

Formation Mechanism Of Wear Resisting Surface Layer On Cast Iron Moulds By Direct Surface Alloying

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Abstract—The resource-saving method of direct (oxide) surface alloying and modification of machine parts is developed. Industrial wastes and semi-processed products of related industries are used as alloying and modifying additives. Metals can be efficiently reduced by atomic hydrogen- and carbon-containing surface layer of mould and core, containing organic high molecular weight polymeric materials. The technology of direct surface alloying with vanadium cast iron castings is tested. It was investigated macro - and microcomposition of the formed chemical associations (non-metallic inclusions and other "secondary" phases) and peculiarities of formation of structure elements during pouring laboratory samples into metal moulds and dry sand moulds. It is shown that the gasketed rings from gray cast iron poured into a dry rod shape and subjected to direct surface alloying have quality surface in the absence of casting defects.

Keywords—Technological and material science principles, complex technology, surface alloying, iron-carbon alloys, cast irons, mould, surface alloyed coating, basic industries, promising research trends

I. INTRODUCTION

There are several methods of surface hardening of cast iron parts to increase their durability or to acquire the physical-mechanical characteristics in their operation under specific conditions. Recently, the scientists and researches have developed unique technologies of surface hardening of machine parts. Among the most outstanding technologies are those of evaporative condensation (magnetron, ion-plasma and atomic ion spray) with controlled plasma flow, supersonic cold gas-dynamic and microplasma spraying, electrolytic modification of nanostructured surfaces, laser prototyping nanocomposite powders, and controlled crystallization from amorphous state [1].

These methods and modern high-performance equipment allows high speed coating and renovating of parts, applying not only metal materials, regardless their melting point [2], as well as their various compounds, like carbides, nitrides, etc.

In small-scale and repair production the thermal diffusion method finds its use to create coatings from

powders, which are in direct contact with the hardened part [3]. Structurally upgraded muffle or chamber furnaces are suitable to implement this method.

Casting with alloying coating is obtained [4] by setting filler made in advance of alloyed powders into a mould. When metal is poured into a mould the filler is melted, forming alloyed layer with the desired characteristics on the surface of the casting.

It should be noted that most of the work on hardening castings by the method of surface alloying is performed on thick pieces. However, there are cases when this technology is performed on thin-walled castings. It is therefore necessary to consider some features of the surface alloyed layer formation mechanism.

Quality surface alloyed layer is formed in applying the alloying components, the melting point of which is below the pouring temperature of the alloy from which the casting is formed. Therefore, the solidification front does not occur on the surface and in the depth of the casting[4], it is equal to the thickness of the alloyed layer, i.e. on the boundary alloyed layer - base metal casting, and the subsequent crystallization develops into the casting. Being overheated liquid, the hardening metal layer through interdendritic channels of the crystallizing base is associated with casting; being exposed to atmospheric pressure it compensates shrinkage in thermal centre, forming honeycombs and "sink marks" (dimples) in the center of its surface. To prevent their occurrence formation of solidifying casting conditions is required for directional solidification of the metal, which is associated with labour-consuming techniques [4].

At the same time, the authors [5-6] found out that alloying coating influences the doped metal like refrigerators having chilling impact, so doping of thin-wall castings with metallic materials and refractory chemical compounds is impossible without additional source of heat.

When implementing surface doping technology [4] of iron-carbon alloys special care should be taken to select the type of flux. The most penetrating and high-quality doped layer is formed when tetra boric-acid sodium is used in the alloying composition [4].

To restore the worn parts and obtain wear resisting surface layer, cast iron is melted by TIG (welding) or undergone alloying [7]. Since melting of alloy foil by

TIG occurs directly on the surface, it is impossible to obtain the required smoothness of the surface, the foil is applied between the main material and alloyed layer. Surface doping is based on convection in the weld puddle due to the temperature difference on the surface and inside the molten metal. The temperature gradient causes surface tension and driving forces [8-9].

Analysis of the methods discussed above shows that some of them (e.g. overlay welding) is rather hard work and it does not provide the precision of geometry and surface finish of the parts; other technologies (e.g. plasma or ion-plasma treatment) require sophisticated, expensive equipment [1].

One of the further directions of improvement of performance properties of materials is development of nanotechnologies and nanomaterials, as well as the use of surface engineering. Further development of these areas will occur due to synergistic effect based on new scientific knowledge of physics of strength, mouldability, materials science, physical and chemical processes of welding and nanotechnology.

Formation of surface layer during chemical interaction of additives with certain elements of the crystallizing substance is a special case of modifying by ready-made centers that are not introduced, but formed in the melt as a result of chemical reactions [10, 11-12].

While choosing between unstable technology of introducing powders of refractory particles and their formation in the melt [13, 14-17] as a result of physical-chemical reactions occurring during the crystallization process, the latter should be preferred.

The influence of additives on the characteristics of the material is implemented through refining action and by influencing composition and structure of the liquid and solid phases, composition and morphology of non-metallic inclusions, intermetallics, borides, nitrides, and conditions of crystallization, size of primary and secondary granules, state of their edges [10, 13].

The aim of the work is to obtain castings with vanadium alloy coating. Because of scarcity and high cost of ferrovanadium, it is necessary to develop methods of doping the surface of the casting without applying expensive and scarce vanadium alloys.

II. FORMATION MECHANISM OF WEAR RESISTING SURFACE LAYERS ON THE CASTINGS USING INDUSTRIAL WASTE AND SEMIPROCESSED PRODUCTS OF RELATED INDUSTRIES

Wear-resisting surface layer can be formed by combining processes of vanadium reduction from chemical compounds and direct surface doping of the casting in the mould.

The reducing agents which are used (carbon in the form of coke and graphite dust, charcoal powder) do not provide a sufficient degree of metal extraction. Effective reducing agents must contain elements with a higher affinity to oxygen. As material is capable of achieving the maximum effect, it is recommended to use polymeric materials of synthetic origin [13,14],

including biologically damaged, subjected to ageing, and unsuitable for processing materials of plastics (carbon is chemically bound), and also unsuitable for regeneration elastomers (carbon is either chemically bound or structurally free).

Homolytic cleavage of bonds with formation of electrically neutral particles occurs during pyrolysis: the atoms of H and hydrocarbon radicals. Hydrogen atoms are stronger reducing agents, as their electronegativity is less than that of carbon atoms.

When the method is implemented on the surface of moulds and cores, where it is required to obtain doped surface layer a special composition comprising inexpensive metal-containing industrial wastes or products of related industries, ground to fraction 0.5 mm from polymeric man-made wastes and liquid glass as binder are introduced. Vanadium oxide ground to fraction up to 0.3 mm was introduced as metal-containing material in the composition. Vanadium oxide and reducing agent ratio was maintained at 1:1 by volume. Liquid glass was introduced in the amount that provides effective surface coating of mould or core with a brush. Thickness of the layer of alloying composition is adjusted by the number of applied layers, but it should not be in dried state greater than 0.3 – 0.5 mm.

The technology was investigated in the laboratory while obtaining cast iron cores with diameter 20 mm and length 150 mm in dry sand moulds and metal moulds.

The technology of direct surface alloying of cast iron with vanadium provides chilling surface layer (Fig. 2a) of the casting to depth 3 mm. Powdered vanadium-containing compounds, polymer industrial wastes ground to 0.5 mm fraction, and liquid glass as binder are introduced into the coating composition of moulds and cores. Thickness of the coating layer is adjusted by the number of applied layers on the surface of moulds and cores.

The gasketed rings made of grey cast iron were poured into dry rod mould in industrial environment; one surface structure (Fig. 1) was coated with mixture of the previously described compositions to obtain surface doped vanadium layer.

Cast iron structure was investigated with metallographic methods according to the National Standard 3443-87. At standard magnifications separate parts of the structure are not clearly differentiated. To study the parts investigations of cast iron structure were conducted by scanning electron microscopy using the microscope JSM-5610LV (IEOL, Japan) with electron-probe microprobe EDX analysis. Alloys structure was fixed with detector of secondary electrons to determine shape, size, and microcomposition of structural components, in the surface layer as well as in the core of the casting.

It is the alloy microcomposition that determines degree of its purity, often significantly affecting nature of crystallization, form of graphite in cast iron, non-metallic inclusions in cast iron, composition and structure of grain edges and immediate areas, cross-sectional view, susceptibility to brittle destruction, i.e.

whole range of technological and service properties.



Fig. 1. The forms of the mould and the coated mould

Microcomposition of alloy refers to main elements, a number of additives, which are accidentally or intentionally introduced into the melt in process of deoxidation, modification or microalloying. Microcomposition also refers to the composition and morphology of chemical associations (non-metallic inclusions and other "secondary" phases) [13].

III. RESEARCH RESULTS AND DISCUSSION

The depth of vanadium alloying coating is determined by crystallization conditions and largely depends on the mould. When pouring into the metal mould coated by alloying composition, thickness of the doped surface layer (Table 1) is 400 – 500 μm (Fig. 2). The surface structure of the casting is ledeburitic (Fig. 2a, b, c, d, e). Vanadium is included in the composition of carbides (pos. 2 and 3, Fig. 2e), while more compact carbides contain its increased concentration (pos. 3 Fig. 2e). While in oblong carbide precipitate (pos. 2, Fig. 2e) concentration of vanadium is not greater than 0.10 %. It should be noted that significant portion of vanadium is in compact complex carbide sulphide inclusions (pos. 1, Fig. 2e). Carbide inclusions of cementite type (pos. 4, Fig. 2e) of about 1 μm are uniformly deposited in the metal substrate of surface doped layer.

TABLE I. CHEMICAL COMPOSITION AND MICROSTRUCTURE OF CAST IRON LABORATORY RODS DOPED WITH VANADIUM TABLE STYLES

| Doping Mode | Distance from surface, μm | Chemical composition, % wt. | | | | | | | | | |
|---------------------------------------|--------------------------------------|-----------------------------|------|-------|-------|-------|-------|--------------|----|-------|--------|
| | | C | Si | Mn | Al | S | P | Bi | La | V | Fe |
| Composition of the starting cast iron | | 3.51 | 2.24 | 0.454 | 0,756 | 0.068 | 0.244 | ≤ 0.001 | | 0.019 | traces |
| Vanadium, metal mould | 50 μm | 3.67 | 0.80 | 2.79 | 0.57 | 0.08 | | | | 0.10 | 92.00 |
| | 250 μm | 1.28 | 1.58 | 3.44 | 0.64 | - | | | | 0.06 | 92.99 |
| | 500 μm | - | 2.79 | 2..35 | 0.84 | - | | | | - | 94.02 |
| Vanadium, dry sandy mould | 50 μm | 20.75 | 1.65 | 1.68 | 0.56 | - | | | | 0.01 | 75.35 |
| | 250 μm | 6.87 | 1.75 | 2.48 | 0.61 | 0.24 | | | | 0.04 | 88.00 |
| | 500 μm | 10.44 | 1.91 | 3.09 | 0.76 | 0.07 | | | | 0.29 | 83.44 |

TABLE II. CHEMICAL COMPOSITION AND MICROSTRUCTURE OF CAST IRON LABORATORY RODS DOPED WITH VANADIUM TABLE STYLES

| Doping Mode | Distance from surface. | Position of the inclusion | Chemical composition, % wt. | | | | | | |
|---------------------------|---------------------------------|---------------------------|-----------------------------|------|-------|-------|-------|------|-------|
| | | | C | Si | Mn | Al | S | V | Fe |
| Vanadium, metal mould | On the surface | 1 fig.2e | 8.91 | 0.31 | 31.68 | 21.01 | 12.83 | 0.40 | 24.86 |
| | | 2 fig.2e | 16.03 | 0.02 | 2.49 | - | 0.10 | 0.10 | 81.26 |
| | | 3 fig.2e | 9.20 | 4.40 | 2.52 | 0.55 | - | 0.28 | 83.05 |
| | | 4 fig.2e | 7.81 | 4.16 | 2.99 | 1.63 | 0.07 | - | 83.34 |
| | More than 5 mm from the surface | 1 fig.2h | 34.07 | 0.79 | 1.97 | 0.32 | 0.01 | 0.38 | 62.46 |
| | | 2 fig.2h | 3.14 | 2.24 | 2.78 | 0.88 | - | 0.17 | 90.80 |
| | | 3 fig.2h | 2.19 | 1.21 | 3.13 | 0.87 | - | 0.46 | 92.14 |
| Vanadium, dry sandy mould | On the surface | 1 fig.3e | 22.46 | - | 49.18 | - | 23.78 | 0.43 | 4.15 |
| | | 1 fig.3d | 7.02 | 0.74 | 0.56 | 0.08 | - | 0.02 | 23.58 |
| | | 2 fig.3e | 18.04 | 1.89 | 2.36 | 1.09 | - | 0.02 | 76.60 |
| | | 4 fig.3e | 8.23 | 2.45 | 2.80 | 1.26 | 0.10 | - | 85.15 |
| | More than 5mm from the surface | 1 fig.3g | - | 3.02 | 2.91 | - | 0.06 | 0.24 | 93.77 |
| | | 2 fig.3g | - | 0.21 | 52.63 | 0.18 | 29.47 | - | 17.1 |
| | | 3 fig.3g | 69.78 | 0.18 | 1.12 | - | - | - | 28.93 |

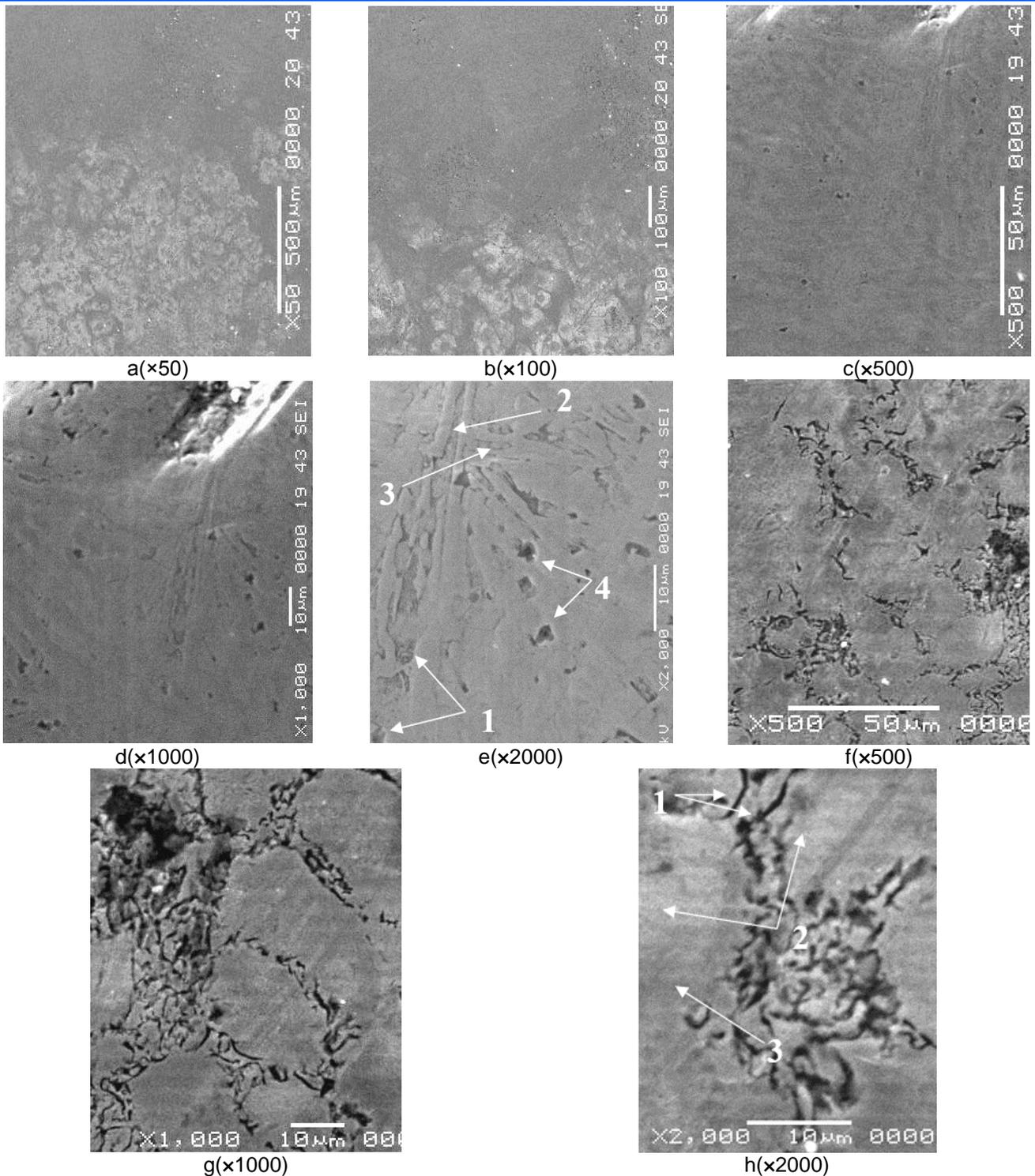


Fig. 2. Surface structure (a, b, c, d, e) and cast iron core (f, g, h) doped with vanadium while poured into the metal mould. (Investigated by scanning electron microscopy)The forms of the mould and the coated mould

The centre structure of cast iron laboratory rods (Fig.2 f, g, h) obtained in the metallic mould is fundamentally different from structure of the surface layer (Fig. 2a, b, c, d, e). In the casting center there are (Table 2) direct and vortex graphite inclusions (pos. 1 Fig. 2h); metal substrate is highly doped with vanadium (pos. 2, 3 Fig. 2 h).

Pouring laboratory samples into dry sandy moulds, coated by the doping composition provides vanadium

concentration increase in the surface layer to depth 500 μm (Table 2).

At the junction of surface layer and the center of laboratory rod, poured into dry sandy mould, there are (Table 2) graphite inclusions (pos. 1 Fig.3d, pos. 2 Fig.3e), compact complex carbide sulphide precipitate (pos. 1 Fig.3e) at low iron concentrations and vanadium amounts 0.43 %. In metal substrate of cast iron vanadium concentration is insignificant (pos. 3 and 4, Fig.3e).

The centre structure of cast iron laboratory rods (Fig. 3 f, g) poured into dry sandy mould is grey cast iron with graphite inclusions (pos. 3 fig. 3g), manganese cementite precipitate (pos. 2 fig.3g); its metal substrate contains significant amount (0.24 %

of vanadium (Table 2).It is important to note that oxygen is not detected in the laboratory cast iron rods after surface doping according to the developed method. This indicates not only full metals reduction, but also high degree of refining and degassing.

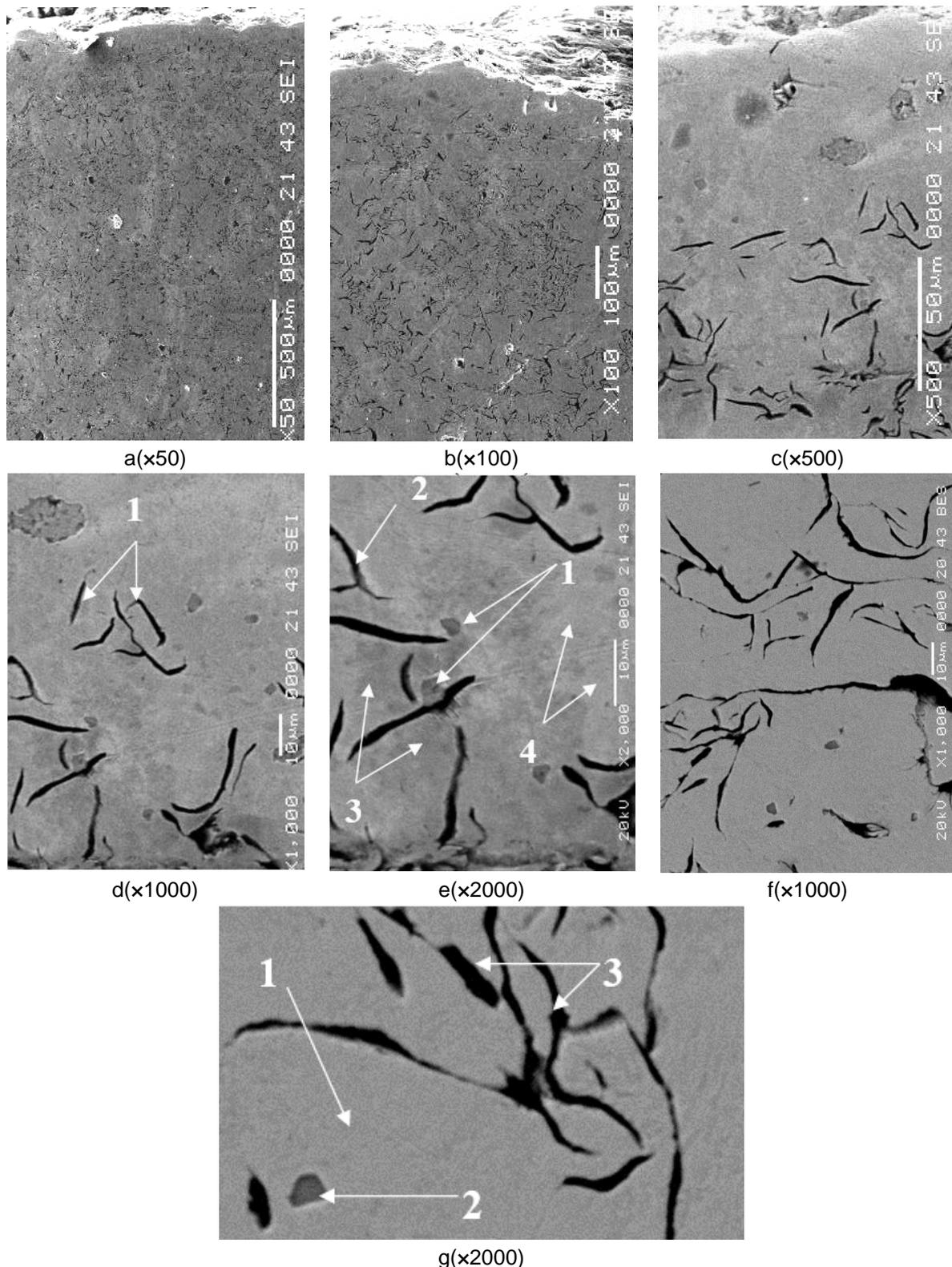


Fig. 3. Surface structure (a, b, c, d, e) and cast iron core (f, g) doped with vanadium while poured into dry sandy mould. (Investigated by scanning electron microscopy)

The gasketed rings from gray cast iron (Fig.1) poured into dry rod shape and subjected to direct

surface alloying have quality surface in the absence of casting defects. The structure of the surface (up to 1.5

mm) is white cast iron (Fig. 4a, b, c). In the surface layer (Table 3) the eutectic colonies are formed: austenite (pos.1 and pos. 6 Fig. 4c) and iron vanadium carbides (pos.4 Fig. 4c). Alongside the austenitic matrix there are compact darker inclusions which have similar composition, but also contain chromium and phosphorus (pos.5 Fig.4c), as well as iron silicon sulfides (pos.2 Fig.4c). There are some separate

compact graphite inclusions (pos.3 in Fig. 4c). The core structure is ferrite-pearlitic grey cast iron (Fig. 2d, e, f). Pearlitic areas (Fig. 4f) of the metal substrate are identified only at high magnification ($\times 5000$). The carbides of cementite type (pos.3 fig. 4e) are close (Table 3) to graphite inclusions (pos.1, 4 Fig 4e). In ferritic component of the metal substrate (pos.1 Fig 4f) 0.33% of vanadium is dissolved.

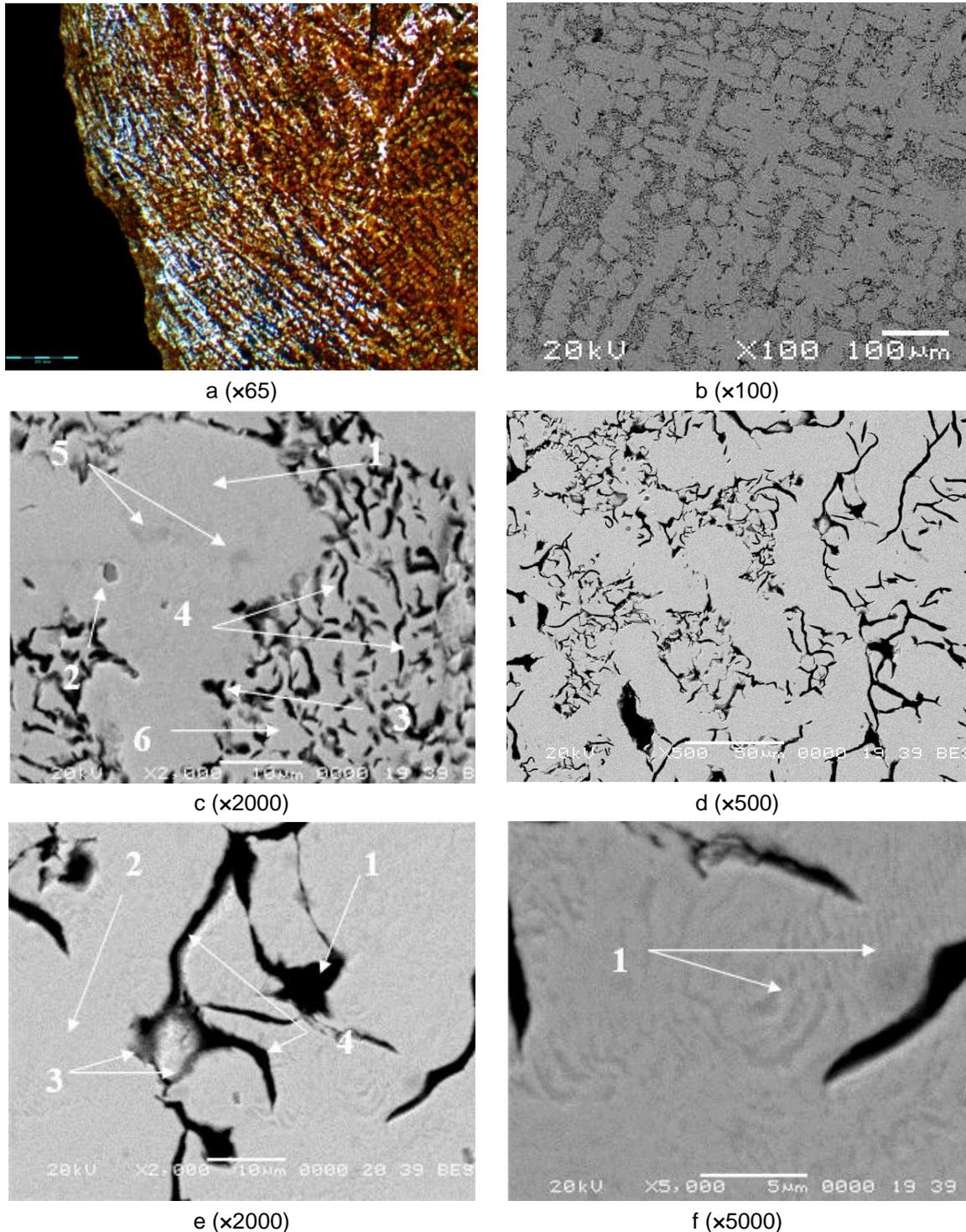


Fig. 4. Surface structure (a,b,c) and cast iron core (d,e,f) of gasketed rings doped with vanadium (a– metallographic investigations; b,c,d,e,f – investigated by scanning electron microscopy)

TABLE III. CHEMICAL COMPOSITION OF NON-METALLIC INCLUSIONS OF GRAY CAST IRON IN GASKETED RINGS DOPED WITH VANADIUM

| | Position of the inclusion | Component composition, % wt. | | | | | | | | | | | |
|---------|---------------------------|------------------------------|------|------|-------|-------|------|------|------|------|------|------|-------|
| | | C | O | Si | Mn | S | P | Al | V | Cr | Cu | Zn | Fe |
| Surface | 1 (fig. 2c) | 0.67 | 0.44 | 2.03 | 3.23 | 0.08 | 0.04 | 0.10 | - | - | 0.07 | - | 93.36 |
| | 2 (fig. 2c) | - | - | 0.38 | 22.59 | 11.04 | 0.14 | 0.34 | - | 0.37 | 0.05 | 0.04 | 65.05 |
| | 3 (fig. 2c) | 47.41 | - | 0.56 | 1.50 | 0.04 | 0.01 | - | - | - | 0.06 | - | 50.01 |
| | 4 (fig. 2c) | 19.17 | 0.12 | 1.21 | 2.46 | - | - | 0.12 | 3.17 | - | 0.54 | 0.16 | 74.50 |
| | 5 (fig. 2c) | 1.29 | 1.44 | 1.62 | 2.84 | 0.10 | 0.37 | 0.22 | - | 0.22 | 0.78 | - | 91.17 |
| | 6 (fig. 2c) | 0.88 | - | 1.85 | 2.84 | 0.02 | 0.15 | - | - | - | 0.93 | - | 93.13 |
| Core | 1 (fig. 2e) | 82.51 | - | 0.26 | 0.24 | - | - | - | 0.34 | 0.28 | 0.25 | - | 16.12 |
| | 2 (fig. 2e) | 0.62 | 0.55 | 1.81 | 2.70 | 0.13 | 0.15 | 0.35 | - | - | 0.16 | 0.18 | 93.36 |
| | 3 (fig. 2e) | 10.15 | - | - | 2.74 | 0.12 | - | - | - | - | 0.88 | - | 83.94 |
| | 4 (fig. 2e) | 61.08 | - | 0.14 | 1.13 | 0.14 | - | 0.01 | - | - | 0.72 | 0.17 | 36.61 |
| | 1 (fig. 2f) | - | 0.19 | 1.53 | 3.04 | - | 0.01 | 0.25 | 0.33 | - | 0.13 | - | 94.52 |

IV. CONCLUSION

The formation mechanism of wear resisting surface layers in the casting of iron-carbon alloys was developed. It provides the surface coating of moulds and cores with special compositions including inexpensive metal-containing industrial waste products or products of related industries, polymeric materials, generating in the process of filling in their pyrolysis powerful reducing agents (atomic hydrogen and carbon), and binders (liquid glass). The technology of direct surface cast iron alloying with vanadium is developed.

It was investigated macro - and microcomposition of the formed chemical associations (non-metallic inclusions and other "secondary" phases) and peculiarities of formation of structure elements during pouring laboratory samples into metal moulds and dry sand moulds.

It is shown that the gasketed rings from gray cast iron poured into dry rod shape and subjected to direct surface alloying have quality surface in the absence of casting defects. In the surface layer (up to 1.5mm) the eutectic colonies are formed: austenite and iron vanadium carbide. The core structure is ferrite-pearlitic grey cast iron.

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