Formed nano-W - WC coatings on the high-speed steel substrate by the electrodischarge explosion

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Abstract. Electric exploding of a tungsten carbide – cobalt material near-by high-speed steel surface forms on it a hardening coating. The essential structure properties of the formed coatings are determined by specifications of contact exploding electrode and the pulse current amplitude and duration. The investigations of coating structures were done by optical and electronic metallography. They have shown that the contact electric exploding caused the transfer of tungsten carbide and cobalt on the surface of high-speed steel. The breakdown of tungsten carbide – cobalt material took place during electrical exploding. The hardening layers of tungsten carbide and pure nanocrystalline tungsten have been formed upon the surface of high-speed steel as a result of electric exploding. Crystalline grains of tungsten have an almost spherical form and their characteristic size less than 400 nm. Micro hardness of the coating layers and high-speed steel structures was measured.

1. Introduction

In the present work WC/W coatings were obtained by electro-thermal explosion directional spraying technology. Tungsten carbide is extreme hard and wear resistant material, but, as a bulk material, WC is also of extraordinary brittleness [1]. As a thin coating on high speed steel (HSS), however, it is used in compound materials combining a number of favorable properties of the base material as well as of the coating. The load of a component may be divided between base material and hard coating; mechanical stress and thermal load should be elastically received and dissipated, respectively, by the base material, whereas sliding quality and wear resistance should be guaranteed by the hard coating. By this method, which takes advantage of contact electrical explosion of a tungsten carbide – cobalt material near-by high-speed steel surface, coatings of good homogeneity and surface quality can be obtained [2]. In this way materials of high boiling temperature can be evaporated and coatings of high speed steel are attainable. In addition, in this method oxidation of the metal vapor is eliminated and better adhesion of the layer to the surface is obtained. Our investigations aimed at finding a method for producing coated surfaces needing no further treatment to improve their surface quality. A metallographic analysis gives the clear picture of distributing of these surface structures and possibility of direct determination of their thickness.

2. Experimental

The spraying process of contact exploding WC-Co electrode uses a pulsed high-current. The equivalent circuit of the Electric Exploding of Contact (EEC) system is shown in figure 1.
for forming of coatings consists of charging unit (1); a bank of capacitors (2) and trigatron switch (3) to connect a coated surface (6) and WC-Co electrode (7) suddenly across the charged capacitor bank. The capacitor bank consists of thirty 200 μF capacitors that can store up to 5 kV. The discharge high density current is measured by a toroidal Rogowsky coil (5). The spraying process was performed in the atmospheric environment. Essential features of electric contact explosion are caused by differences of electrical resistance between a contact surface and volume and their sharp change during passage of high current pulse. During the spraying process, the exploding WC-Co electrode is molten firstly, and then explodes into fine molten droplets because of the electric explosion. The molten droplets of tungsten carbide are sprayed onto the high speed steel substrate and solidify quickly to form a belay (WC and pure W) compact coating with a metallurgical bonding between the coating and substrate.

![Figure 1. Schematic of Electric Exploding of Contact (EEC) system: 1 – charging unit, 2 – capacitor bank, 3 – trigatron switch, 4 – electrical discharge ignition system, 5 – pulse electrical discharge registration system, 6 – coated surface, 7 – WC-Co electrode.](image)

The following commercial WC-8%Co material (table 1) of exploding electrode was used as starting material for the spraying process. Figure 2 shows the representative micrograph of typical microstructure of WC-8%Co material before electrical explosion.

![Figure 2. The typical microstructure of WC-8%Co material before electrical explosion (×1250).](image)
Table 1. The chemical composition of commercial WC-Co material.

| Chemical element | WC   | Co  | free carbon | total oxygen |
|------------------|------|-----|-------------|--------------|
| mass %           | ~ 92 | 8   | 0.101       | 0.13         |

The commercial high-speed steel was used as starting material of a coated substrate. Characteristics of the chemical composition of this steel are resulted in table 2.

Table 2. The chemical composition of high speed steel (M2 (AISI/ASTM) P6M5 (Russia)).

| Chemical element | C     | Cr     | W     | V     | Co  | Mo   | N       |
|------------------|-------|--------|-------|-------|-----|------|---------|
| mass %           | 0.82–0.90 | 3.80–4.40 | 5.50–6.50 | 1.70–2.10 | < 0.50 | 4.80–5.30 | —       |

Figure 3 shows the representative micrograph of typical high speed steel structure.

![Figure 3](image)

Figure 3. The typical high speed steel structure before electrical explosion (×400).

The essential structure properties of the formed coatings are determined by parameters of contact exploding electrode at the pulse current amplitude from above 1 MA·cm\(^{-2}\) and duration less than 10\(^{-4}\) s [3]. The scheme of coating layers and thermal modified substrate (HSS) after electrical explosion is shown in figure 4.

![Figure 4](image)

Figure 4. The scheme of coating layers and thermal modified substrate after electrical explosion: 1 – unmodified HSS; 2 – modified HSS; 3 – WC layer; 4 – nanostructure pure W.

The metallographic investigations of coating structures were done with a microscope “Neophot-24”. Micro hardness of coating layers was measured on micro hardness meter M-400G3
(Germany) using the Knup (HK) method under 50 g load according to the standard procedure. The samples were prepared by the standard method.

3. Results and discussion

Figures 5 and 6 are surface SEM photos of coated specimen by electro-thermal contact explosion. In figures 5-6 it can be seen clearly that the coating is extremely dense. The interface between the coating and the substrate without vacancy suggests that the coated materials are anchored strongly on the originally smooth surface of the substrates by a high velocity impact of the powder. Figure 7 shows the optical microscopic image of cross section of the tungsten carbide/nanostructure pure tungsten coating formed on high speed steel substrate.

![Figure 5. Surface SEM photo of coated specimen by electro-thermal contact explosion (×500).](image)

![Figure 6. Surface SEM photo of coated specimen by electro-thermal contact explosion (×1500).](image)

![Figure 7. Optical microscopic image of the polished surface of the WC/W coating (×400): 1 – unmodified HSS; 2 – modified HSS; 3 – WC layer; 4 – nanostructure (mean grain size < 400 nm) pure W.](image)
The metallographic investigations of coating structures have shown that the contact electric exploding caused the transfer of tungsten carbide and nanostructure pure tungsten on the surface of high-speed steel. The hardening layers of tungsten carbide and pure nanocrystalline tungsten have been formed upon the surface of high-speed steel as a result of electric exploding. The small amount of cobalt (< 1%) is revealed only between WC coating layer and substrate surface. The breakdown of tungsten carbide-cobalt material took place during electrical exploding. Crystalline grains of tungsten have an almost spherical form and their characteristic size less than 400 nm. The layer of tungsten carbide has a high hardness (HV ~ 1800). Localization of heating and subsequent high-speed cooling in the small volume of high-speed steel results in formation of different structures. A metallographic analysis gives the clear picture of distribution of these structures and possibility of its direct determination. It is established, that heat energy of electric explosion is located in a high speed steel contact zone of a width of ~ 20 µm. The analysis ("Tesla BS - 340", XNL 2001 A Spectrometer) of distribution of the maintenance of basic elements W, Co, Fe, Cr, Mo, V at scanning from a surface deep into a material has shown, that Co, Fe and other elements are absent on a surface.

The micro hardness of the coating and substrate was determined across its whole thickness. The measured micro hardness (HV) shows substantial variance of data, see table 3.

| Layer number | 1   | 2   | 3   | 4   |
|--------------|-----|-----|-----|-----|
| HV           | 700±750 | 800±850 | 1000±1800 | 400±600 |

Theoretical analysis [4] made it possible to establish the dependence of the volume ($\Delta V$) of an electrically exploded material on the amplitude of the electric current pulse – $J$ and the properties of the material (electrical resistivity – $\rho$ and boiling point – $T_b$):

$$\Delta V \sim \rho J^2 T_b^{-4}$$

4. Conclusion
The coating of WC and nanostructure pure W was produced by the electrothermal contact explosion technique. A specially designed exploding WC-Co electrode allowed electric energies to be located in thin surface zone (the width ~ 20 µm) of a high speed steel substrate. Molten particles ejected from the exploding WC-Co electrode formed deposits through deformation and solidification during impingement on a high speed steel substrate. The thickness of the coating obtained by electric explosion was about 17 µm (WC layer ~ 7 µm, nanostructure pure W ~ 10 µm).

The WC and nanostructure pure W coating exhibited small change in chemical composition due to decarburization. Refractory WC-Co composite material was sprayed and deposited to form a WC/W coating on high speed steel without the use of additives or sintering agents to suppress chemical decomposition and enhance bonding of coating with substrate.

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