The condition for high cutting properties is primarily a rather large interphase surface characterized by the presence of thin carbide particles of size ~ 1 μm and smaller. A structure free of these fine fractions lacks high cutting properties [3–4]. It is found that for rather short electrosintering, no appreciable growth of carbide phase grains takes place.

3.4. Electron-beam modification of the hard alloy structure

One of the efficient methods of modification of the hard alloy structure is electron beam treatment in the mode of surface melting of the material. The alloy to be tested was the hard alloy TiC–NiCr. Electron beam treatment was realized on "Solo" setup at the following parameters: $E_S = 10–45$ J/cm^2, $\tau = 50–200$ μs, $f = 0.3$ Hz, $N = 3–5$ pulses.

The studies reveal two mechanisms of the formation of uniformly sized (the carbide phase) hard alloy structure: the mechanism of brittle fracture (Fig. 1, *a*) and the mechanism of liquid-phase dissolution (Fig. 1, *b*) of TiC crystallites responsible for the exploitation properties of cermet in pulsed electron beam treatment over a wide range of the electron beam parameters.

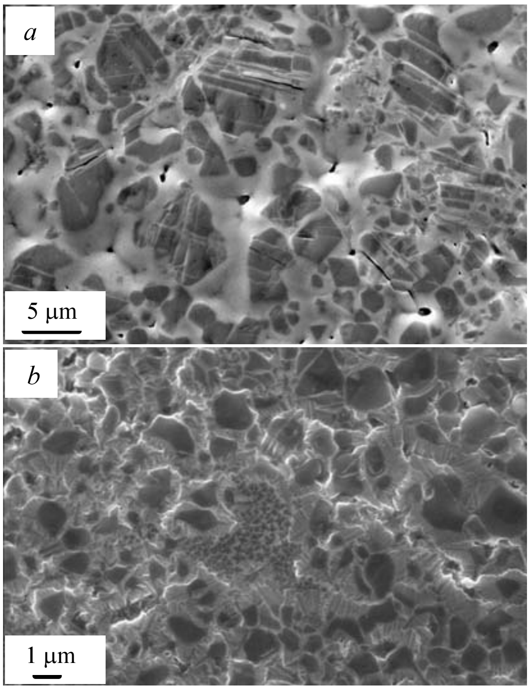

Fig. 1. SEM image of surface structure of hard alloy samples treated by electron beam

Criteria of the formation of a uniformly sized (1.8–2.2 μm) defect-free (weakly defect) carbide component and a metal binder with a nanograin structure (100–200 nm) stabilized by precipitation of the second phase were determined and modes of electron beam treatment making possible a multiple increase in the service characteristics of cermet (for realization of the mechanisms of brittle fracture of TiC crystallites, $\tau = 50$ μs, $E_S = 30$ J/cm^2, $N = 15$ pulses, $f = 1$ Hz and for that of liquid-phase dissolution of TiC crystallites, $\tau = 200$ μs, $E_S = 40$ J/cm^2, $N = 15$ pulses, $f = 1$ Hz).

By analyzing the hardening mechanisms of cermet (solid solution, grain boundary, lattice, second-phase particles, strain hardening) based on experimental quantitative structural parameters (average size and morphology of the phases, scalar dislocation density, element concentration in the binder solid solution), physical bases for attaining the optimum parameters of the hard alloy surface layer in pulsed electron beam treatment were formulated (average TiC crystallites $D_{TiC} = 1.8–2.2$ μm and their size spread $\delta D = 1.5$ μm, average grain size of the binding material $D_{NiCr} = 100–200$ nm and average size of the second-phase particles stabilizing these boundaries $d = 60–80$ nm that opens up new fields of efficient and wider use in industry.

Physicomechanical and tribological tests of cermet alloys reveal a multiple (1.5–3 times) increase in the exploitation properties of the cermet (an about twofold increase in bending strength), an about threefold increase in metal cutting distance to a critical (0.2 mm) wear level of the leading cutting edge (Fig. 2), an about 1.75 fold increase in friction coefficient, and about 1.5 fold increase in microhardness.

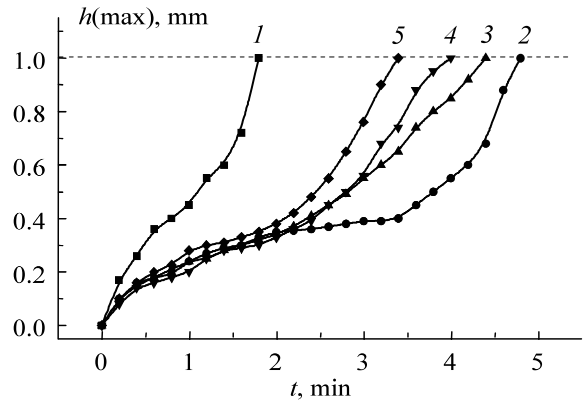

Fig. 2. Curves of cutting plate wear in initial state (curve *1*) and after electron beam treatment with power density (W_S, W/cm^2): *2* – $6.0 \cdot 10^5$; *3* – $2.2 \cdot 10^5$; *4* – $1.5 \cdot 10^5$; *5* – $1.0 \cdot 10^5$

4. Conclusions

The multistage control of the formation of the structure and phase composition of TiC-based hard alloys reveals the following mechanisms.

The most suitable for optimum transformations of the hard alloy macrostructure are methods of powder metallurgy and low-energy treatment. As a result of choice of optimal method of powder synthesis, the application of thermal force treatment, and the use of sintering under pressure through direct current conduction allow an increase in the strength properties of the cermet material and in its resistance to high friction loads.

The further multiple increase in the service properties of hard-alloy material is possible by electron beam treatment. The performed studies suggest that submillisecond pulsed electron beams make it possible to modify both the carbide phase and the metal binder. Quantitative dependences of the average size of TiC crystallites and secondary-phase particles on the pulse duration and on the electron beam energy density were obtained. The mechanisms of modification of TiC crystallites (brittle fracture, dynamic recrystallization, liquid-phase dissolution) and binding material (nanostructuring, age hardening, solid solution hardening, cold-work strain hardening) were determined.

At the same time, for retention of the unique properties of the material, the problems of control of the structure formation and properties of hard alloys based on titanium carbide at the stage of powder production and at all subsequent stages of the technological process require further investigation and comprehension.

References

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