

PHASE TRANSFORMATIONS

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Phase and Structural Transformations of High-Carbon Alloy of the Fe–V–C System During Chemical-Thermal Processing and Deformation

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The regularities of the phase and structural transformations during decarburization of a high-carbon Fe–V–C alloy are studied. The eutectic $L \rightarrow \gamma + VC$ transformation is established by the geometric thermodynamics method and metallographic analysis. This transformation is accompanied by a diffusion redistribution of the carbide-forming elements ahead of the crystallization front. Decarburization in a liquid–solid state allows forming a favourable structure with VC fibres oriented perpendicularly to the surface in the near-surface zone. Structural changes, which occur under deformation in a liquid–solid state, in preliminary decarburized synthetic vanadium-containing cast iron are investigated. The regularities of structure formation in various diffusion zones during subsequent carburization are revealed. As shown, the subsequent carburization of a pre-decarburized Fe–V–C alloy under special conditions makes it possible to obtain a natural composite with high wear resistance in the surface layer. Secondary hardness and heat resistance of carbonized layer of vanadium-containing cast iron deformed in a liquid–solid state after the final heat treatment are studied.

Key words: Fe–V–C system, decarburization, carburization, diffusion, deformation, crystallization front, eutectic transformation.

Досліджено закономірності фазових і структурних перетворень, що відбуваються при знеуглецюванні високовуглецевого ступу Fe–V–C. Мето-

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дою геометричної термодинаміки та металографічною аналізою встановлено евтектичне перетворення $L \rightarrow \gamma + VC$, що супроводжується дифузійним перерозподілом карбідоутворювального елементу попереду фронту кристалізації. Знеуглецювання у рідко-твердому стані уможливило сформувати в приповерхневому шарі сприятливу структуру з волокнами VC, орієнтованими перпендикулярно поверхні. Досліджено структурні зміни у попередньо знеуглецьованому, синтетичному ванадійовому чавуні, що відбуваються при деформації у рідко-твердому стані. Встановлено закономірності формування структури у різних дифузійних зонах при подальшому науглецюванні. Встановлено, що подальше науглецювання попередньо знеуглецьованого стопу системи Fe–V–C в особливих умовах уможливило одержати в поверхневому шарі природний композит високої зносостійкості. Проведено визначення вторинної твердості та теплостійкості науглецьованого шару ванадійового чавуну, деформованого у рідко-твердому стані, після остаточного термічного оброблення.

Ключові слова: система Fe–V–C, знеуглецювання, науглецювання, дифузія, деформація, фронт кристалізації, евтектичне перетворення.

Исследованы закономерности фазовых и структурных превращений, происходящих при обезуглероживании высокоуглеродистого сплава Fe–V–C. Методом геометрической термодинамики и металлографическим анализом установлено эвтектическое превращение $L \rightarrow \gamma + VC$, сопровождающееся диффузионным перераспределением карбидообразующего элемента впереди фронта кристаллизации. Обезуглероживание в жидко-твёрдом состоянии позволяет сформировать в приповерхностной зоне благоприятную структуру с волокнами VC, ориентированными перпендикулярно поверхности. Исследованы структурные изменения в предварительно обезуглероженном, синтетическом ванадийсодержащем чугуна, происходящие при деформации в жидко-твёрдом состоянии. Установлены закономерности формирования структуры в различных диффузионных зонах при последующем науглероживании. Установлено, что последующее науглероживание предварительно обезуглероженного сплава системы Fe–V–C в особых условиях позволяет получить в поверхностном слое естественный композит высокой износостойкости. Проведено определение вторичной твёрдости и теплостойкости науглероженного слоя ванадиевого чугуна, деформированного в жидко-твёрдом состоянии, после окончательной термической обработки.

Ключевые слова: система Fe–V–C, обезуглероживание, науглероживание, диффузия, деформация, фронт кристаллизации, эвтектическое превращение.

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1. INTRODUCTION

Vanadium forms solid refractory monocarbide VC in steels. The microhardness of the carbide VC is about 24.000 H_μ [1]. In this connection,

steel alloyed with vanadium have high hardness and wear resistance [2, 3]. VC carbide dissolves sufficiently well in austenite at high temperatures (Fig. 1). Thus, steels with high concentration of vanadium and carbon are secondary hardening and heat-resistant with appropriate heat treatment (quenching at high temperatures and tempering at temperature of ≈ 820 K) [4]. However, such a material contains a significant structural defect such as carbide heterogeneity, and carbides have a rough differentiation. The most common way of eliminating carbide heterogeneity is regulated forging. The regulated forging is labour-intensive process and it does not always produce a positive result.

The carbonization of low-carbon vanadium-containing steels is one of the methods for obtaining evenly distributed dispersed carbides in the product surface. The $\alpha \rightarrow \gamma + \text{VC}$ phase reaction can be used for forming a natural composite in the surface layer during carburization [6, 7]. Such a reaction is carried out when the composition of the carbon-changing alloy crosses the ferrite corner of the conic $\alpha + \gamma + \text{VC}$ triangle at the isothermal section of the Fe-V-C diagram (dotted line in Fig. 1). There is a general directed growth of austenite and VC fibres, which reinforce the austenitic matrix. The surface layer becomes highly wear-resistant after quenching of the martensitic matrix due to the orientation of reinforcing carbide fibres.

However, as can be seen on the diagram, the surface should have a

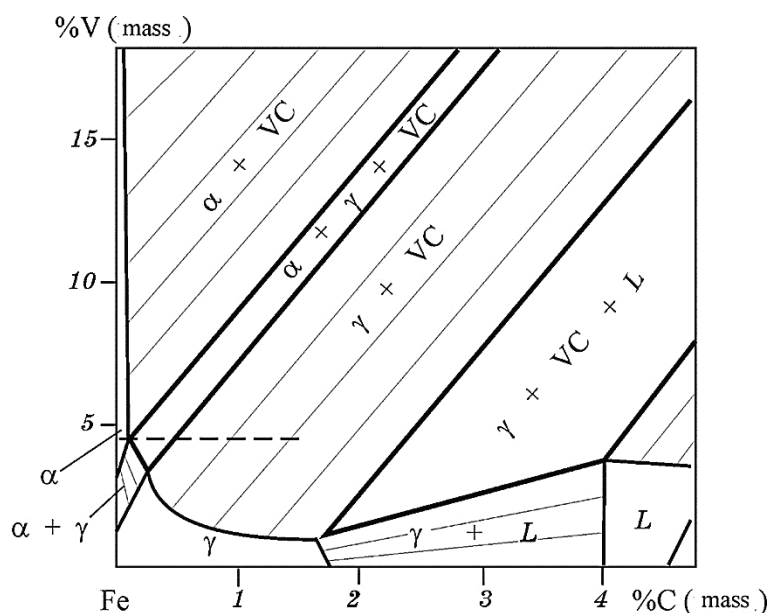


Fig. 1. Isothermal section of the Fe-V-C state diagram at 1470 K [5].

single-phase ferrite structure for obtaining the composite material. That is possible with at carbon concentration of $\leq 0.05\%$ and vanadium in the range of 2.5–3.0%. This requires the use of special metallurgical methods. The significant energy and material costs are inevitable due to the high temperature of liquidus.

We proposed two-stage chemical–thermal treatment. The workpieces is obtained by casting by this method of production. The surface is decarburized to a homogeneous ferrite, after that the material is finally formed, and then the surface layer is carburized. The deformation in the liquid–solid state is carried out at temperatures above the melting point of eutectic. The eutectic melts and decarburized surface layer does not allow flowing eutectic liquid and retains shape of the sample. The deformation in closed stamps leads to the crystallization of finely dispersed eutectic. In addition, the deformation leads to formation a dense defect-free structure in products.

It is expedient to use cast iron as the initial material to improve the casting properties, because cast iron has reduced dendritic segregation and initial carbide heterogeneity. Thus, the core structure of the product is of interest. It is possible to obtain the required structure of the working surface with specified operating characteristics by further carbonization of the surface. This is regulated by selection of modes of carbonization and final heat treatment.

The goal of this work is the study of the phase and structural transformations during the chemical–thermal treatment as well as the study of the effect of hot plastic deformation in the liquid–solid state on structural transformation in synthetic vanadium-containing cast irons.

2. THEORETICAL METHODOLOGY

Experimental synthetic cast iron was produced in a resistance furnace in an inert atmosphere. The concentration of the main components was 3.3% C, 2.7% V, 0.035% Mn, 0.03% Si, 0.025% S, 0.015% P. The structure of alloy in the initial state is dendrites of the primary austenite, ledeburite eutectic, and the inclusion of VC (Fig. 2).

The decarburization was carried out in a humid hydrogen environment. The decarburization was carried out in 2 stages. Preliminary samples were decarburized at a temperature of 1370 K. This temperature is below the melting curve. The first stage is realized for formation a decarburized casing. The temperature was raised to 1470 K after 1 hour. The processing was continued in the liquid–solid state for 3 hours, after which samples were rapidly cooled.

The decarburized samples were heated in a vacuum to 1470 K for 1 minute. Then, samples were extracted from the working space of furnace. After that, samples were subjected to deformation. The samples

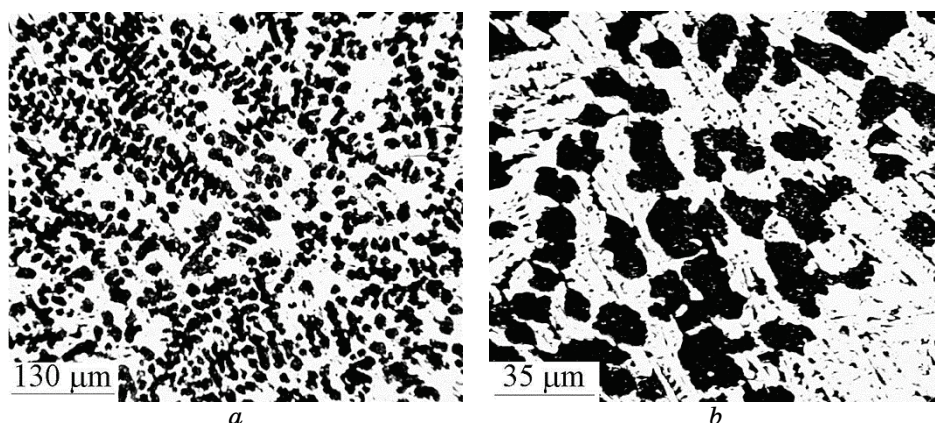


Fig. 2. Microstructure (*a*) and distribution of microhardness of surface layer (*b*) of steel 40X sample after aluminizing EEA at $W_p = 6.8$ J.

were cooled in air after deformation.

Carbonization was carried out in a laboratory installation in a gas environment such as inert gas and propane at a temperature of 1440 K for 1 hour.

The phase and structural transformations were investigated using methods of optical metallography and geometric thermodynamics.

3. RESEARCH RESULTS AND DISCUSSION

The structure of the vanadium-containing cast iron surface after decarburization consists of ferrite (Fig. 3, *a*). The number of inclusions in the ferrite increases with increasing carbon concentration. The austenite (martensite)–carbide zone is followed by ferrite–carbide zone (Fig. 3, *b*).

We used the isothermal intersection of the Fe-V-C state diagram at a temperature of 1470 K to describe the sequence of phase transformations during decarburization in the liquid–solid state (Fig. 4).

The initial composition of the experimental alloy corresponds to the point *a* (Fig. 4). The austenite (composition *b*) and melt (composition *c*) are in equilibrium in the alloy of such composition at the temperature of decarburization. If we agree with an assumption that concentration of the components in the coexisting phases are equal to the equilibrium at the interphase boundaries, then, concentration difference of the main components $\Delta\% V^{\gamma-L}$ and $\Delta\% C^{\gamma-L}$ is on the boundary of austenite and melt. Decarburization of this alloy leads to the crystallization of austenite. Vanadium is redistributed into the melt due to the difference $\Delta\% V^{\gamma-L}$. The stationary process is not achieved due to the high rate

of diffusion in the liquid and the convective mass transfer. The composition of the melt varies along the line $c-e$ on diagram. Further carbonation leads to the simultaneous crystallization of the austenite (composition d) and carbide VC upon reaching the melting point of the composition e . The carbide grows in the form of fibres directed along the direction of the carbon flow.

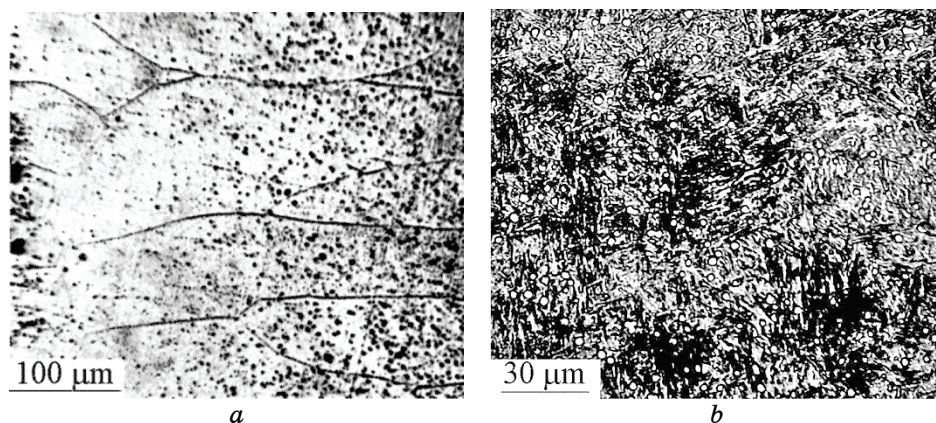


Fig. 3. The structure of surface zones after decarburization at a temperature of 1370 K for 1 hour and 1470 K for 3 hours: a —surface, b —transition zone.

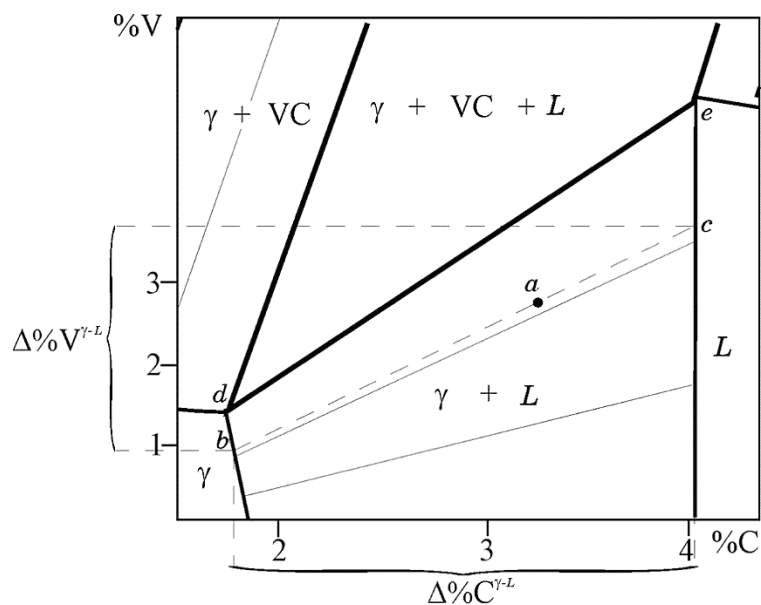


Fig. 4. Isothermal section of the Fe-V-C state diagram at 1470 K [5].

The distribution of carbides is well observed on the unetched microsections due to VC forms a relief on the polished surface due to its high hardness (Fig. 5, *a*).

The alloy components are completely redistributed by the products of the transformation. In the case of three-phase $L \rightarrow \gamma + VC$ crystallization. The composition of the liquid does not change ahead of the transformation front during the growth process. Austenite and carbide grow co-operatively, just as it occurs in eutectic crystallization. However, in our case, the thermodynamic stimulus of the phase reaction $L \rightarrow \gamma + VC$ is depletion of the melt with carbon, not the supercooling. The structures of the $\gamma + VC$ colonies and the residual liquid after cooling are presented in Fig. 5, *b* and Fig. 5, *c*, respectively.

Diffusion is a structurally sensitive process. Its rate depends on the structural state that obtained as a result of previous treatments. Heating to a temperature of 1440 K transforms the core of the sample into a liquid–solid state. The steel decarburized casing with a ferrite structure in the outer layer persists on the surface. Such a sample is easily deformed in closed stamps, acquiring the necessary shape.

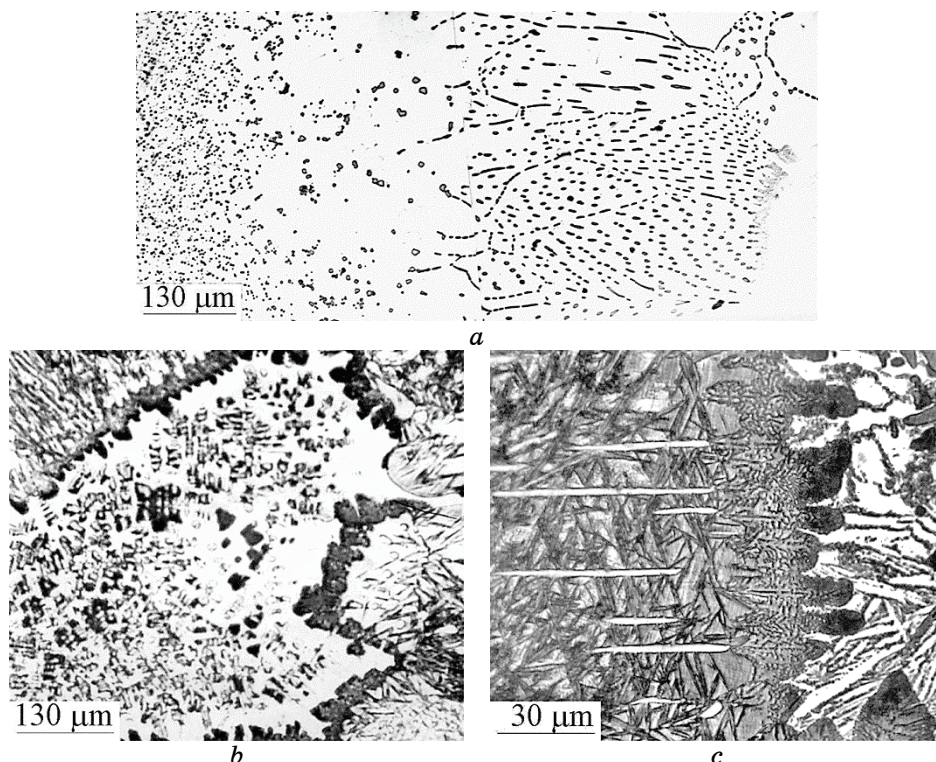


Fig. 5. Microstructure of the diffusion zone.

The deformation practically does not change the structure of the core of the sample (Fig. 6, *a*). The austenite dendrites and the ledeburite eutectic are retained. The inclusions of vanadium carbides are enlarged in comparison with the initial structure.

The ferritic casing is remained on the surface (Fig. 6, *b*). Other structural zones of the steel part of the sample have changed.

The main effect of deformation on structural transformations in decarburized vanadium-containing cast iron was observed in the zone adjacent to the cast iron part of the sample, *i.e.*, where there was a liquid-solid state. Carbides in austenitic-carbide colonies have been split (Fig. 7, *a*), there are rounded carbide precipitates in these places (Fig. 7, *b*).

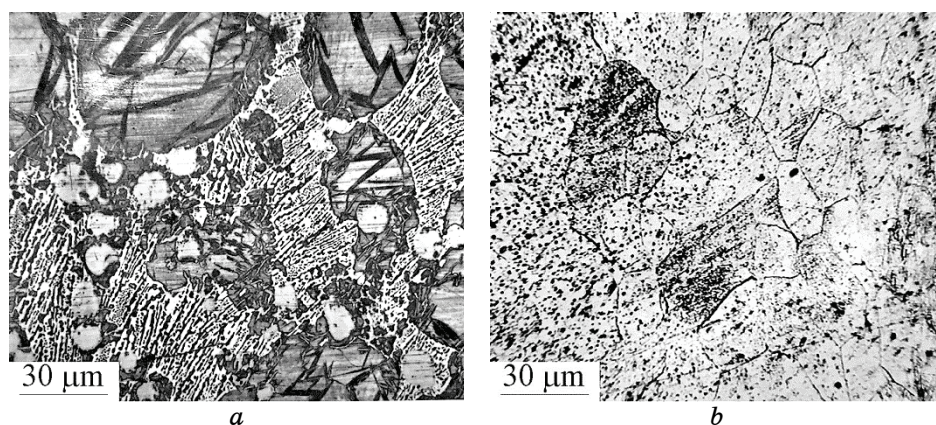


Fig. 6. Microstructure of vanadium-containing cast iron after decarburization and deformation in the liquid-solid state: *a*—core, *b*—surface.

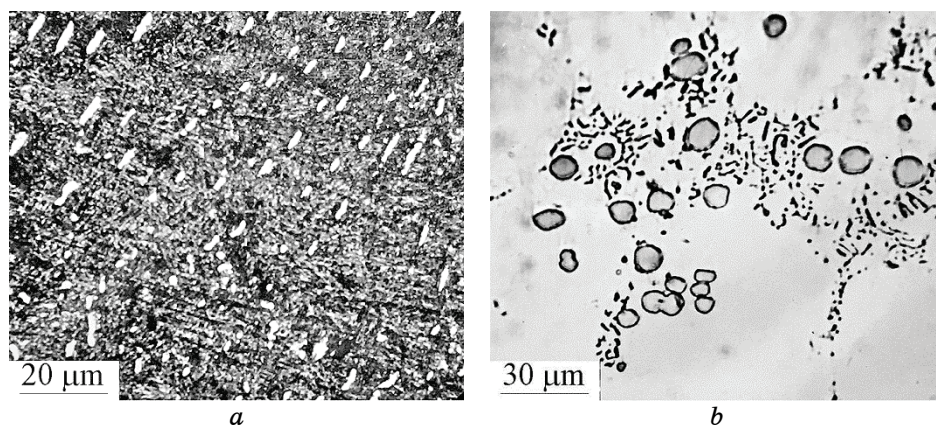


Fig. 7. Microstructure of the transition zone of vanadium-containing cast iron after decarburization and deformation.

There are no carbides in ferrite near the surface of the sample.

Based on previous studies [7], the carbonization of the previously decarburized surface of vanadium-containing cast iron, which deformed in the liquid–solid state, was carried out to construct the structure of the surface layer. By investigating the microstructure of the carburized surface, it was established that carbonization leads to the formation of austenitic–carbide colonies with rod and plate carbides on the sample surface (Fig. 8, *a*). The carbides are enlarged in colonies and located without a definite orientation closer to the core of the sample (Fig. 8, *b*). Consequently, the growth of austenite–carbide colonies during carburization may occur in the presence of a ferrite structure on the surface after the decarburized state. The structure of the hypoeutectic cast iron remains in the core of the carburized sample (Fig. 8, *c*), but in a more enlarged state compared with the initial cast iron due to diffusion processes.

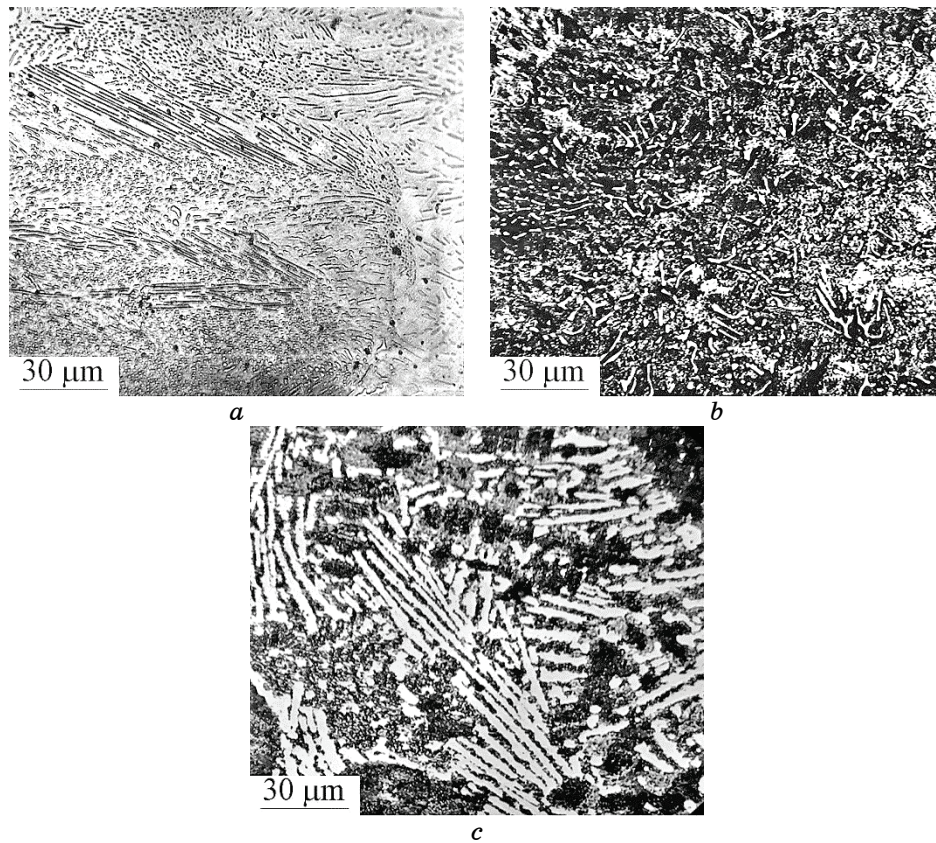


Fig. 8. Microstructure of vanadium-containing cast iron after decarburization, deformation and carbonization: *a*—surface, *b*—transition zone, *c*—core.

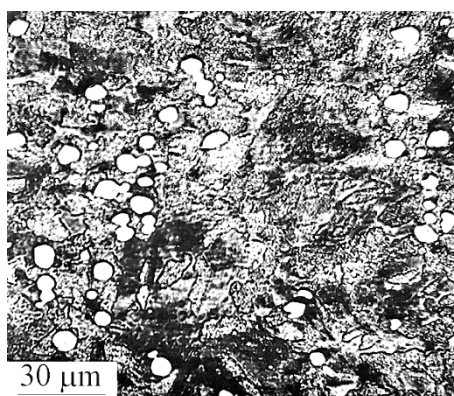


Fig. 9. Microstructure of the diffusion zone of vanadium-containing cast iron after decarburization, deformation and carbonization.

It can be concluded that the process of carbonization is also due to the carbon of the cast iron core, because it contains a zone with large carbides by considering the microstructure of the transition zone between the cast iron core and the carburized steel part of the sample (Fig. 9). Obviously, the distribution of ice burst and the transfer of carbon in the direction of its lower content.

It was of interest to determine the secondary hardness and heat resistance of the carbonized layer of vanadium iron deformed in the liquid–solid state after the final heat treatment with austenitic–carbide colonies in the surface layer.

The samples were hardened at the carburization temperatures, which makes it possible to retain austenite–carbide colonies in the surface layer. The hardness of the carburized surface after quenching was 58–59 HRC. A three-time tempering was carried out at a temperature of 830 K for 1 hour each after quenching. The hardness of the carburized surface after tempering is 60–61 HRC. The heat resistance was determined according to the method adapted to high-speed steels (heating to 890 K during 4 hours). The hardness after that was 59–60 HRC.

Thus, the carburized casing of vanadium cast iron with the colonial structure has a secondary hardness and a heat resistance.

4. CONCLUSIONS

1. The utilization factor of the material is increased when the workpieces are obtained by casting. Cast iron with a carbon concentration close to eutectic was used as an initial material. This reduces the dendritic segregation and the initial carbide inhomogeneity. Thus, if VC carbides are retained in the surface ferrite layer, then, they have mor-

phology of uniformly distributed dispersed inclusions.

2. Decarburization of high-vanadium Fe–V–C alloys let us get a ferrite structure in the surface layer. Decarburization in the liquid–solid state makes it possible to form a favourable structure with VC fibres oriented perpendicular to the surface in the near-surface zone.

3. The deformation of samples of vanadium-containing cast iron with decarburized surface at a liquid–solid state temperature is carried out.

4. Further carbonization in special conditions allows obtaining natural composite on the surface. The composite possesses high wear resistance, hardness, and heat resistance.

5. The obtained data allow more flexible control over the final structure of tool alloys and, consequently, solve practical problems of improving the technological and operational characteristics of the cutting tools.

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