Application of SiC Based Moulding Sand in Technology of Layered Castings

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Abstract

The article concerns the technology of layered castings made with a system where the base part is made of gray cast iron with flake graphite and the working part is made of high-chromium steel X46Cr13. The castings were produced using mould cavity preparation method utilizing a molding sand based on SiC. The idea of the research was to perform heat treatment of X46Cr13 steel directly in the casting mould, with the success of this approach guaranteed by selecting molding sand with appropriate physicochemical parameters. During the pouring and cooling of the mould, the temperature on the outer surface of the steel insert was recorded to check if it reached the required austenitization temperature. The castings were then examined for the quality of the bond between the gray cast iron base part and the steel working part, microstructure studies were conducted using light and scanning microscopes, and hardness was measured on the surface of X46Cr13 steel. Based on the conducted research, it was found that the high thermal conductivity of the molding sand made with a silicon carbide base disqualifies it for use in the analyzed technology of integrating heat treatment of X46Cr13 steel with the process of producing a bimetal system with gray cast iron. In the microstructure of the steel, in addition to martensite, pearlite and ferrite were present. Therefore, a satisfactory increase in the hardness of the working surface compared to the annealed state of X46Cr13 steel was not achieved, which ultimately confirmed that the hardening of the steel insert was unsuccessful.

Keywords: Layered casting, SiC, High chromium steel, Gray cast iron, Heat treatment

1. Introduction

The type of binder used, as well as the size, shape, and density of the grains, determines the thermophysical properties of the mass, which affect the rate of heat transfer from the casting to the mould and to the environment. This can be utilized to control the microstructure of the casting, consequently influencing its functional properties [1]. The thermophysical properties of solids, such as thermal conductivity λ, determine the behaviour of the material when subjected to various thermal loads. Knowledge of the numerical values of these parameters, which are primarily functions of temperature, is essential during the design, manufacturing, and operation stages of specific structural

elements [2]. The technology of sand casting is a simple and effective method for producing layered castings in a liquid-solid system using monolithic inserts [3]. The starting point in this case is the commonly used moulding material, quartz sand. Its undeniable advantages are its cost and availability, although it does not exhibit outstanding thermophysical properties (λ=1,3-1,5) [4-5].

Silicon carbide, on the other hand, exhibits different properties. Due to its high mechanical strength, hardness, and resistance to thermal shocks, it is a promising material for manufacturing casting moulds. It is characterized by high thermal resistance and stability, as well as high thermal and electrical conductivity [6]. Compared to other materials used in the production of casting moulds, SiC demonstrates several times

higher thermal conductivity, reaching 130 W/mK at a temperature of 20°C. Thanks to its high thermal conductivity, the use of SiC can create new possibilities for controlling the macro (grain size) and microstructure (dendritic spacing) of castings, thereby increasing their mechanical strength at elevated temperatures [7]. The essence of layered castings lies in the ability to combine materials with diverse properties in such a way that the advantages of each component are utilized, resulting in a final element with properties that could not be achieved with a monolithic material. However, the dynamic development of many industrial sectors necessitates continuous efforts to simplify processes, save time, and minimize costs. In this context, attempts were made in studies [8-9] to integrate the heat treatment of steel used for the working layer with the process of producing a layered casting in combination with gray cast iron. The castings made with the above material configuration can be used, for example, for plates serving as linings for firefighting coke trucks or lining plates for ball mills, which are expected to have high wear resistance and good corrosion resistance. Typically, due to the high concentration of C and Cr, which ensure high hardenability, the final functional properties of X46Cr13 steel are achieved through heat treatment, such as quenching in oil or in open air [10]. According to the recommendations of the standard [11], after quenching, X46Cr13 steel should meet the following criteria for mechanical properties: Rm ≥ 1000 MPa, $Rp_{0.2}$ ≥ 650 MPa, A ≥ 10%, ≥ 610 HV (56 HRC). The results obtained in [8-9] indicate that the proposed concept is likely feasible, but the use of quartz and chromite sand did not meet the requirements specified by the standard [11] as the minimum after quenching. The cooling rates of the mould achieved were too low, resulting in the appearance of pearlite alongside martensite in the microstructure of the steel insert. Therefore, an attempt was made to produce layered castings with similar geometry to those in studies [8-9]. However, for these castings, a molding material based on silicon carbide was used, which, in reference to the research conducted in [12], seems justified from the perspective of the thermal conductivity coefficient of this material.

2. Methodology

Nine layered castings were made using the X46Cr13 steel - GJL250 gray cast iron system. The experimental plan detailing the parameters for producing layered castings is presented in table 1. The research conducted within this study is part of a larger project, and therefore, the experimental plan was predetermined. Layered castings were made using a moulding material based on silicon carbide, which was bonded with synthetic Carbophen 9600 in a ratio of 30:1.

Based on the sieve analysis conducted in accordance with the requirements of standard [13], it was determined that for all three types of binder, the dominant fraction is 0.40 mm / 0.32 mm / 0.20 mm, allowing them to be classified as coarse sands according to [14]. Moreover, since the main fraction constitutes over 80% of the total material in all three binders, they can be considered homogeneous binders.

The castings were made using the method of preparing the mould cavity with a monolithic insert made of X46Cr13 steel measuring 50x50x5 mm. After sandblasting and applying a boron and sodium-based flux, the insert was poured with gray cast iron. The application of a surfactant in the form of a flux based on B and Na aims to remove barriers to achieving a durable bond between the insert material and the casting material. Three different pouring temperatures were applied: 1400, 1450, and 1500°C, along with three different heights of the riser: 20, 40, and 60 mm.

Table 1.
Experimental plan

No. of casting	Tp, °C	g, mm
W1		20
W2	1400	40
W3		60
W4		20
W5	1450	40
W6		60
W7		20
W8	1500	40
W9		60

A Pt-PtRd10 thermocouple was placed at the geometric center of the outer part of the insert, and temperature during pouring and cooling of the casting was recorded using a Crystaldigraph M24 recorder.

The chemical composition of the cast iron and steel insert was controlled using a LECO GDS500A emission spectrometer and a LECO CS-125 analyzer (table 2 and 3).

The quality assessment of the bond between the two materials in the layered casting was conducted using non-destructive ultrasonic testing with a DIO1000 STARMANS ELECTRONICS flaw detector equipped with a PN10-4C flat probe.

Microstructure and phase composition analyses of the layered castings, particularly focusing on the working layer, were carried out using light optical microscopy (LOM) and scanning electron microscopy (SEM). For these analyses, metallographic specimens were prepared from the obtained castings by grinding on abrasive papers with grit sizes ranging from 200 to 1000, polishing on a felt disc with an aqueous Al_2O_3 solution, and electrolytic etching in a Mi19Fe reagent composed of 3g $FeCl_3$, 10 cm^3 HCl, and 90 cm^3 C_2H_5OH at 15 V for 20 seconds. Microstructure observations were made using a Phenom ProX scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectroscopy (EDS) system. SEM studies utilized backscattered electron (BSE) imaging mode at accelerating voltages of 10 and 15 kV, along with point, line, and surface chemical composition microanalysis via EDS.

Surface hardness tests of the working layer of the layered castings were performed using the Rockwell method on a SUNPOC SBRV-100D hardness tester, with automatic conversion to HV (Vickers hardness). Measurements were taken on the working surface of the casting at 16 evenly distributed points.

Table 2.
Chemical composition of steel grade X46Cr13

Chemical composition, wt. %											
C	Cr	Ni	Mn	Mo	Co	Si	Al	Cu	V	W	P
0,43	13,6	0,125	0,375	0,015	0,011	0,383	0,003	0,069	0,099	0,021	0,025

Table 3.
Chemical composition of gray cast iron with flake graphite EN-GJL-HB 255

Chemical composition, wt. %.									
C	Mn	Si	Cr	Ni	Cu	Al	V	P	S
3,55	0,47	2,18	0,24	0,04	0,12	0,012	0,06	0,22	0,11

3. Discussion of the results

According to the literature [15], the austenitization temperature range for the selected grade of steel is 950 to 1050°C, and the proper austenitization time t>950°C, i.e., the duration of the material staying in the austenitization temperature, for a 5 mm thick sheet is 450 seconds.

Referring to these assumptions, the hardening requirements for X46Cr13 steel were not met for most of the castings made using a moulding sand with a silicon carbide base. Only for two of them (W5 and W9) was the temperature recorded in the lower range of austenitization for the selected steel grade. However, the duration of staying in that temperature was significantly too short, being 16 and 76 seconds respectively. In general, based on the recorded temperature curves over time, it was found that, regardless of the pouring temperature used, a similar Tm was obtained on the outer surface of the steel insert. However, within the same pouring temperature, it was observed that the higher the height of the cast iron support part, the higher the temperature recorded (fig. 1, table 4).

As the pouring temperature Tp and the thickness of the base part g increase, the surface area exhibiting a permanent bond between the components of the layered casting also increases. For all castings with a supporting part thickness of 60 mm, a permanent bond was achieved over the entire contact surface between the steel working part and the cast iron base part (fig.2).
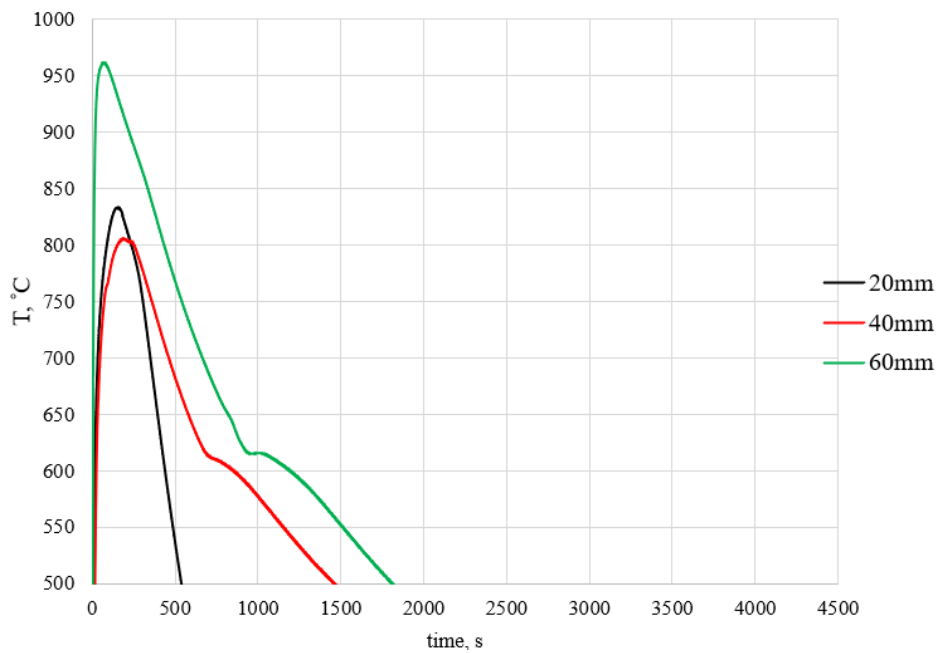
a)
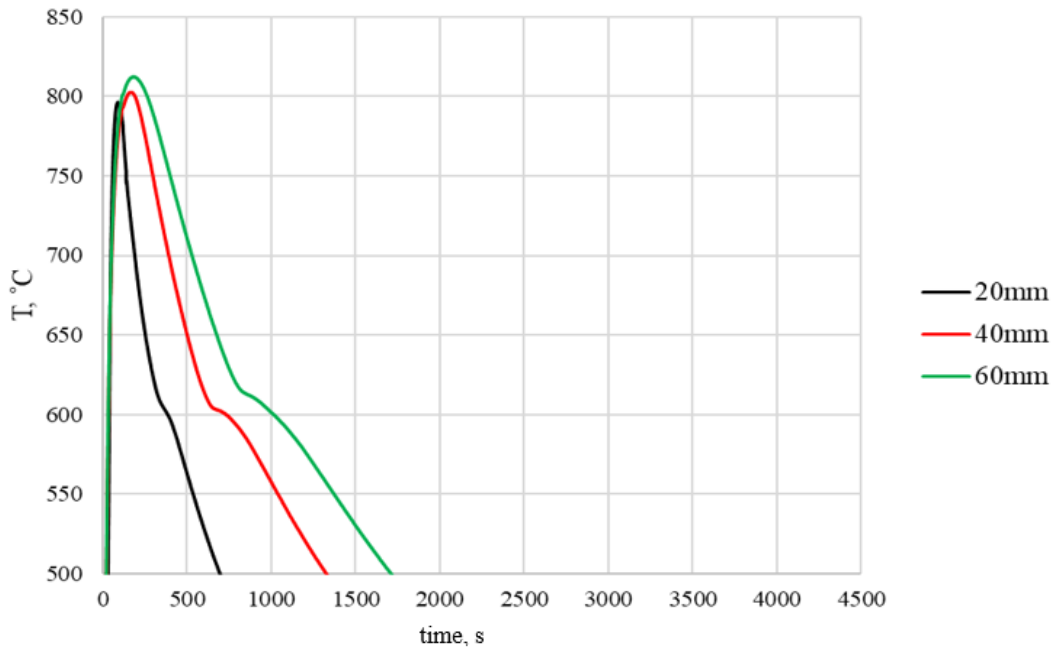
b)
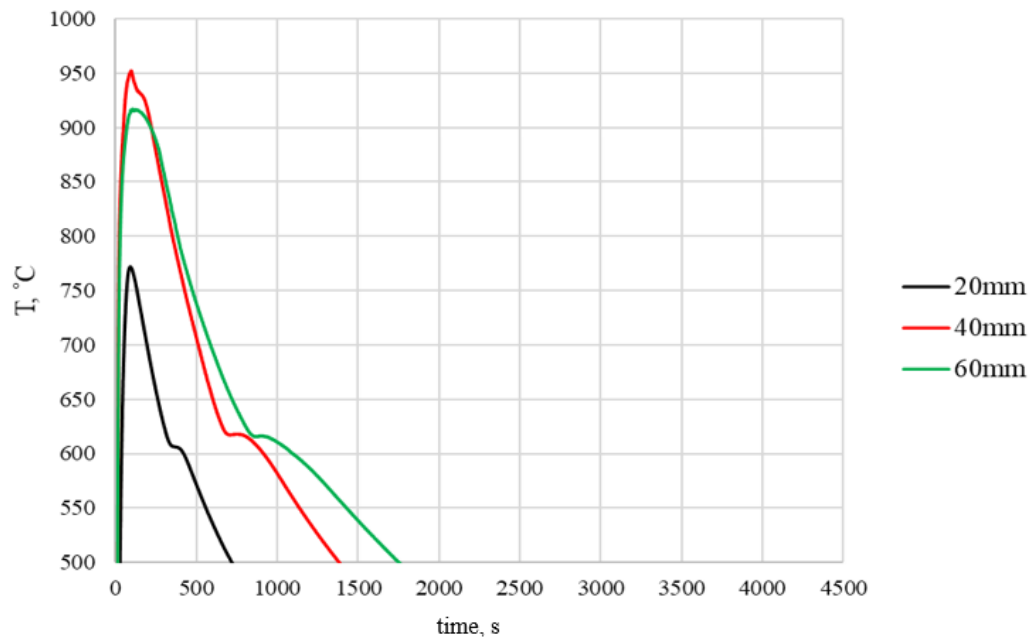
c)

Fig. 1. T = f(t) for the outer surface of the X46Cr13 steel insert cast with gray iron in the form of a silicon carbide matrix. Pouring temperature: (a) 1400°C, (b) 1450°C, (c)1500°C

Table 4.
Thermal and Kinetic Parameters of the Working Parts of Layered Castings

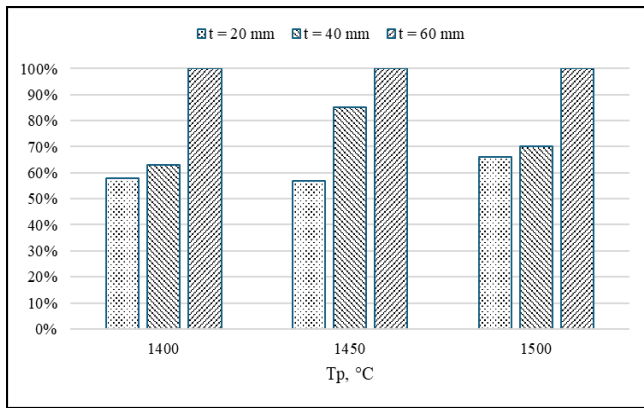|	W1	W2	W3	W4	W5	W6	W7	W8	W9
Tm, °C	797	803	813	772	952	917	833	806	961
t800, s	-	190	263	-	351	384	236	252	433
t500, s	693	1324	1708	718	1382	1750	538	1460	1809
t >950°C, s	0	0	0	0	16	0	0	0	76

Fig. 2. The surface area P where a permanent bond occurred between the base part and the working part in the tested layered castings.

In the areas of the layered castings where defectograms identified a proper connection between the X46Cr13 steel (insert) and the gray cast iron (casting alloy), diffusion of elements caused the formation of so-called transition zones. As a result of carbon and heat transport from the cast iron to the steel, a multi-zone microstructure of the layered casting has been formed, in which the following components are present from the cast iron to the steel (Fig.3):

1. The base part section (1) with a microstructure primarily composed of flake graphite in a pearlitic matrix. This microstructure is typical for the gray cast iron used in the supporting part of the layered casting.

2. The first transitional zone (2) with a pearlitic microstructure. This microstructure results from the decarburization of the cast iron due to the transport of carbon towards a lower concentration, i.e., towards the steel insert.

3. The second transitional zone (3) with a microstructure of Cr(Fe) carbides in a pearlitic matrix. This microstructure is a result of the reduction in melting temperature in this area due to carburization of the boundary zone of the steel insert and its subsequent melting by heat from the liquid cast iron.

4. The third transitional zone (4) with a macrostructure of Cr(Fe) carbides in a pearlitic matrix and a small amount of martensite.

5. The working layer (5) with a microstructure consisting of Cr(Fe) carbides in a martensitic–pearlitic matrix.

Within the working layer, which was crucial for this study, Cr(Fe) carbides in a martensitic-pearlitic matrix were identified (Fig. 4). Additionally, it was found that in the castings where the insert was "undercooked," there was also the presence of ferrite, which reduces hardness (Fig. 5c-d). This ferrite did not transform into austenite and subsequently into martensite or pearlite during the cooling of the bimetal in the casting mould (Table 5).

Figure 6 shows the hardness measurements on the surface of the working parts of layered castings made from X46Cr13 steel. Additionally, according to the PN-EN 10088-1,2 standard recommendations, the hardness of this steel grade should be at least 610 HV (56 HRC) after hardening. For comparison purposes, this value is also indicated in the mentioned figures. Due to the high thermal conductivity (λ) of moulding material prepared on the basic of SiC, this material excessively dissipated heat from the system, preventing the steel inserts, which form the working part of the casting, from reaching the full austenitization temperature. It was found that in castings where the insert was "underheated" due to the use of molding sand based on silicon carbide, there was also the presence of ferrite, which did not transform into austenite and later into martensite or pearlite during the cooling of the bimetal in the casting mold, thereby lowering the hardness. As a result, the microstructure of the material contained martensite, pearlite, and free ferrite. However, there is a noticeable increase in the hardness of the steel working surface of the casting compared to the as-delivered state of the steel (250 HV), especially in castings W5 and W9, where the hardness reached 471 and 446 HV, respectively. Based on the recorded heating curves, it was found that for most castings in this group, the steel insert forming the working part was heated to at least 800°C. According to the phase equilibrium diagram [10], above this temperature, the γ phase, which is part of a mixture including α iron and Cr carbides, is present. During cooling at a sufficiently high rate, austenite transforms into martensite, which is accompanied by an increase in hardness, as observed in the mentioned castings. The lowest recorded maximum temperature (Tm) was for casting W4 (772°C), which resulted in the lowest surface hardness of the working layer.
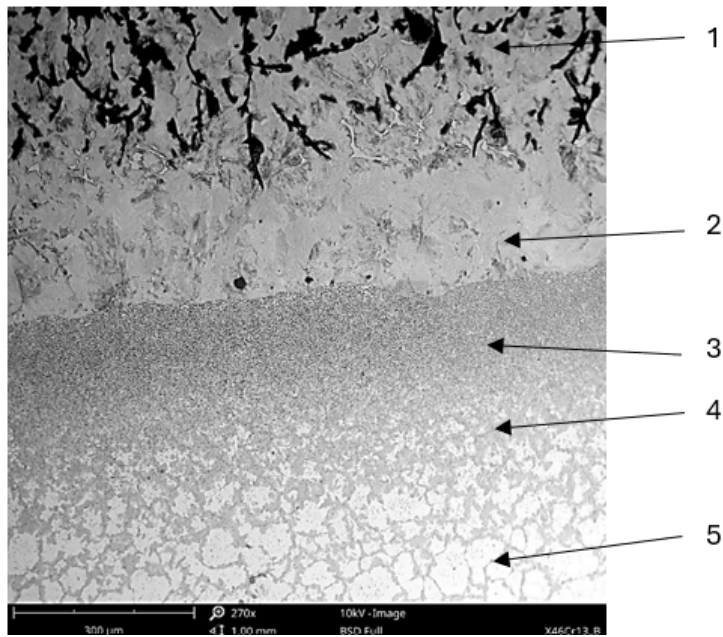
Fig. 3. Microstructure of a layered casting: gray cast iron EN-GJL-HB 255 - steel X46Cr13, SEM, mag. 270x
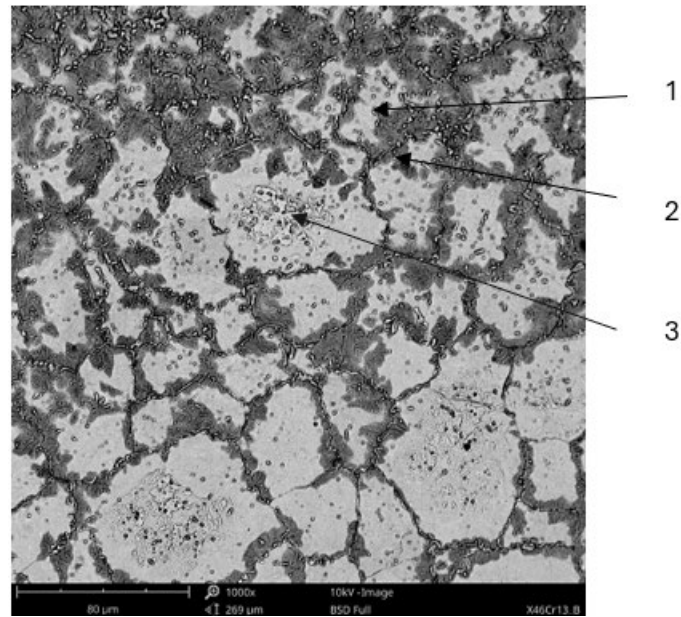

Fig. 4. Microstructure of working layer of layered casting made of X46Cr13 steel containing Cr(Fe) carbides in a martensitic-pearlitic matrix and free ferrite within the grains in the working layer of the bimetal: (1) martensite, (2) pearlite, (3) free ferrite. SEM, mag. 1000x
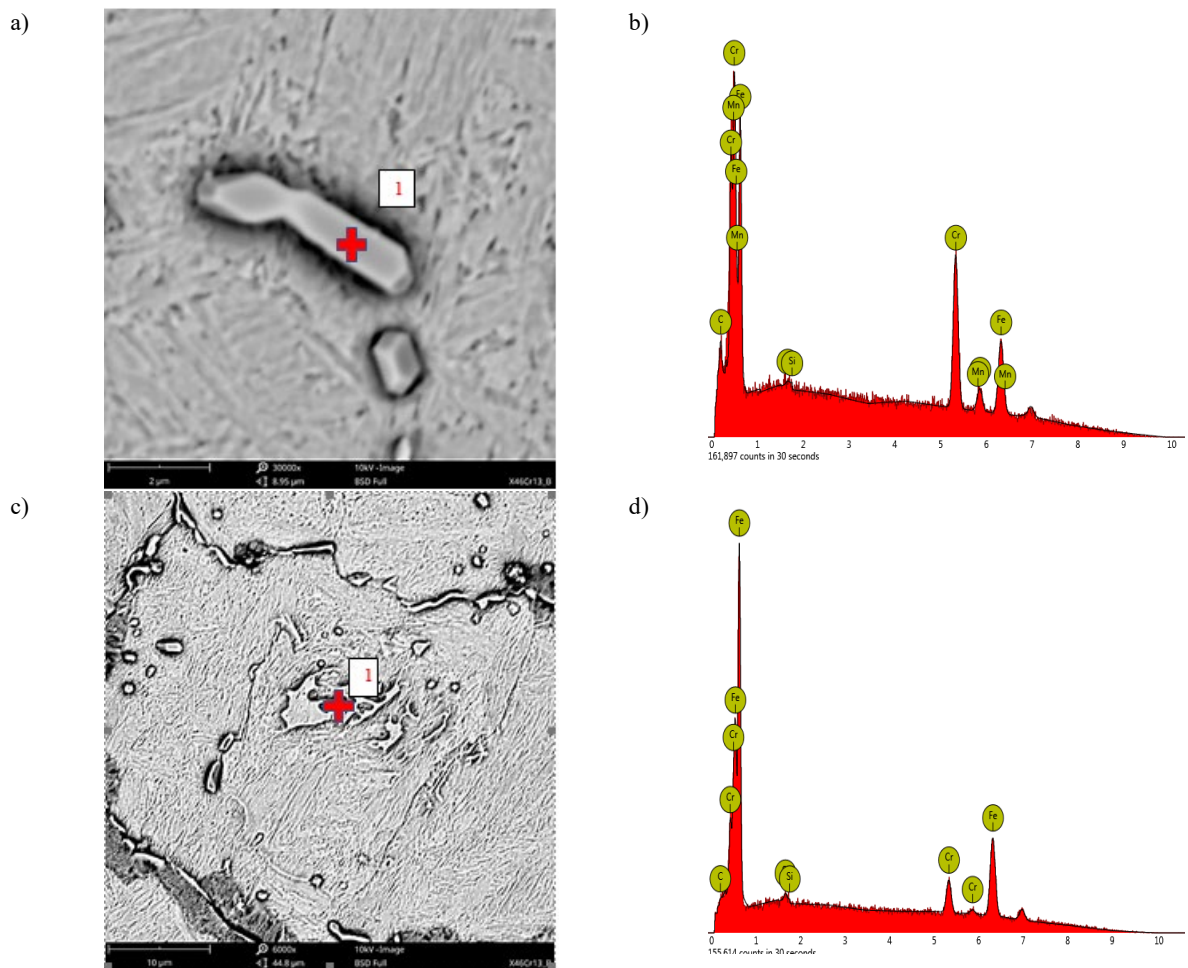
Fig. 5. Example microstructure: (a) Cr(Fe) carbides in a martensitic matrix with the location of the point EDS analysis marked, SEM, mag. 30000x, (b) result of EDS analysis at point 1 from fig. 3a (c) microstructure of steel X46Cr13 containing Cr(Fe) carbides in a martensitic-pearlitic matrix and free ferrite in the working layer of the bimetal with the location of the point EDS analysis marked, SEM, mag. 6000x, (d) result of EDS analysis at point 1 from fig. 3c

Table 5.
Result of EDS analysis

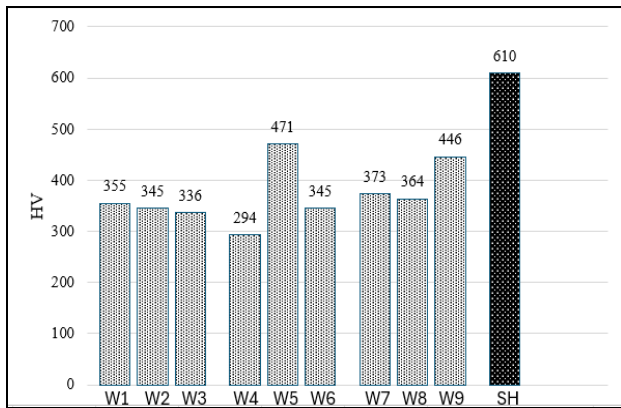| No. of point	Element	%at.	%wt.
1 from Fig. 3a	Fe	45.6	51.8
	Cr	41.0	43.4
	C	11.7	2.9
	Mn	1.6	1.8
	Si	0.2	0.1
1 from Fig. 3c	Fe	84.7	85.9
	Cr	14.6	13.8
	Si	0.7	0.4
	C	0.0	0.0

Fig. 6. Hardness on the surface of the working part made of X46Cr13 steel in layered castings made using SiC-based material (W1-W9), SH - minimum hardness of X46Cr13 steel after hardening according to [6]

4. Conclusions

Based on conducted studies, following conclusions have been formulated:

- For the castings made using a SiC-based moulding sand, it was observed that the intense heat dissipation from the system, directly resulting from the high thermal conductivity λ (4,20 to 13,94 W/m*K) in the analysed temperature range, prevented the surface of the steel working part from reaching the required austenitization temperature Tγ,
- In the microstructure of the working layer of the castings, martensite was indeed observed, but there was also a significant presence of pearlite and ferrite. There was no satisfactory increase in the hardness of the working surface compared to the annealed state hardness of X46Cr13 steel, ultimately confirming that the hardening of the steel insert failed. Therefore, it seems justified to conclude that the high thermal conductivity of the moulding sand with a silicon carbide base disqualifies it from use in the analysed technology of integrating the heat treatment of X46Cr13 steel with the process of producing bimetal in conjunction with gray cast iron.
- Additionally, the bonding surface of the bimetal components depended on the height of the cast iron base part and increased with its height. Regardless of the pouring temperature used, bonding across the entire division surface was achieved for all castings where the thickness of the base part was 60 mm.

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