A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 55 2010 Issue 3

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DIFFUSION PHENOMENA BETWEEN ALLOY STEEL AND GRAY CAST IRON IN LAYERED BIMETALLIC CASTING

ZJAWISKA DYFUZYJNE POMIĘDZY STALĄ STOPOWĄ I ŻELIWEM SZARYM W BIMETALICZNYM ODLEWIE WARSTWOWYM

The work presents bimetallic layered casting technology in configuration: the upper layer of high chromium steel or chrome-nickel steel with layer made of cast iron casting. In presented technology of layered bimetallic castings steel elements with a thickness of 1.5 and 5mm. It was used a process of overlay of a surface layer, directly during casting process so-called mould cavity preparation method. Steel elements were placed in sand mould just before pouring the liquid gray cast iron. Verification of bimetallic castings was based on ultrasonic non-destructive testing and examination of the structure and selected utility properties.
Keywords: Casting, Bimetal, Grey cast iron, Steel, Austenite, Ferrite

W pracy przedstawiono technologię bimetalicznych odlewów warstwowych w konfiguracji: warstwa wierzchnia na bazie stali wysokochromowej lub chromowo-niklowej z podłożem w postaci odlewu z żeliwa szarego. W przedstawionej technologii bimetalicznych odlewów warstwowych użyto do uszlachetnienia warstwy wierzchniej elementów stalowych o grubości 1,5 i 5mm, które w wyniku zastosowania metody nakładania warstw bezpośrednio w procesie odlewania tzw. metoda preparowania wnęki formy, zostały umieszczone w formach piaskowych bezpośrednio przed zalaniem ciekłym żeliwem szarym. Weryfikację wykonanych bimetalicznych odlewów warstwowych przeprowadzono w oparciu o nieniszczące badania ultradźwiękowe oraz badania struktury i wybranych własności użytkowych.

1. Introduction

In the engineering industry noticeable is a growing demand for castings with special properties such as abrasive wear resistance, corrosion resistance at room or elevated temperature. Elements of this type often carried out entirely from expensive and hard to reach materials like of Ni, Co, Ti, or others. In many cases the requirements for high performance properties affect only the working surface of the casting. Especially if wear of an element leads to its destruction through exceeded the allowable main dimension decrease.

Among many methods for producing metallic coatings on materials for specific performance properties to be mentioned is casting technology called method of mould cavity preparation in which the element which is the working surface layer of the casting is placed in a form immediately before pouring molten metal. This technology is the most economical way of enrichment the surface of castings, both ferrous and nonferrous alloys, as it allows the production of layer elements directly in the process of casting [1, 2]. Therefore, this technology can provide significant competition for the commonly used welding technologies and thermal spraying [3÷5], because in addition to economic advantages do not generate opportunities for the development of cracks in the heat affected zone, which arises as a result of making layer by welding method. The idea of the proposed technology of layer casting was taken from the relevant mining industry method of manufacture of composite layers of surface based on Fe-Cr-C granularity inserts and placed in a form immediately before pouring molten metal. Obtained in this way working surface layers have a high hardness and metal-mineral wear resistance [1, 2]. Another, also has common features with the proposed technology is layered bimetallic castings cast steel- chromium alloy cast iron, in which part of the casting is made of cast steel plate is designed to allow connection by welding to another part, and part is made of cast iron to ensure high hardness and abrasive wear resistance [6, 7]. However, a significant economic limitation of this method is the need to preheat the cast steel

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component placed mould. This treatment is carried out by two-stage form pouring with the liquid cast iron (Fig. 1).

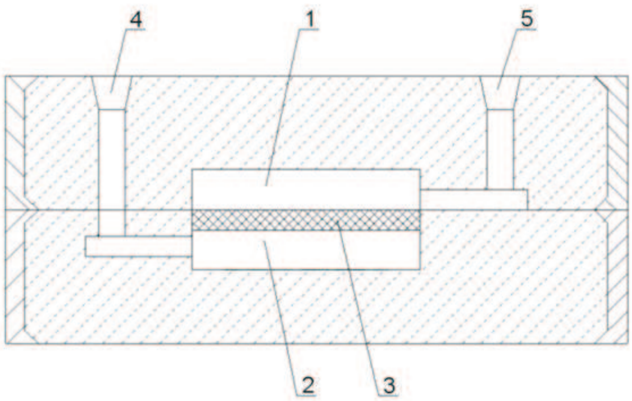

Fig. 1. Technology of bimetallic layer castings with use of two gating systems: 1 – cast iron layer, 2 – cavity (preheater) 3 – steel sheet, 4,5 – gating[6]

In the first stage mould cavity beneath a cast steel plate is filled with liquid metal for preheat of cast steel element. Formed in this way, layer after cleaning cast iron is separated from the casting. In the second stage mould cavity over cast steel plate is filled, in which the liquid metal forms a layered connecting with the plate creating a layered bimetallic casting. Restrictions resulting from the application of preheating on the first reduce yield and the inability to make high mass and stiffness of the casting. According to the authors those problems can be eliminated by applying appropriate cover activation, applied on steel surface in contact directly with liquid metal.

Next method of bimetallic casting technology is based on a skeleton steel structure filled with cast iron. The advantages of this method include large surfaces of contact of both materials and the ability to carry out several connections anywhere in casting [8].

In addition, attention should be paid to the method of producing bimetallic castings casted in a continuous process. In this method, the casting process is carried out using two independent crucibles, from which two streams of molten metal is introduced to the crystallizer equipped with a special barrier that allows a combination of both materials connect in the bimetal. However, this innovative technology is so far limited only to selected non-ferrous alloys such as Al-Zn, Al or Al-Sn-Pb [9].

2. Range of research

For the researches, the casting with a rectangular shape and dimensions of 125×105×40 mm was used. In sand moulds steel sheet X8Cr X10CrNi 18-8 13 of 1.5 and 5mm thick was placed with cover activation. No procedure of preheating was applied (Fig. 2). Then casted low-alloy cast iron EN-GJL-XCr1 with temperature 1450°C. In effect bimetallic layer casting was obtained (Fig. 3).

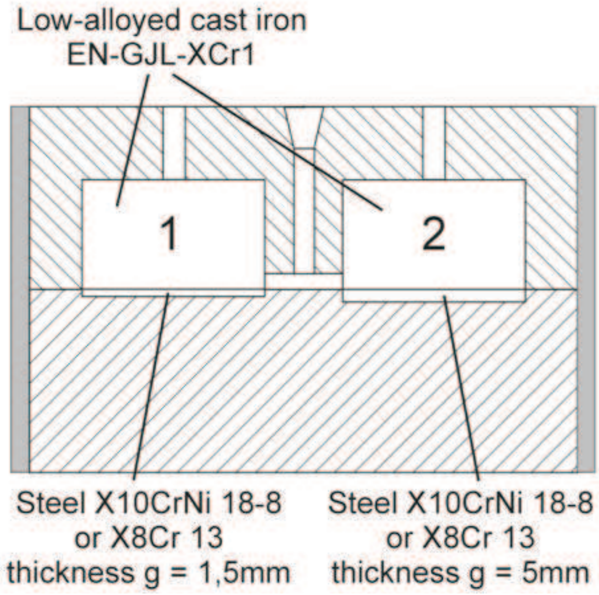

Fig. 2. Section of the sand mould ready to be poured by liquid alloy

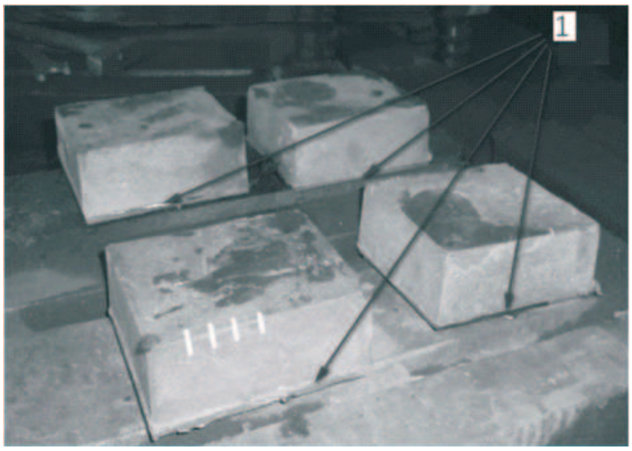

Fig. 3. View of cast iron test-castings with the surface enriched by alloy steel plate – 1

The quality of the bimetal layer casting was evaluated on ultrasonic NDT made using the DIO 562 flaw detector by Starmans Elektronics. Next metallographic examination of macro-and microscopic was carried out. Metallographic specimens etched in the reagent Mi19Fe containing [13]: 3 g of ferric chloride, 10cm^3 hydrochloric acid and 90cm^3 of ethanol. Qualitative microstructure research was conducted on the Nikon light microscope and electron scanning InspectF equipped with EDS system.

The study was extended to phase X-ray structure analysis carried out on the X-ray diffractometer

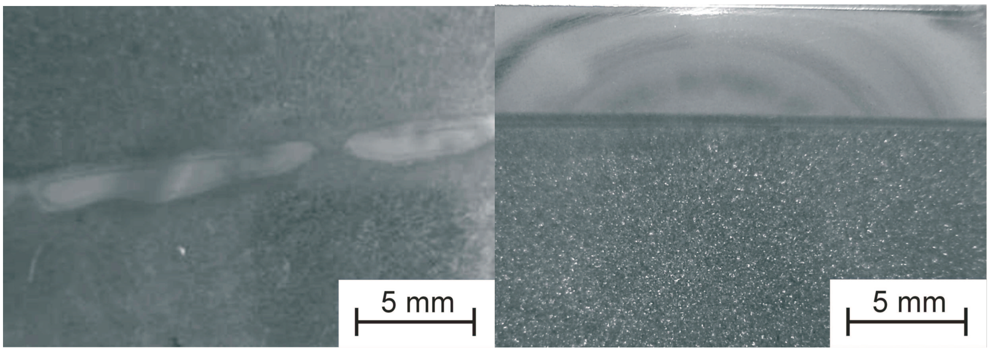

Fig. 4. View of cross-section of bimetallic low-alloy cast iron casting with enriched surface by austenitic steel plate about thickness 1,5mm (a) and 5mm (b)

XPertPro by Panalytical with the angular range 2θ from 35° to 125° in steps of 0.05° at the time of counting 5s. Using filtered X-rays from the lamp with a cobalt anode. Phase identification was based on data from the database International Centre for Diffraction Date ICDD. Samples for investigations were cut from the layer castings with surface enrichment of chromium-nickel steel plate after one cycle operation of abrasion of the metal – mineral according to the guidelines of ASTM G 65 – 00, to check whether there is a possibility of increasing the resistance to wear by plastic deformation induced by transformation austenite to martensite ($\gamma \rightarrow \alpha'$).

In addition, measurements of macro-and micro hardness test were made using appropriately MIC2 Krautrkramer-Branson's and FM 700's Future-Tech.

3. Results

On the basis of non-destructive ultrasonic testing it was found that the entire sample bimetallic casting surface (head placed on the side of the metal sheet) the bottom echo was larger than the echo of the transition zone, which indicates a good diffusion connection.

These results are confirmed in Fig. 4 that shows an example of the cross-section of the bimetallic casting. Furthermore, it was found that in the case of thin sheet metal that is 1.5 mm thick stainless steel, both X8Cr13 and X10CrNi18-8 a deformation occurs that is due to the low heat capacity that generates stress. As a result, a part of the liquid iron poured on the top of the plate, causes its partial dissolution (Fig. 4) and determines the lack of usefulness of this type of castings for industrial applications. The described phenomenon does not apply to cast steel sheets with a thickness of 5 mm (Fig. 4b), which allows to obtain the correct shape of the surface layer.

Figures 5 and 6 presents the results of metallographic microscopic examination. As a result of C diffusion phenomena in the direction from iron to steel metal sheet and to a lesser extent Cr in the opposite direction, transition zone has been formed at the junction of cast iron – steel. Shaped transition zone, structurally different from the iron and steel plates used, has the character of diffusion in determining the quality of a combination of both bi-metallic composite components. In addition, the formation of microstructure transition zone and adjacent areas is affected by the heating temperature of steel, because of the iron poured to form. For the temperature of pouring iron 1450°C, the temperature Ts at the border of the contact liquid metal – steel plate was fixed on the basis of dependence [11]:

$$T_s = \frac{\sqrt{\lambda_z \cdot c_z \cdot \rho_z} \cdot T_z + \sqrt{\lambda_s \cdot c_s \cdot \rho_s} \cdot T_s}{\sqrt{\lambda_z \cdot c_z \cdot \rho_z} + \sqrt{\lambda_s \cdot c_s \cdot \rho_s}} \quad (1)$$

λ_z, λ_s – coefficient of thermal conductivity, respectively for the liquid iron and steel, W/(m·K),

c_z, c_s – appropriately for the heat of molten iron and steel, J/(kg·K),

ρ_z, ρ_s – mass density, adequate for the liquid iron and steel sheet, kg/m^3,

T_z – the temperature of molten cast iron °C,

T_s – temperature of the sheet metal which is for the ferrite stainless steel X8Cr13, about 870°C, and for austenitic stainless steel, about 950°C.

Effect of diffusion of the basic components of alloys in combination with a high temperature heating of steel sheet, and its effects an cast iron during its solidification like chill, decide on the formation of microstructure in the area diverse combination of both materials.

In the case of bimetallic layer casting X8Cr13 steel – high chromium iron EN-GJL-XCr1, the analysis carried out on the metal sheet side allows to distinguish the zones shown in Fig. 5 and outlined in Tab. 1.

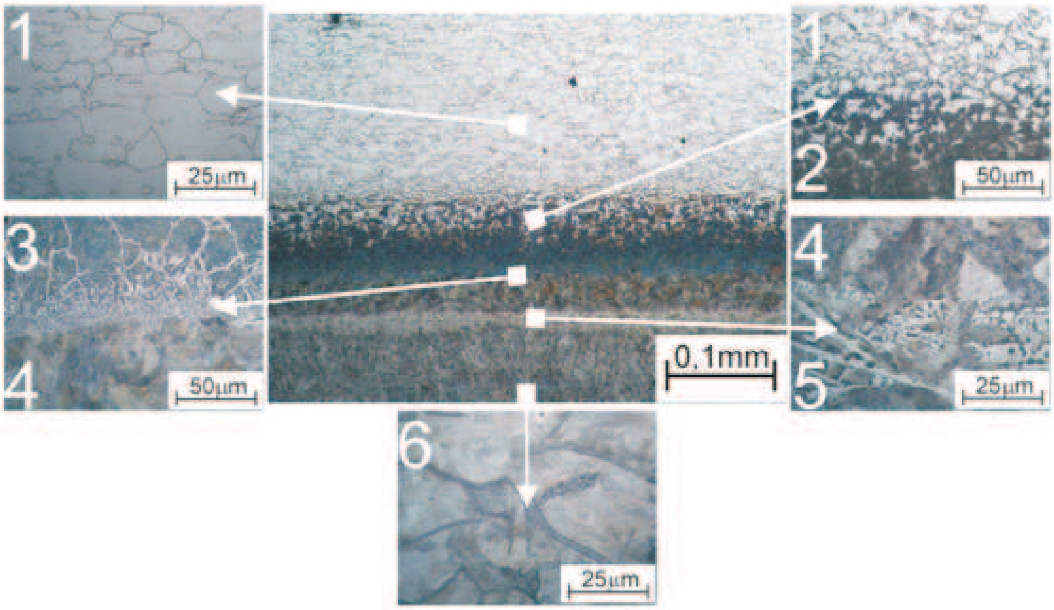

Fig. 5. Microstructure of bimetallic layer casting in configuration: surface layer on the basis of X8Cr 13 ferritic plate of the thickness about 5 mm on low-alloy cast iron EN-GJL-XCr1 base – etching Mi19Fe

TABLE 1
Microstructure characteristic of bimetallic layer casting in configuration X8Cr 13 steel – low-alloy cast iron EN-GJL-XCr1

Zone number*	Microstructure component	Microhardness µHV
1	Ferrite (α)	205
2	Martensite (α')	365
3	Martensite with carbides $(Fe, Cr)_xC_y$	α' = 410, $(Fe, Cr)_xC_y$ = 900
4	Pearlite	300
5	Hard spots-pearlite, ledeburite with carbides $(Fe, Cr)_3C$	Matrix = 420, $(Fe, Cr)_3C$ = 800
6	Flake graphite in pearlite matrix	Matrix = 300
* – zone designation according to fig. 5		

In the surface layer of this type bimetallic layer casting a single phase ferritic structure was obtained which provides high corrosion resistance also at elevated temperatures.

As a result of carbon diffusion in the direction from iron to steel in the outer area of the metal sheet (zone 2) the concentrations of carbon increases above 0.1%, which, combined with the high temperature heating of this area leads to the structure of the solid solution γ, which during cooling of the casting with a not to high speed transforms in to martensitic. The ratio of martensite to the amount of ferrite increases towards the border bimetallic.

In the last zone (no. 3) on the side of steel sheet, as evidenced by preserved the original orientation of crystal grains, as a result of intensive carburizing from iron martensite occurs with iron and chromium carbides.

The first zone (no. 4) on the side of cast iron creates perlite. This zone is combined with the previous one, no.3 non-linear connections border creates perlite. The presence of pearlite results from the depletion of this zone in the carbon, which prevents the emergence of phases i.e. graphite or cementite, typical for cast iron.

Then, in zone 5, as a result of high-speed solidification of molten metal at a concentration of carbon appropriate for cast iron, hard spot area is consisted of iron and chromium carbides, probably in the form of cementite $(Fe, Cr)_3C$.

Last zone 6 consists of a typical structure for the iron poured into molds such as flake graphite in a pearlitic matrix.

In the case of bimetal layer casting steel composition of high chromium X10CrNi 18-8 – low alloy cast iron EN-GJL-XCr1, the analysis carried out on the side of steel sheet allows to distinguish the zones shown in Fig. 6 and outlined in Tab. 2.

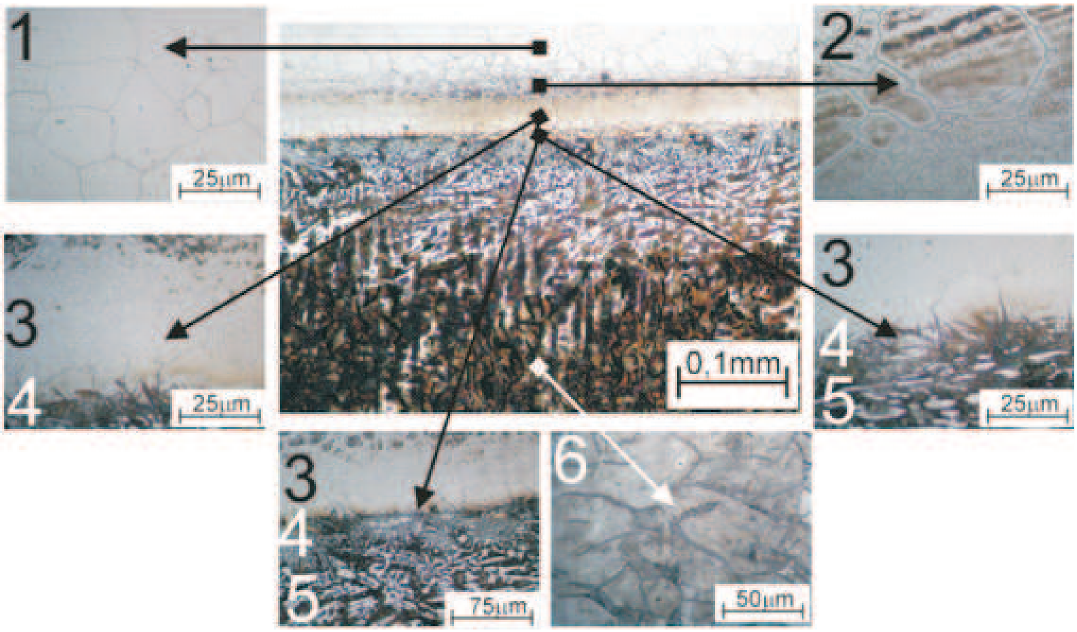

Fig. 6. Microstructure of bimetallic layer casting in configuration: surface layer on the basis of X10CrNi 18-8 austenitic steel plate about thickness g = 5 mm on low-alloy cast iron EN-GJL-XCr1 base – etching Mi19Fe

TABLE 2

Microstructure characteristic of bimetallic layer casting in configuration X10CrNi 18-8 steel - low-alloy cast iron EN-GJL-XCr1

Zone number*	Microstructure component	Microhardness μHV
1	Austenite (γ)	220
2	Austenite with carbides $Cr_{23}C_6$	330
3	Ferrite and austenite	275
4	Martensite	350
5	Hard spots-pearlite, ledeburite with carbides (Fe, Cr)$_7$C$_3$	Osnowa = 430, (Fe, Cr)$_7$C$_3$ = 1100
6	Flake graphite in pearlite matrix	Matrix = 300
* – zone designation according to fig. 6		

The surface layer of this type bimetal layer casting obtained single phase austenitic structure, which is similar like the ferritic layer provides high resistance to corrosion, also at elevated temperatures.

However, compared to a purely ferritic (150HV), austenitic structure has a greater resistance to abrasive wear. The increase in hardness of austenite (from 220HV to 400HV) in operating conditions occurs as a result inducted of plastic deformation martensitic transformation $\gamma \rightarrow \alpha'$.

The presence of martensite Fe'_{α} confirms carried out a qualitative X-ray phase analysis (Fig. 7). Martensite is increasing hardness and wear resistance of Fe_{γ} austenitic steel surface layer of layer bimetallic casting.

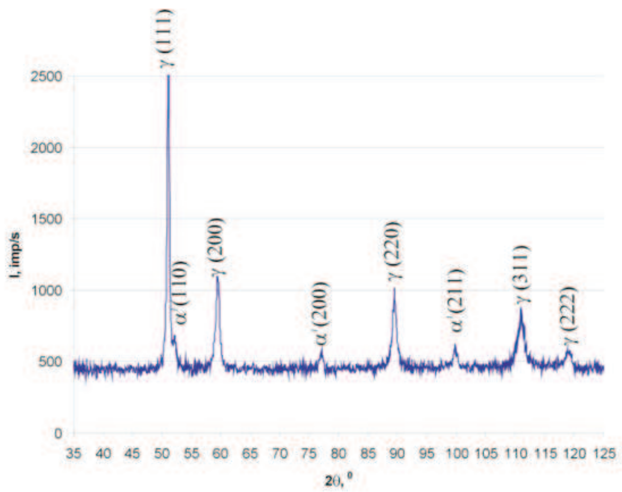

Fig. 7. X-ray diffraction of bimetallic casting with enriched surface by austenitic steel plate after one cycle exploitation in conditions of abrasive action of type metal-mineral

The result of heating the external area of the steel sheet from molten cast iron to a temperature above 900°C, in this area (zone 2) is dissolved carbon interstitial diffusion in austenite, which migrates from the whole volume of γ phase to the grain boundaries and in combination with vacancy chromium diffusion from near border grains areas $Cr_{23}C_6$ chromium carbides are formed. In addition besides presence of this type of carbides on the borders, they occur in the central areas of austenite grains. The presence of carbides $Cr_{23}C_6$ result in a decrease of corrosion resistance in this area, as

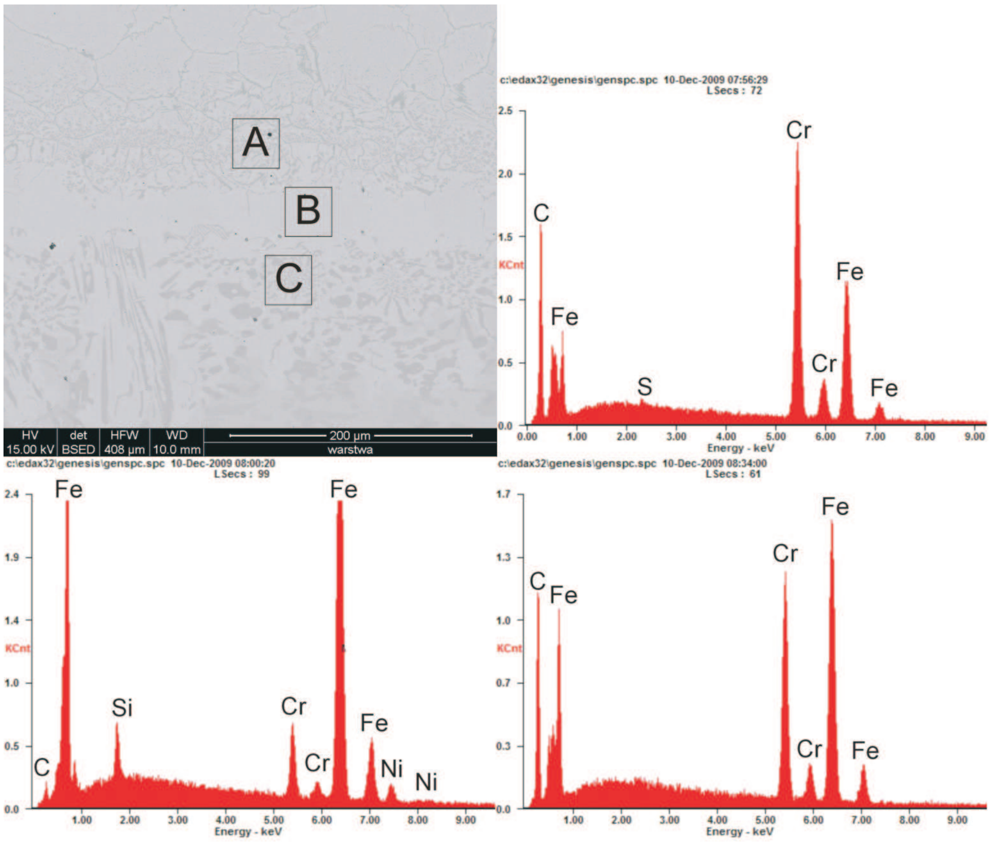

Fig. 8. Distribution of C, Fe, Si, Cr and Ni in transition zone between austenitic steel cast steel and low-alloy cast iron in bimetallic layer casting: a) structure of research area, b) pointwise microanalysis of chemical composition in point "A", c) pointwise microanalysis of chemical composition in point "B", d) pointwise microanalysis of chemical composition in point "C"

illustrated by the effects of etching metallographic specimens appear explicitly in those areas.

Another, distinct in structural terms is typical transition zone connecting the areas typical of steel on one side and iron on the other. Taking into account the complexity of the microstructure in this zone, the phase composition was based on the microanalysis of chemical composition (Fig. 8) and predicting the presence of components based on the analysis done in THERMOCALC. On this basis, the area marked 3 is characterized by a duplex microstructure consisting of austenite and ferrite.

High quality of both materials connection in this type of bimetallic casting provides the diffuse nature, which illustrates the phenomenon of penetration of strips of martensite formed in the impoverished in carbon cast iron layer (zone 4) in the transition zone (zone 3). Furthermore, it was found that depending on local concentrations of carbon and other elements, as well as local cooling rate in zone 4, in place of perlite martensite occurs (Fig. 9). However, this does not affect the reduction of connection quality in layered bimetallic casting.

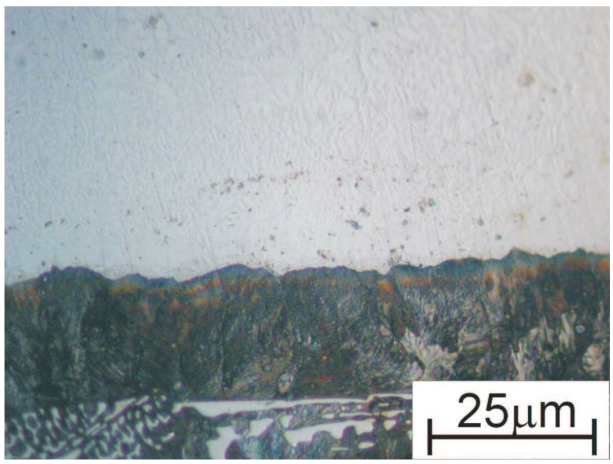

Fig. 9. Microstructure of joint zone in bimetallic layer casting in configuration: austenitic steel plate – low-alloy cast iron. In direction from surface is visible following: $\alpha + \gamma$, pearlite, ledeburite + pearlite – etching Mi19Fe

Then, in zone 5, as a result of high-speed solidification of molten metal at a concentration of carbon appropriate for iron, whitened area is composed of iron and chromium carbides (Fig. 10).

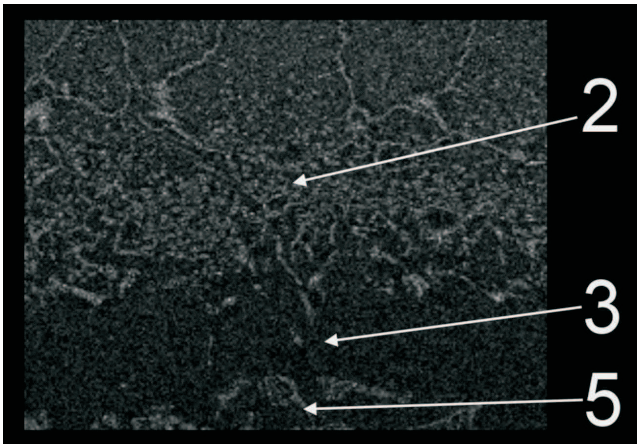

Fig. 10. Superficial distribution of Cr in transition zone between austenitic steel and low-alloy cast iron in bimetallic layer casting. Structure of research area from Fig.8a

Last Zone 6 consists of a typical structure for the iron that is poured into molds flake graphite in a pearlitic matrix.

4. Conclusion

Based on analysis of research results was found that:

1. Casting technology based on mould cavity preparation method allows to obtain a layered bimetallic casting in high chromium steel or chrome-nickel steel with gray iron configuration, free from defects especially in the sensitive area of a connection of both materials. Obtained permanent connection sheet steel with a cast iron is characterized with diffusion, which is determined primarily by diffusion of carbon in the direction from cast iron to steel.

2. Application of thin sheets 1.5 mm thick, resulting in their deformation during the casting, which disqualifies a casting for industrial applications. Much better results were obtained as a result of the application sheet with greater thickness, i.e. 5 mm.

3. Made of layered bimetallic casting can work in conditions demanding from the surface layer of high heat resistance and / or resistance to corrosion in environments such as industrial water. In addition, if the configuration with the austenitic steel is possible to obtain high resistance to abrasive wear.

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Received: 10 February 2010.