Study of steel part hardening coating microstructure

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Abstract. The article describes the research results of hardening coatings obtained by induction surfacing of hard alloy with various base materials and the coating itself. Information is given on measurements of the hardness of the resulting coatings and the microhardness of various phases of the coating. Macrophotographs of coatings obtained by various methods are presented, and various phases in the resulting coating are isolated. Conclusions are made concerning the potential wear resistance of the obtained coatings.

1. Introduction

As the literature review [1-3] showed, structural carbon and alloy steels of 40-45, 50HG(A), 50-60HG, 35-65G grades, promising 20-30MnB5 boron steels, etc., as well as tool steels of 40-50HF(A), 18-60HG (T), HS, HVG, 5-6HV2S grades are currently used in Russia and abroad as the main materials used for the manufacture of knives for various cutting devices, grinders, crushers, and other similar equipment. Due to their high corrosion resistance, high heat resistance and excellent formability [4], they are widely used in aerospace, chemical, nuclear, food industries [1]. Corrosion causes major economic losses worldwide [4–6]. Surface hardening processes are extensively investigated to improve the wear resistance of metal parts [7]. It is known that the mechanical properties of the materials used in engineering are greatly improved by the use of case hardening or coating methods [8]. Following the appropriate heat treatment, the above-mentioned steels (with rare exceptions) allow obtaining the part surface hardness of up to 48-54HRC for structural steels, and up to 58-64 HRC for tool steels.

Meanwhile, it is known that manufacturers increasingly use 30MnB5 boron steel instead of the widely used 65G steel, and 5-6HV2S tungsten steel is recommended instead of the boron steel in cutting elements (knives) in the last 3 or 5 years.

However, despite certain advantages in wear resistance, these materials are 1.5-2 times more costly, require higher heating temperatures (800-900 °C) for quenching, as well as tightened requirements for heat treatment (narrow temperature range and prolonged times of austenization and tempering, stricter requirements to isothermality of quenching, etc.), which also increases the production cost of steel parts. For example, 6HV2S steel, when quenched to maximum hardness, is very sensitive to quenching and tempering temperatures, as well as the time of these processes (up to 2-3 hours), and a soft decarburized layer up to 1 mm thick is formed on its surface after the heat treatment, which requires final machining of the part, or application of protective media in furnaces.
Coating technologies are used to extend the service life by preventing damage to the surfaces of the materials working in harsh environments [9]. The applied surface treatment is carried out to increase the hardness and to improve the tribological properties of alloys [10-11]. In this study, we study hardening coatings differing in their composition, properties and potential wear resistance.

2. Material choices and design
Taking into account the information search results, chemical analysis [12] and hardness test data of the base material of imported knives, low market value of the manufactured part, structural and technological properties of the materials, availability at delivery, ease of heat treatment of the material, possible supply of finished workpieces, and the required increase in the wear resistance of knives by 8-10 times, 65G steel was chosen as an up-to-date material for the knife base for replacement of imported analogs, and 6HV2S steel was chosen as a promising material.

In the course of the study, four methods of knife hardening were tested (induction hard alloy surfacing, 2-modifier allow surfacing, deposition on a EIL pre-modified surface) being different in the base material, hardening coating material and hardening coating structure (strip shape).

A description of the hardening methods used is presented in Table 1.

All hardened knives were subjected to heat treatment, including quenching with or without subsequent tempering and medium-temperature tempering in optimal temperature ranges corresponding to the steel grades. Data on hardness of the base material of hardened knives are presented in Table 2.

| Method | Nature, sequence and description of operations | Notes |
|--------|------------------------------------------------|-------|
| 1      | Induction surfacing (IS) of hardening coating by 2/3 of the length of a knife with a milled back surface of the knife blank; facing material is a hard alloy with hardness, friction and wear-resistance modifiers (Rostov 1). | Coating shape coincide with the predominant wear figure of the knife (length-wise and/or projection-wise; shapes studied: rectangular strip (1), triangle (2). |
| 2      | Same; differing character is the composition the hard-facing charge (Rostov 2). | |
| 3      | Same; differing character is the modifier-free standard charge-surfaced specimens (control). | Base charge facing. |
| 4      | Same + preliminary consecutive (joint) electro-spark alloying (ESA) of the facing surface with BK8, P6M5 materials. | Base charge facing. Hardening coating is a rectangular strip (1). |

| Hardening method, charge | Code* | HRCe |
|--------------------------|-------|------|
| 1, Rostov 1              | 1111  | 30; 40; 43 |
| 2, Rostov 2              | 2111  | 23; 22; 39 |
| 3, Hard alloy (control)  | 3111  | 40; 42; 53 |
| 4, Hard alloy             | 4111  | 13; 22; 24 |
Considering the results of the study of hardening coating material of imported analogs, the composition of the surfacing base charge was changed, optimized and presented in two versions (Rostov 1, 2).

Both compositions contained spherical tungsten carbide powder, Ø 0.25-0.5 mm fraction as the main wear-resistance modifier, both compositions contained boron carbide as the additional modifier, and composition 2 additionally contained nickel powder introduced instead of solid alloy to maintain the optimum balance of the metal matrix and ceramic filler. Instead of AN-348 welding flux, P-0.66 borate flux was used in the charge. The compositions of charges for induction surfacing of knives with optimized technological parameters (melting rate, wetting ability, flowability, formation of a continuous coating, etc.) is presented Table 3.

| Charge          | Ingredient           | Content, wt. % |
|-----------------|----------------------|----------------|
| Rostov 1        | PG-S27 hard alloy    | 80-85          |
|                 | Tungsten carbide     | 3-5            |
|                 | Boron carbide        | 1-1.5          |
|                 | P-0.66 flux          | - the rest     |
| Rostov 2        | PG-S27 hard alloy    | 75-78          |
|                 | Tungsten carbide     | 8-10           |
|                 | Boron carbide        | 1.5-2.5        |
|                 | PT-19N powder        | 2-3            |
|                 | P-0.66 flux          | - the rest     |
| Rostov 3, 4 (base) | PG-S27 hard alloy  | 80-85          |
|                 | P-0.66 flux          | - the rest     |

Samples of the obtained charge materials, as well as the basic composition, were volumetrically dosed on the upper parts (flat and non-milled) of the prepared knife blanks (conditioned for methods 1-3, or subjected to electro-spark alloying for method 4), and then, if it is specified by a hardening method, the shape of the charge strip was changed by the knife into a triangular, and simultaneous induction surfacing of both sides was carried out according to the optimized two-stage middle program on the ELSIT-100-40/70 inverter with the following parameters: first stage — current 95%, time 20 sec.; second stage — current 75%, time 40 sec.

Thereafter, the knife was removed from the inductor and immediately (grade 40 steel), or after prequenching (65G steel), was placed in a quenching medium (water, oil). After quenching, all knives were subjected to medium-temperature tempering.

Simultaneously with preparation of an experimental lot of hardened knives, samples of hardening coatings on 65G steel were prepared under identical conditions following all proposed methods (1-4) in order to examine them using instrumental methods.

### 3. Experimental results

The prepared samples were examined for hardness, macro- and microstructure and microhardness. Data on the hardness of the resulting coatings are presented in Table 4.

| No. | Hardening method, charge | HRCe |
|-----|--------------------------|------|
| 1   | 1, Rostov 1              | 62-67|
| 2   | 2, Rostov 2              | 54-57|
Photos of thin sections of coatings are presented in Figure 1.

![Photo of thin sections of coatings](image)

**Figure 1.** Samples of knife hardening coatings, prepared for metallographic analysis.

It is clearly seen from Figure 1, that the thickness of the coatings obtained by methods 1, 2 is considerably greater than that of coatings of samples 3 and 4. On the macrographs, inclusions of spherical particles of tungsten carbide, uniformly distributed in these coatings along the length and thickness of the layer being hardened, and the presence of pores and cracks, especially in sample No. 2 is also of interest.

The study of macrographs (50×) of hardening coating sections makes it possible to identify the main structures (characteristic phases) composing the coating and determine their characteristics by the morphology of their most typical regions. Thus, Figure 2 shows the panoramic macrographs of hardening coatings with characteristic phases and their microhardness indicated.

In all coatings modified with tungsten carbide, there are its spherical inclusions with a hardness of up to 1620-1970 HV.

| Method | Sample | Thickness |
|--------|--------|-----------|
| 1      | 3, Base| 54-55     |
| 2      | 4, Base| 54-57     |
Method 4.

**Figure 2.** Macrophotographs (50×) of hardening coatings obtained by various methods 1-4 with typical regions (phases) and their microhardness indicated.

Also, in all boron carbide-modified coatings, regions (phases) are found represented by finely dispersed Fe-C-B system eutectic, whose hardness exceeds that of the phases unmodified by boron by 1.2-1.5 times, comes up to 1080-1110 HV and is equal to the previously established values.

The common feature of modified coatings is the edge flashing with the base metal, and that for unmodified coatings is the presence of dendritic regions (phases) with hardness reduced to 500-700 HV. The base material of all samples has a microhardness of 400-450 HV.

The fine structure of the coatings and the effects caused by char material modification with tungsten and boron carbides are clearly visible on microphotographs of the hardening coatings (100, 200×) shown below (see Figures 3-7).

**Figure 3.** Microstructure of the 1st sample: a – coating with a WC particle (100×); b – in the region of carbide eutectic (100×).

Based on Figures 3 a, b showing the main, hardest coating phases of the 1st sample, size reduction of acicular chromium carbides and flashing of their edges and boundaries of the deposited and base metal layers are observed in both cases, which is associated with the formation of a easily fusing boron eutectic within the system.

**Figure 4.** Microstructure of the WC particle and the deposited metal interface (200×).
The chemical interaction of boron carbide with chrome cast iron during surfacing and the dissolution of boron in the coating metal matrix leads to modification of the interface between the WC ceramic particles with the formation of new interlayers (phases) of tungsten-boride eutectic and an increase in the adhesive interaction of the wear-resistance modifier with the coating matrix (see Figure 4).

However, an increase in boron carbide content above 1.5-2.0 wt. % (as in case of Rostov 2 charge surfacing) leads to its stoichiometric excess, concentration inhibition of diffusion and dissolution in the molten metal with the formation of a brittle matrix, pores, non-metallic inclusions not curable even by the additional introduction of nickel powder, which greatly affects the quality of the coating (see Figure 2).

Figure 5. Microstructure of coating of the 2nd sample within a defect-free region (100×).

Nevertheless, the general mechanism of the modifying action of boron is maintained, and boride eutectics with the inclusions of crushed and fused carbides, as well as the molten interface between the deposited and base metal are also found in defect-free regions of the 2nd sample coating (Figure 5).

The microstructure of the 3rd (control) sample matches the “classical” version described in most manuals on induction surfacing of hard alloys like high-chromium cast irons, which include PG-C27 material used.

Figure 6. Microstructure of the 3rd sample coating (100×).

In Figure 6, the elements (phases) typical for structures obtained by induction surfacing are clearly distinguishable: an interface layer, dendrites (of 1st and 2nd orders), zone of finely dispersed carbide eutectic, and acicular chromium carbides in the upper part of the coating.

In terms of potential wear resistance, the microstructure of the 4th sample, also obtained by induction surfacing of the previously prepared surface with the base charge subjected to sequential electro-spark alloying with a VK-type alloy and P6M5 steel, is also of interest (see Figure 7 a, b.).
As it follows from Figures 7 a, b., two zones clearly distinguished by their phase morphology, basic structure, and hardness are formed in the hardening coating of the 4th sample. In the first zone located at the interface between the deposited and base metal and occupying up to 1/3 of the layer thickness, the following are observed: boundary layer, dendrites, and the forced-out carbide eutectic with the inclusions of acicular chromium carbides. In the second zone located above the first one, a finely dispersed carbide eutectic with a very uniform structure both through the thickness and along the entire length of the layer is observed up to the outer boundary of the coating.

4. Conclusions

Thus, all four hardening methods used (3 original + 1 basic) allow to obtain hardening coatings differing in their composition, properties and potential wear resistance. As an optimal content of modifying components (based on price/quality ratio, hardness and manufacturability), the following values should be recommended (in wt. %): tungsten carbide — up to 5-8, boron carbide — not more than 1.5. Moreover, in order to prevent pore and crack formation, the amount of the metal portion of the charge should be not less than 78-80 wt. %, and the particle size of boron carbide should be minimal (0.05-0.1 mm).

That is, the 1st method (with the use of Rostov 1 charge) with an additional adjustment of tungsten carbide content to 8-10 wt. % is best hardening option (method) among the studied ones.

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