INFLUENCE OF TECHNOLOGICAL FACTORS ON FORMATION PROCESS OF BIMETALLIC CASTINGS

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Abstract. The analysis of the modern state of wear-resistant metallic material production showed that one of the promising directions for improving their quality is the use of bimetallic steel-cast iron castings, which have a complex of properties differentiated over the volume and surface of the products. However, the problem of obtaining a high-quality joint of the steel base and the working cast iron layers is not completely solved at present. So, the research aims to determine the quality criterion of a good diffusion joint and to study the selected technological factor influence on the formation process of bimetallic castings using the developed mathematical model. The paper examines the effect of the steel base temperature at liquid cast iron pouring over it, the temperature of pouring cast iron, as well as the ratio of liquid cast iron mass to the unit surface of the steel base on the contact surface temperature as selected quality criteria, and the structure of the transition diffusion layer of bimetallic castings. It was determined that a high-quality joint is realized when this temperature is larger than the solidus temperature of the cast iron. Moreover, the results of the mathematical model application showed maximum contribution of the liquid cast iron mass/steel unit surface ratio, less effect of the pouring iron temperature and minimum influence of the solidified steel base temperature onto the quality criteria. The metallographic analysis established the diffusion joint formation in the transition steel-cast iron layer consisting of pearlite on the side of the steel base and without the carbide matrix area on the side of the working iron layer. The results obtained are of great importance for the designing bimetallic machine parts worked under intensive wear conditions.

Keywords: steel, cast iron, temperature, transition layer, solidus, melt, solidification, contact surface.

Introduction

The problem of increasing wear resistance of materials and the technical resource of machine parts operating under intensive abrasive and shock-abrasive wear, reducing irreversible metal loss and the costs of alloyed alloys is continuously in focus [1]. The application of bimetallic castings with the differentiated properties over the volume and surfaces of the products is a promising way to solve this problem.

Such castings should have a plastic base, a strong highly wear-resistant working layer and a reliable diffusion connection between the base and the working layer to ensure long-term operation under conditions of shock-abrasive.

For the production of the working surface the complex alloyed white cast irons are most widely used with the following chemical composition [2-12] (wt.%): C = 1.6-3.4%; Si = 0.2-1.0%; Mn = 0.5-5.2%; Cr = 11.0-30.0%; Mo = 0.5-2.5%; S ≤ 0.08%; P ≤ 0.1%; Cu ≤ 1.5%; V ≤ 0.35%; Ti ≤ 0.35%. Such irons are characterized with high hardness and wear resistance but have low toughness [8; 9].

So, the base metal should possess high tensile and yield strength, toughness as well as structural strength to stand over failure under high dynamic loads. Thus, it is the most appropriate to use carbon and low-alloyed (up to 2-3% of alloying elements) chrome-manganese, chrome-molybdenum and other steels as the base metal material, which also have increased hardness and wear resistance.

The optimal chemical composition of such base steels was previously determined as: C = 0.22-0.50%; Si = 0.17-0.90%; Mn = 0.35-1.30%; Cr ≤ 3.0%; Mo ≤ 0.5%; V ≤ 0.15%; S ≤ 0.045%; P ≤ 0.04%; Ni ≤ 0.9%; Ti ≤ 0.09% [3; 5; 8; 13-16].

Among the production methods for bimetallic castings the most widely used is pouring liquid metal onto a solid base previously placed in a foundry mold [17].

Regardless of the method, a qualitative diffusion joint between the base and the working layer of bimetallic castings could be obtained when the directional solidification of the melt is realized from the layer toward the base surface and then to the riser. Moreover, the maximum temperature of the contacting layers should exceed the solidus temperature of cast iron that is the criterion for assessing the joint quality.

The main technological factors affecting the temperature of the contact surfaces are the temperature of the solidified steel base at cast iron pouring, the temperature of pouring liquid cast iron over the solidified base, as well as the ratio of the mass of liquid cast iron to the unit surface area of the steel base.

The paper aims to study the influence of the parameters above on the maximum temperature of the contact surface and the structure of the diffusion transition layers of bimetallic castings.

Materials and methods

Bimetallic castings with overall dimensions of 320x223x40 mm were obtained by successive pouring of a steel base and a cast iron working layer into a liquid glass casting mold (CO_2 process) through autonomous gating systems. The smelting of the original steels was carried out in an induction furnace of 160 kg with a basic lining. The cast iron was melted in a 60 kg induction furnace with acid lining. The chemical composition of the steels was varied by alloying and includes as follows (wt.%): 0.22-0.5 C; 0.2-0.9 Si; 0.2-0.9 Mn; 0.1-0.2 Cr; up to 0.1 V. The chemical composition of the cast iron was varied by alloying and includes as follows (wt.%): 2.4-3.4 C; 0.5-0.8 Si; 0.6-2.5 Mn; 13-21 Cr; 0.5-2.4 Mo. The chemical composition of the steels and cast iron was controlled using the SPAS-05 optical emission spectrometer.

After melting steel was poured into molds at 1550 ºC and cast iron was poured at a temperature (t_{cip}) from 1420 to 1530 ºC after steel base solidification. The mass of liquid cast iron was chosen so that its ratio to the unit surface area of the workpieces (G_{lci}/F_{sb}) was from 6.5 to 82.0 g·cm^{-2}. The heating temperature of the steel base (t_{sb}) at cast iron pouring and the change in the temperature of the contact surface (t_{cs}) during cooling after pouring cast iron were determined with Pt-PtRh (PPR 6/30) thermocouples and four-channel analog input modules WAD-AIK-BUS through the RS-485 interface. The recording of temperatures on the computer was made with the help of an interface converter with galvanic isolation WAD-RS 232/RS 485-BUS. Thermocouples were installed in the contact zone of the alloys of bimetallic pairs and in the working layer at a distance of 10 mm from the outer surface of the casting.

The microstructure was studied on samples with dimensions of 20x20x10 mm that were cut from the experimental bimetallic castings using a MIM-10 optical microscope. The structural components were identified by chemical etching of samples in an alcohol solution with a mass fraction of nitric acid of 2-4%. After etching, the samples were washed in alcohol.

Multiple correlation analysis was carried out according to the methodology in [18].

Results and discussion

The chemical composition of the steel base and the working layer, the solidus temperature of cast iron (t_{sci}), cast iron pouring (t_{cip}), the steel base at cast iron pouring (t_{sb}), the ratio of the mass of liquid cast iron to the unit surface area of the base (G_{lci}/F_{sb}), the maximum temperature of the contact surface (t_{cs}), as well as its change during heating and cooling of the bimetallic casting are shown in Table 1 and Fig. 1.

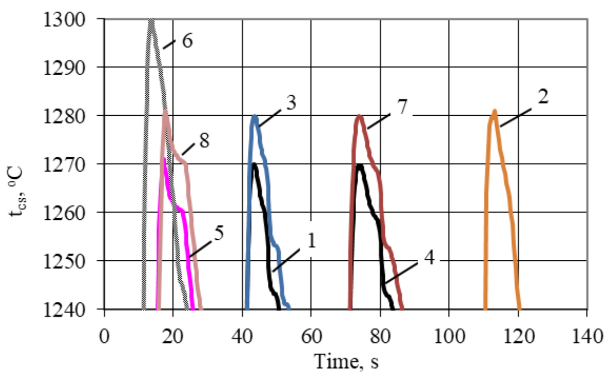

Fig. 1. **Temperature changing of the contact surface of bimetallic castings during heating and cooling after cast iron pouring on a solidified steel base**

The numbers of the curves in Fig 1. are corresponding to the casting numbers are given in Table 1.

Table 1

Chemical composition of the steel base and the working layer, the solidus temperature of cast iron (t_{sci}), cast iron pouring (t_{cip}), the steel base at the cast iron pouring (t_{sb}), the ratio of the mass of liquid cast iron to the unit surface area of the base (G_{lci}/F_{sb}) and the maximum temperature of the contact surface (t_{cs})

No	Part of casting	C	Si	Mn	Cr	V	Mo	t_{sci}	t_{cip}	t_{sb}	G_{lci}/F_{sb}	t_{cs}
		wt.%						°C			g·cm^{-2}	°C
1	Base	0.42	0.20	0.40	0.1	0.10	-	-	1480	1000	6.5	1270
	Working layer	2.40	0.50	1.50	13.0	-	0.5	1132				
2	base	0.50	0.52	0.90	0.2	0.08	-	-	1515	1090	6.5	1281
	Working layer	3.40	0.70	2.50	19.0	-	2.0	1268				
3	base	0.22	0.20	0.35	0.1	-	-	-	1510	1100	15	1280
	Working layer	2.60	0.70	1.70	14.0	-	0.7	1195				
4	base	0.30	0.52	0.90	0.2	-	-	-	1420	980	13.5	1269
	Working layer	2.90	0.90	1.90	16.0	-	0.9	1266				
5	base	0.28	0.36	0.65	0.14	-	-	-	1450	1070	17	1271
	Working layer	3.10	0.60	2.10	17.0	-	1.5	1213				
6	base	0.22	0.35	0.20	0.1	-	-	-	1490	1100	82	1300
	Working layer	2.80	0.60	0.60	19.0	-	1.8	1213				
7	base	0.30	0.90	0.52	0.1	-	-	-	1520	1050	24.5	1280
	Working layer	3.00	0.73	0.80	21.0	-	2.4	1275				
8	base	0.26	0.62	0.36	0.1	-	-	-	1530	1070	12	1281
	Working layer	2.90	0.80	0.70	20.0	-	2.2	1279				

The data given in Table 1 show that the maximum temperature of the contact surface of bimetallic castings is higher than the solidus temperature of cast iron. This indicates that the conditions for the formation of a high-quality diffusion connection between the base and the working layer of bimetallic castings were observed during the experiments.

Multiple correlation analysis showed that such technological factors as the temperature of the solidified steel base (t_{sb}) at cast iron pouring, the temperature of pouring liquid cast iron (t_{cip}) onto the solidified base, as well as the ratio of the mass of liquid cast iron to the unit surface area of the steel base (G_{lci}/F_{sb}) affect the maximum temperature of the contact surface (t_{cs}) as follows:

$$t_{cs} = 1102 + 0.097 \cdot t_{cip} + 0.025 \cdot t_{sb} + 0.324 \cdot G_{lci}/F_{sb}, \quad (1)$$

$$R = 0.973; \ \delta = 0.14\%$$

where R – multiple correlation coefficient;

δ – relative approximation error, %.

The results of calculations, according to formula 1, of the technological factor influence on the change of the maximum temperature of the contact surface at their minimum (line 1), average (line 2) and maximum (line 3) values are shown in Fig. 2.

The graphs show that an increase, within the studied limits, of the temperature of the solidified steel base at cast iron pouring (Fig. 2a) leads to an increase of the maximum temperature of the contact surface (t_{cs}) from 1265 to 1268 °C at the minimum values of technological factors (line 1, Fig. 2a) and up to 1301-1303 °C at their maximum values (line 3, Fig. 2a).

The effect of the pouring temperature of liquid iron on the solidified base is more significant. With its increase there is an increase of the contact surface temperature (t_{cs}) from 1265 to 1277 °C at the minimum values of technological factors (line 1, Fig. 2b) and up to 1292–1303 °C at their maximum values (line 3, Fig. 2b).

An increase of the ratio of the mass of liquid iron to a unit area of the steel base surface leads to an increase of the temperature of the contact surface (t_{cs}) from 1265 to 1289 °C at the minimum values of technological factors (line 1, Fig. 2c) and up to 1279 - 1303 °C at their maximum values (line 3, Fig. 2c).

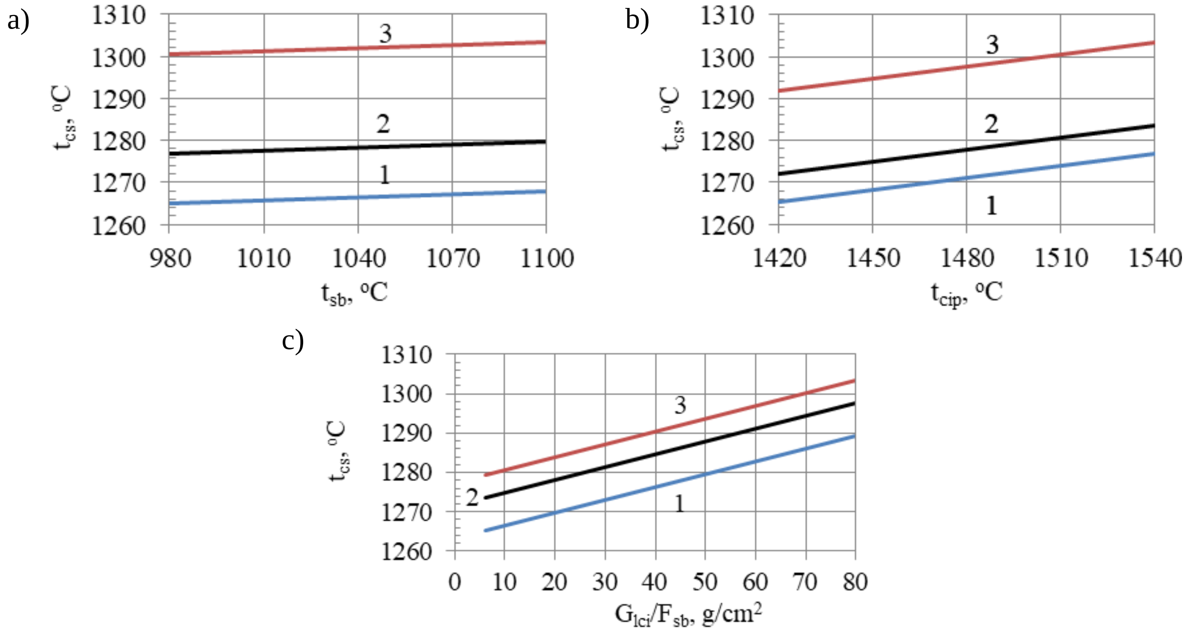

Fig. 2. **Influence of the temperature of the solidified steel base at pouring cast iron (a), the temperature of cast iron pouring onto the solidified base (b) and ratio of the cast iron mass to unit of the surface area of the steel base (c) on the maximum temperature of the contact surface (t_{cs})**

In Figure 2:

a) line 1 – t_{cip} = 1420 ºC; G_{lci}/F_{sb} = 6 g·cm^{-2}; line 2 – t_{cip} = 1490 ºC; G_{lci}/F_{sb} = 22 g·cm^{-2}; line 3 – t_{cip} = 1540 ºC; G_{lci}/F_{sb} = 80 g·cm^{-2};

b) line 1 – t_{sb} = 1000 ºC; G_{lci}/F_{sb} = 6 g·cm^{-2}; line 2 – t_{sb} = 1060 ºC; G_{lci}/F_{sb} = 22 g·cm^{-2}; line 3 – t_{sb} = 1100 ºC; G_{lci}/F_{sb} = 80 g·cm^{-2};

c) line 1 – t_{sb} = 1000 ºC; t_{cip} = 1420 ºC; line 2 – t_{sb} = 1060 ºC; t_{cip} = 1490 ºC; line 3 – t_{sb} = 1100 ºC; t_{cip} = 1540 ºC

Evaluation, according to the Student's criterion (t_{St}) [18], of the effectiveness of the influence of the technological factors on the maximum temperature of the contact surface showed that the ratio of the mass of liquid iron to the unit surface area of the steel base (t_{St} = 6.12) has the greatest effect, the effect of pouring temperature of liquid iron on the solidified base is less significant (t_{St} = 2.38) and the temperature of the steel solidified base at pouring iron (t_{St} = 0.66) has a minimal effect, which is of 67%, 26% and 7%, respectively.

Metallographic analysis showed that at realizing $t_{cs} > t_{sci}$ condition a good diffusion joint is formed between the steel base and the cast iron working layer. The study of the microstructure of the transition layers of bimetallic castings in the as-cast state with the minimum (No. 4, Table 1) and maximum temperature of the contact surface (No. 6, Table 1) showed the following.

The microstructure of the transition zone on the side of the base of bimetallic casting No. 4 (Fig. 3 a) has a pearlite structure with a distance between cementite plates of up to 0.8 µm. The thickness of this zone is 180-240 µm, and the grain size is about 60 µm. The pearlite structure changes to a ferrite-pearlite with a grain size of 31-41 mm at moving to the base metal. On the other hand, the transition zone is in contact with the carbide-free zone of the working layer. The thickness of the zone is in the range of 20-60 µm. The cast iron working layer is characterized by a dendritic structure. In the interaxial spaces of the dendrites, lamellar 20-30 µm long and smaller (up to 10 µm) carbide particles of Me_7C_3 type are located.

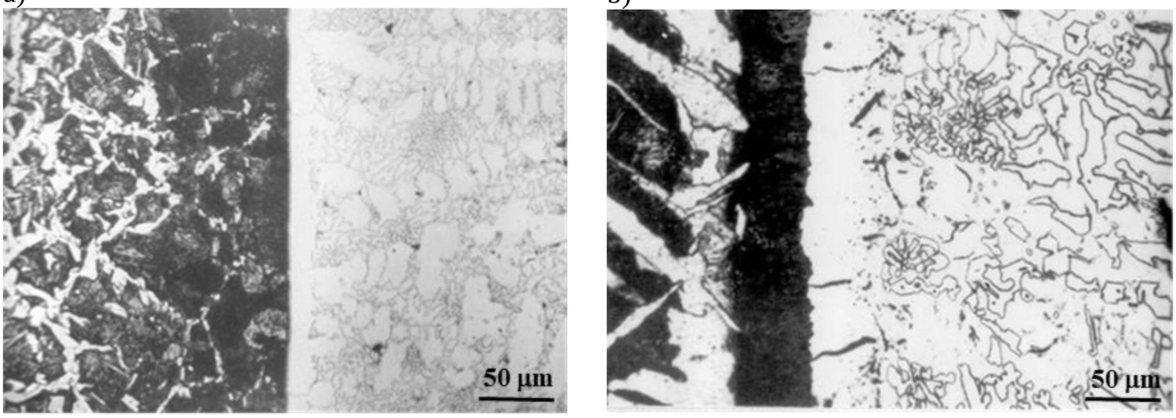

Fig. 3. **Microstructure of the transition layers in bimetallic castings No 4 (a) and No 6 (b)**

Metallographic studies of the transition zone of bimetallic casting No. 6 (Fig. 3 b) showed that the upper layer of the steel base is chromic pearlite with a carbon content of 0.8% on the steel side, the distance between cementite plates is up to 0.3 μm and up to 1.2 μm from the cast iron side (distance between cementite plates is from 0.3 to 0.5 microns).

Between the pearlite band and the cast iron, there is a layer of metal that has a structure of chromic ferrite and dispersed carbides, which precipitated along the pearlite zone both along the boundaries of the ferrite grains and inside them. Behind the pearlite band is a narrow band of steel decarburized to ferrite that transforms into the carburized zone having a Widmannstätt structure with a ferrite to pearlite ratio of 50:50. A less carbonized layer of steel is located next. Widmannstätt occurs in the form of small areas. A steel base is located behind the carburizing zone. The microstructure of cast iron consists of a ferrite matrix, ledeburite eutectic, and carbides of the $(Cr, Mo, Fe)_7C_3$ type, which are located along the boundaries of primary grains and between dendritic areas.

Summarizing the presented results, the improvement could be stated of the method of pouring the melt of the working layer on a pre-poured and solidified steel base [17]. The targeted control of the studied technological factors results in the formation of high-quality bimetallic castings that are technologically advanced in manufacturing, for example, bimetallic castings made by high-temperature synthesis [19]. It can also be stated that the results of modeling the influence of such technological factors as the temperature of the solidified steel base at pouring of cast iron and the temperature of pouring liquid iron onto the solidified base, as well as the ratio of the mass of liquid iron to the unit surface area of the steel base on the maximum temperature of the contact surface are quite close to the experimental results. It allows further research using a larger number of technological factors.

Conclusions

1. It was established that the selected technological factors such as the temperature of the solidified steel base at cast iron pouring, the temperature of pouring liquid cast iron onto the solidified steel base, as well as the ratio of the mass of liquid cast iron to the unit surface area of the steel base influence significantly the process of bimetallic castings formation.
2. A high-quality connection between layers is found to be realized when the maximum temperature of the contact surface exceeds the solidus temperature of the cast iron of the working layer. It was determined that with an increase of the temperature of the solidified steel base at pouring cast iron, the temperature of pouring liquid cast iron onto the solidified steel base, as well as the ratio of the mass of liquid cast iron to the unit surface area of the steel base, the maximum temperature of the contact surface of bimetallic castings increases.
3. The mathematical model developed confirmed that the ratio of the mass of liquid cast iron to the unit surface area of the steel base has the greatest effect, the temperature of pouring liquid cast iron on the solidified base has a less significant effect, and the temperature of the solidified steel base at casting cast iron reveals the minimum influence.

4. The metallographic analysis has shown the creation of bimetallic castings by pouring liquid cast iron onto a solidified steel base with the diffusion joint through the formation the transition layer consisting of pearlite on the side of the steel base and without the carbide matrix area on the side of the working layer.

The results obtained are of great importance for the designing bimetallic machine parts worked under intensive wear conditions.

Author contributions

Conceptualization, Y.A.; methodology, Y.A. and S.G.; experimentation, S.G. and H.M.; results analysing, Y.A., S.G., H.M. and V.K.; formal analysis, Y.A. and S.G.; writing – original draft preparation, Y.A. and S.G.; writing – review and editing, S.G., H.M. and V.K. All authors have read and agreed to the published version of the manuscript.

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