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Technology of forming a wear-resistant thermite alloy layer based on the Fe-Cr-C system by self-propagating high-temperature synthesis

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Abstract. The technology of forming a thermite alloy layer on the basis of Fe-Cr-C system on a metal basis by self-propagating high-temperature synthesis is offered, which allows to obtain cast functionallayers withphysico-mechanical and exploitativeproperties. The optimal technological parameters of the forming a wear-resistant layer of thermite alloy process are determined: the amount of metal filler with the maximum yield of suitable alloy, the heating temperature of the thermite charge and the mold to obtain additional heat, the temperature ranges of the melt to melt the metal base with further formation of the functional layer. Metallographic studies of the obtained wear-resistant layer of thermite allo[y showed that the zone of formation of the functional layer is characterized by the stability of the macrostructure and the positive effect of non-metallic inclusions in the form of Al_2O_3, which influences the formation of chromium carbides in the obtained alloy by creating the effect of inoculative modification of thermite alloy.

1. Introduction

In foundry production, the "classic" (basic) technology for obtaining a liquid melt which is poured into the mold is metal smelting in a steelmaking unit (for example, in an arc steelmaking or induction furnaces) [1, 2]. Overheating of the obtained metal is not allowed primarily due to increased wear of the furnace lining and increased soot of the alloying elements. It is known that it is optimal to pour molten metal into a mold with a temperature close to the crystallization temperature, but even so it is not possible to obtain two-layer bimetallic castings due to the lack of a quality zone for the formation of functional layers [3–5]. That is why the use of self-propagating high-temperature synthesis (SHS) to form a wear-resistant layer of thermite alloy on a metal basis can be a cost-effective alternative for the production of bimetallic products.

The main physical parameters of the SHS process are the maximum combustion temperature at the level of 8004000 °C and the linear combustion rate of 1-150 mm/s. The combustion process consists of two main stages: reduction of oxides with the formation of metal (metallothermic stage) and the stage of direct synthesis of elements [6].

The mechanism of structure formation and product formation in self-propagating thermite reactions is described in Orrù et al [7–9]. In order to obtain a dense SHS material with high

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physical and mechanical characteristics, it is necessary to take into account the patterns of the reaction mixture combustion, the formation of chemical and phase compositions of the final product, the crystallization behavior of the alloy [10].

A general overview of thermite reactions, which are exothermic redox reactions involving metal and oxide, is presented by Wang et al [11]. Scientists have presented theoretical and experimental results related to ignition and combustion in self-propagating high-temperature synthesis.

In [6] the technology of materials synthesis based on combined (self-propagating high-temperature synthesis plus metallothermy) processes is described. The author considers theoretical issues of synthesis and technological features of running the combined processesfor micro fusion conditions. Reactions based on the proposed charge compositions led to the synthesis of carbidosteels, which contained a binder component and high-speed steel, and a base tungsten carbides. The parameters of carbide steel yield from the charge were experimentally established, and the microstructure, features of chemical composition, mechanical and technological properties were investigated for the synthesized alloys.

The issue of synthesis of steels and cast irons by metallothermy is considered in more detail in [12]. In particular, the synthesis of different types of steels: heat-resistant, tool, spring and others, as well as different types of cast iron: grey, white and high-strength. The author shows that the mechanical properties of thermite steels are better than those of industrial analogues and reveals the influence of the metallothermic method of synthesis on the features of the microstructure and phase composition of thermite steels. Theoretical and experimental studies have also shown the possibility of using thermite cast irons not only to obtain castings, but also for thermite welding technology.

In [13] the results of experimental and theoretical studies of the combustion of iron-aluminum thermite mixtures for iron and composites based on ironwas given. The effect of granulation and addition of flux on the combustion process, composition and structure of final products was evaluated. The author proposed a method of burning thermite mixture with bottom ignition and a model of a combustion plant. Also, the results of research on the combustion of granular thermite mixture are given in [14, 15].

The study of Coffey et al [16] is devoted to the use of additives and fluxes in metallothermicprocesses in self-propagating high-temperature synthesis.

Lonsdale [17] presents an overview of the features of thermite welding rails, and in particular, the practical and technical advantages and disadvantages of welding and focuses on improving the quality of thermite welding. Welding aspects of railway connections by means of thermite welding or aluminothermic welding are also considered in [18].

The research of the obtaining steelcomposites of the Fe-TiC system using aluminum thermic reactions of the SHS process possibility are presented in the study [19].

The work of Yeh and Wang [20], which considers the effect of stoichiometry on the formation of intermetallic compounds of the Nb-Al type is also of particular interest. The authors investigated the production of various niobium aluminides (such as Nb_3Al, Nb_2Al and $NbAl_3$) using extruded samples from Al and Nb_2O_5 powder mixtures using the SHS process.

The study by Sereda et al [21] is devoted to the thermodynamic analysis of reactions possible in the production of intermetallic nickel-aluminum alloys in high-temperature synthesis. Thermodynamic analysis showed that for the nickel-aluminum system, the adiabatic combustion temperature is at the level of the melting point of the final product such as intermetallic one, which is the sufficient condition for the SHS reaction under normal conditions.

We should note the scientific achievements of Sereda et al [22], which considered modelling of production processes of alloys based on TiAl and NiAl in the SHS process.

The work of Belokon and Belokon [23] is devoted to the study of the regularities of high-temperature synthesis of intermetallic compounds, in particular Ti-Al, and it is shown that

the synthesis of metals and alloys based on them can take place under conditions of thermal explosion. The compositions of SHS mixtures and technological modes of self-propagating high-temperature synthesis proposed by the authors allow to create intermetallic alloys based on titanium aluminides.

Therefore, there is reason to believe that the issue of determining the optimal technological parameters of the process of forming a wear-resistant layer of thermite alloy based on the Fe-Cr-C system has not been given sufficient attention. This area of research is quite relevant in the production of bimetallic products.

2. Materials and methods

When considering the technology of forming a layer of thermite alloy based on the Fe-Cr-C system on a metal basis using the SHS process, next materials were used as components of the charge (table 1): scale, aluminum powder of the PA-2 brand (GOST 6058-73) with the fraction of 45 μm, iron powder of the PZHRV 2.300.28 brand (GOST 9849-86) with the fraction below 300 μm, chromium powder of the PHA brand (GOST 14-00186482-051-2005) with the fraction of 300 μm and carburetor in the form of a modifier by MK91A brand with the fraction up to 5 mm. Calcification of rolled scale to remove grease and oxidation was performed in a muffle furnace SNOL 7.2/900 at a temperature of 600 °C for 30 min.

Table 1. The composition of the charge for forming a layer of thermite alloy.

Batch composition, kg	Batch 1	Batch 2
Cinder	100,00	100,00
Iron powder of the PZHRV brand 2.300.28	45,64	–
PA-2 aluminum powder	30,00	30,00
PHA chromium powder	–	16,60
MK91A brand modifier	8,90	6,30

The study of the process of a thermite alloy surfacing on a metal base was carried out in a mold consisting of a sand-clay shell with a lid (figure 1).

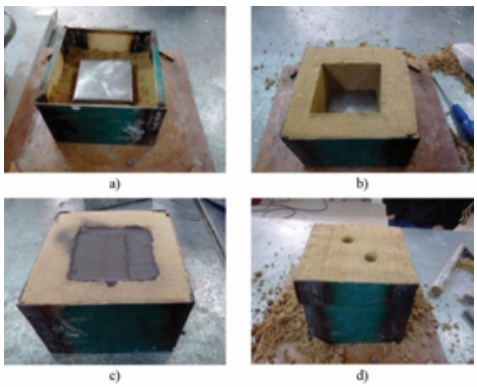


Figure 1. Experimental mold: (a) installation of a metal basis in the form on model; (b) sand-clay form with a cavity for thermite charge; (c) compacted thermite mixture in the form; (d) form assembled with a hole for burning thermites and gas removal.

To remove moisture, the mold was subjected to a drying process at a temperature of 524 K

for 1.5 hours. To control the temperature, four tungsten-rhenium thermocouples were installed in the mold (figure 2). Sealing of the thermite alloy was performed on a vibrating table.

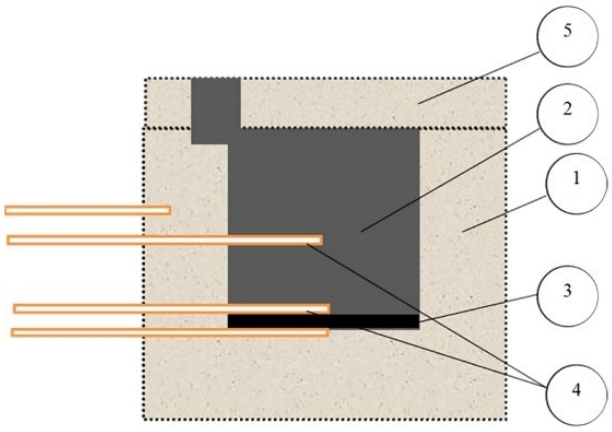


Figure 2. Scheme of experimental mold: 1 molding mixture; 2 thermite mixture; 3 metal base; 4 thermite charge; 5 lid of the mold.

To study the kinetics of thermal processes occurring in the mold during the formation of a layer of thermite alloy during the SHS process, an experimental laboratory setup was additionally developed (figure 3). The temperature measurement range lasted from the moment of ignition of the thermite charge (873 K) to the temperature of the combustion wave of the thermite charge (2774 K). Thermocouples were insulated with ceramic tubes with two holes with a diameter of 0.3 mm and connected to a high-speed self-recording device H 32-4.

3. Results and discussion

In the study of the influence of the mold heating time on the change in temperature, the prepared mold was heated in a preheated to 873 K laboratory muffle furnace SNOL 7.2/900. The data in figure 4 show that the temperature of the mold wall, after installing it in the oven, increases rapidly to 873 K. During the first 40 min the rate of temperature rise is 13.5 K/min and gradually decreases to 3.7 K/min in the heating time range from 40 min to 80 min. Upon further finding the form in the furnace, the heating rate increases at a rate of 5.3 K/min.

To accelerate the heating time of the mold with direct contact of open surfaces with the heated atmosphere of the furnace, a mold with an open metal base in the lower part was made (figure 5). The use of this design has reduced the heating time of the mold from 120 min up to 90 min. However, it should be noted that the open surface of the metal base in the lower part of the mold makes significant changes in the course of self-propagating high-temperature synthesis. After initiating the combustion of the thermite mixture, for 0.5 min from the beginning of the process, there is a sharp decrease in the temperature of the lower surface of the metal base to the ambient temperature (4-5 °C), which persists for 3.5-4 sec (figure 6, curve 1).

Analysis of these thermocouples installed on the upper surface of the metal base (figure 6, curve 2) showed that the total combustion time of the thermite charge is 8.5 sec, where the combustion front reaches the surface of the metal base and its temperature for 1 sec, rapidly increases to 2024-2054 K, which indicates the beginning of the formation of a thermite alloy. This temperature is maintained for 5-7 sec, which contributes to the fusion of the liquid phase and the metal base. At 15.5 sec from the beginning of the process, the temperature of the formed layer decreases to the temperature of crystallization of iron, and the tendency to decrease the temperature is observed up to the 20th sec.

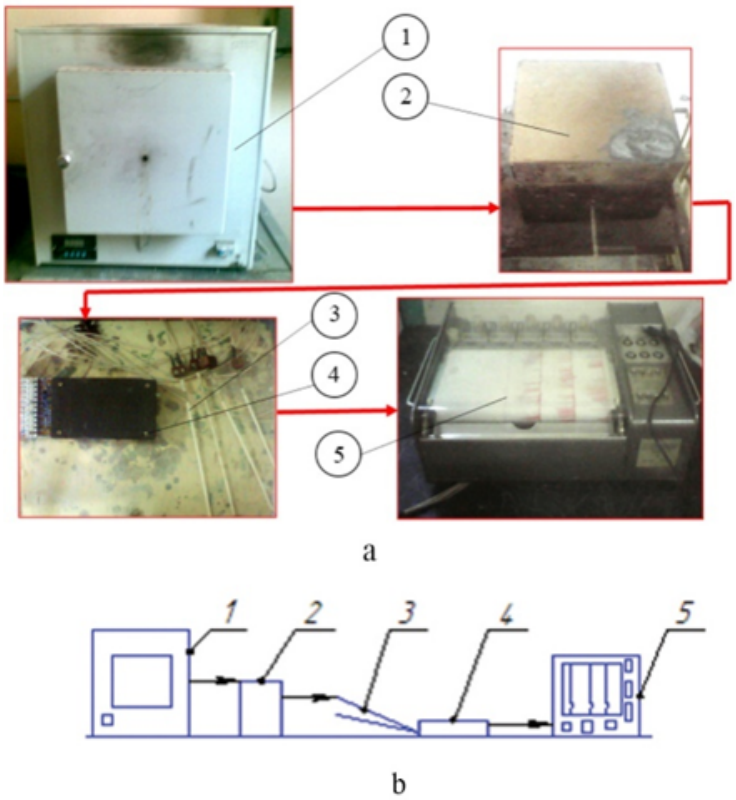


Figure 3. General view (a) and scheme (b) of the experimental laboratory installation for studying the kinetics of thermal processes: 1 laboratory muffle furnace; 2 experimental form assembled with thermocouples; 3 tungsten-rhenium thermocouples BP 5/20; 4 signal amplifier thermocouples with compensates; 5 high-speed self-recording device H32-4.

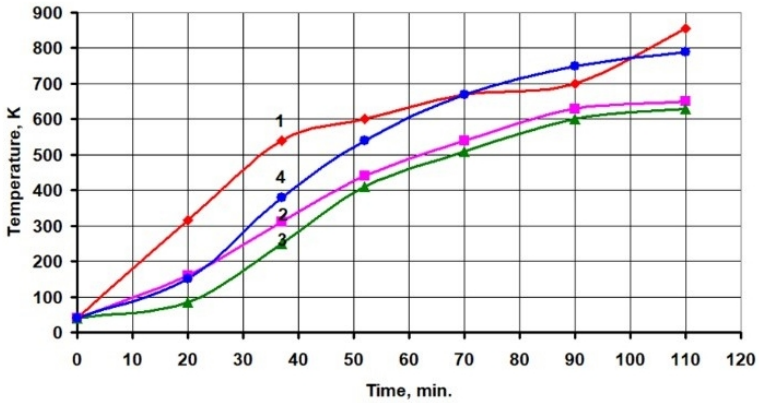


Figure 4. Influence of time of heating of a mold on change of temperature: 1 heating of a wall of a form; 2 heating under the plate; 3 heating of the thermite charge over the plate; 4 heating of the thermite charge in the middle of the mold.

Studies of the temperature behavior of the molding mixture (figure 6, curve 3) showed an initial rapid (within 0.5-1 sec) decrease in temperature from 873 K to 723 K, but with its subsequent increase at a speed of 284-286 K/sec for the next 10 sec. The tendency to maintain

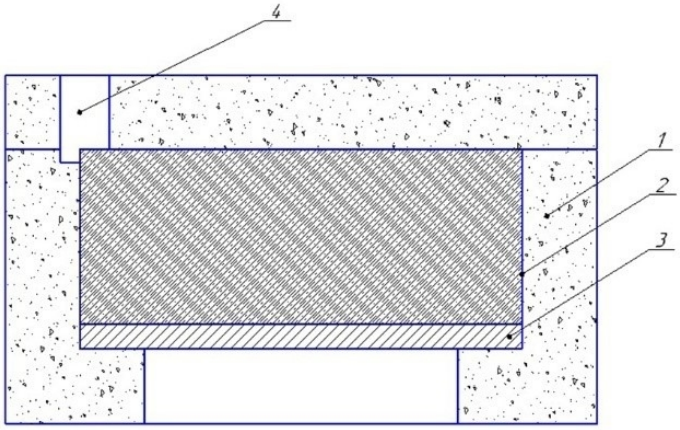


Figure 5. Foundry mold with an open metal base in the lower part: 1 molding mixture; 2 thermite charge; 3 metal base; 4 hole for igniting the thermite charge and exhaust gases.

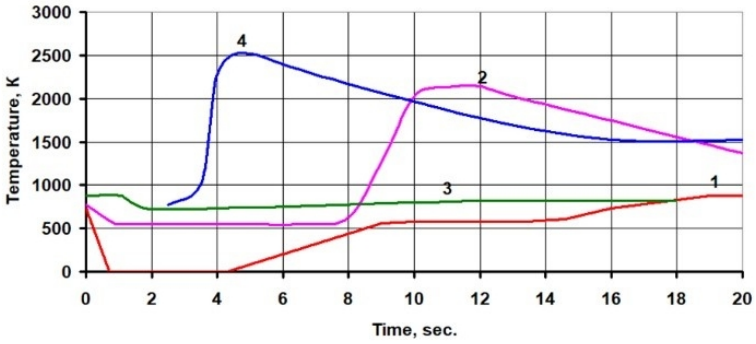


Figure 6. The effect of heating time of the mold with an open metal base in the lower part on the temperature change: 1 the lower surface of the metal base; 2 the upper surface of the metal base; 3 molding mixture; 4 temperature of the working medium thermite; charge-thermite alloy.

the temperature at 823 K must be preserved till complete crystallization of the metal.

The process of burning thermites takes place at a temperature of 3100-3200 K, which exceeds the boiling point of iron. This, in turn, allows you to add to the charge of the metal filler in such a volume that the temperature of the melt to form a functional layer was not lower than 2474-2674 K (figure 6, curve 4).

It should be noted that the open metal base in the lower part of the mold accelerates the preheating of the mold in the muffle furnace, but on the other hand there is also cooling of both the molding mixture and the metal base after firing the thermite charge. Thus, the analysis of thermo-grams from thermocouples of the mold shows that for 20 sec depending on the location of the thermocouple, there is an abrupt fluctuation of the temperature behavior.

When determining the optimal technological parameters of the process of forming a wear-resistant layer of thermite alloy based on the Fe-Cr-C system during SHS process, it was noted that the temperature of the thermite alloy after the combustion wave should not exceed the boiling point of iron, and the lower temperature limit of thermite alloy should exceed crystallization of the alloy not less than 1000 °C. The increase in the temperature of the thermite alloy directly depends on both the preheating of the mold and the amount of metal filler in the thermite charge. It should be borne in mind that the introduction of a very large amount of

metal filler reduces the yield of a suitable thermite alloy. Therefore, the optimal content of metal filler in the thermite charge heated to 873 K is a composition of 40%.

It was experimentally determined that the mass of the formed wear-resistant layer of thermite alloy obtained from the charge 1 and the charge 2 was 97.94 kg and 68.9 kg, respectively.

The obtained samples of thermite alloy were investigated for structural properties such as density in accordance with GOST 20018-74, porosity in accordance with GOST 9391-80, and macro-structure evaluation in accordance with GOST 10243-75.

So in (figure 7, a) the dependence of the density of the thermite alloy on the heating temperature of the mold and the content of the metal filler is showed.

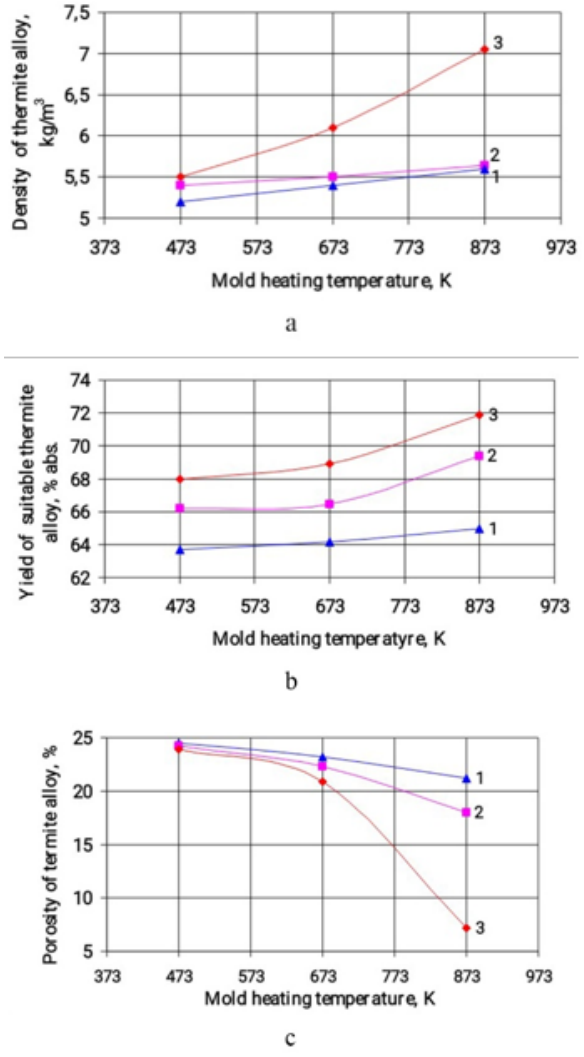


Figure 7. Dependence of density (a), yield of suitable (b) and porosity (c) of thermite alloy on heating temperature of mold and content of metal filler: from 1 to 20% of metal filler; from 2 to 30% of metal filler; from 3 to 40% of metal filler.

It is shown that increasing the amount of metal filler in the charge from 20% to 40%, when heating the mold to 873 K, increases the yield of suitable thermite alloy to 71.9% by weight of the original charge (figure 7, b) and it increases the density to 7.05 kg/m^3. Increasing the amount of metal filler to 40% and it also reduces the porosity of the formed thermite alloy to 5.5% (figure 7, c).

Metallographic studies of the samples of the obtained wear-resistant layer were performed in order to analyze the influence of the heating temperature of the mold on the process of formation of macrostructure defects in the zone of formation of functional layers. Metal graphic studies of samples of the mixture based on chromium (charge 2) were performed on an optical horizontal microscope of MIM-8 brand (light field mode). The samples were pre-cut at the level of the part by a water-cooled abrasive cutting wheel. When studying the quality of the connection of functional layers and analysis of structure formation, the samples were ground on the surface, baited on the macrostructure by electrical chemical etching in a saturated solution of ferric chloride (cathode a plate of corrosion-resistant steel).

In metal graphic studies of the formation zone of the thermite alloy layer based on the Fe-Cr-C system with a metal base at a heating temperature of the mold below 473 K, there was a loose connection of layers with the base, there were inclusions of slag, and in the upper part there were shrinkage shells (figure 8, a).

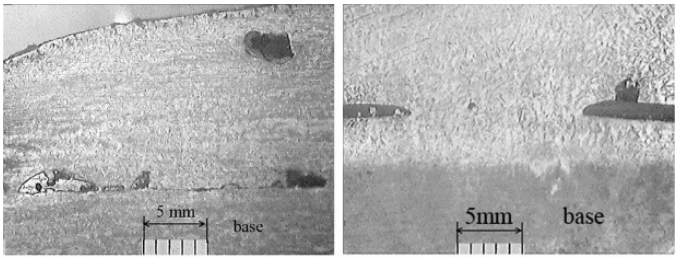


Figure 8. Metal graphic studies of the formed wear-resistant layer of thermite alloy based on the Fe-Cr-C system: (a) when heating the mold to 473 K; (b) when heating the mold to 873 K.

Layered, perpendicular and elongated crystallization (movement of the crystallization front in the form of terraces parallel to the crystal surface) was observed in the formed layer of thermite alloy.

In the analysis of samples obtained by heating the mold to 673 K, in the zone of formation of functional layers, a line of discontinuities was observed, the metal base was not welded, because the aluminum thermic reaction products did not float to the alloy surface due to rapid cooling of the thermite alloy layer.

For samples obtained by heating the mold to 873 K, the liquid state of the thermite alloy was longer, the time to crystallization was 16 sec. The surface of the metal base melted, and the slag consisting of Al_2O_3 (corundum) emerged from the zone of formation of the functional layer (figure 8, b) [24]

Thus, the zone of formation of the functional layer is characterized by the stability of the macrostructure and the positive effect of corundum, which, creating the effect of inoculating modification of the thermite alloy, in turn contributes to the formation of chromium carbides.

Thus, the result of the proposed technology of forming a layer of thermite alloy based on Fe-Cr-C system by self-propagating high-temperature synthesis are obtained samples of thermite alloy, on the surface of which when the mold is heated to 873 K in the slag phase metal inclusions are formed in separate spherical shape (figure 9).

This is due to the rapid stage of combustion and is accompanied by intense spraying of the resulting synthesized metal. The results of the study of adding to the thermite charge a 40% of the metal filler when heating the mold to 873 K are presented in (figure 10).

When the thermite charge contains more than 40% of metal filler, regardless of the heating temperature of the mold, there is a decrease in melt temperature, which leads to its significant porosity, as well as the presence of oxidized areas in the joint that did not melt (figure 11).



Figure 9. Samples of the formed layer of thermite alloy obtained by SHS process (heating of the mold to 873 K) with different amounts of metal filler: (a) 20% metal filler; (b) 30% metal filler.

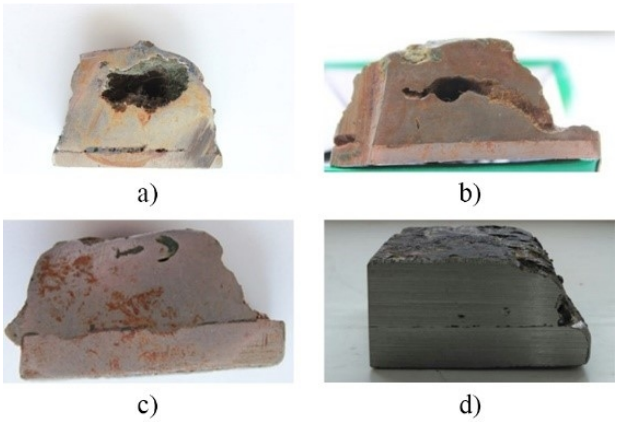


Figure 10. Section of samples of the formed layer of thermite alloy obtained by SHS process (40% metal filler) at different heating temperatures of the mold: (a) without heating; (b) when heated to 473 K; (c) when heated to 673 K; (d) when heated to 873 K.

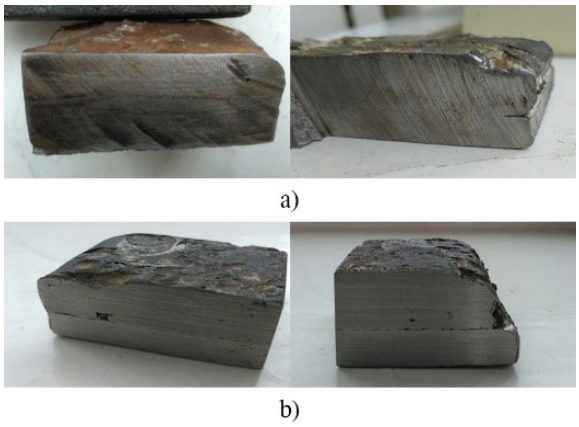


Figure 11. Section of samples of the formed layer of thermite alloy obtained by SHS process when heating the mold to 873K: (a) samples with 40% metal filler; (b) samples with more than 40% metallic filler.

4. Conclusions

The technology of forming a thermite alloy layer on the basis of the Fe-Cr-C system on a metal basis by SHS process is offered, which allows to obtain cast functional layers with improved

physical and mechanical, and operational properties. It is shown that the use of open mold in the lower part for the needs of foundry production has a negative effect on the SHS process and maintaining the temperature of the metal base, which is associated primarily with the flow of air from the environment in the lower cavity of the mold due to reactive jet of gas released from the mold through the outlet in the lid during the combustion of the thermite mixture.

The optimal technological parameters of the process of forming a wear-resistant thermite alloy layer are determined: the amount of metal filler with the maximum yield of suitable alloy, the heating temperature behavior of the thermite charge and the casting mold to obtain additional heat, the temperature ranges of the melt to melt the metal base. It is established that the optimal amount of metal filler in the mold, heated up to 873 K for the formation of a wear-resistant layer of thermite alloy is 40%. It is shown that increasing the amount of metal filler from 20% to 40% affects the structural properties of the formed layer of thermite alloy: increases the density of the alloy by 33% and decreases porosity of the alloy by 17.3%, while the yield of suitable thermite alloy increases to 71.9 absolute percent. It should be noted that lowering the heating temperature of the mold below 873 K degrades the quality of the formed layer of thermite alloy: thermite alloy does not separate from the slag and is released into separate spherical formations.

Metallographic studies of the obtained wear-resistant layer of thermite alloy penetrating into the metal base to a depth of 3 mm showed that the zone of functional layer formation is characterized by macrostructure stability and positive effect of corundum (as a residue of aluminothermic reaction product) in the obtained alloy. In this case, non-metal inclusions in the form of corundum, creating the effect of inoculating modification of the thermite alloy, in turn contribute to the formation of chromium carbides.

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