DISTRIBUTION OF CHROMIUM IN TRANSITION LAYER OF BIMETALLIC CASTINGS

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Abstract. The constantly increasing requirements for machine components and mechanisms operating under conditions of impact and abrasive wear determine promising use of bimetallic cast parts. Their quality significantly depends on both the technological factors of manufacture and the properties of the transition layer between the base and the working layer. The aim of the work was to study the influence of the casting mass, the ratio of the mass of the steel base and the working layer of cast iron and the difference in the chromium content in the layers, the pouring temperature of steel and cast iron on the quality of the casting. Research was carried out on bimetallic castings of steel 25L – cast iron 300Kh12G5 and steel 70GL – cast iron ChKh22. The mathematical model of the influence of selected parameters on the width of the chromium transition zone from cast iron to steel and the average rate of chromium concentration change in the transition layer was developed. It was established that the most effective influence on this zone and the rate of chromium change is exerted by the mass and temperature of the steel base, the contribution of which is 67.7% and 60.2%, respectively. It was shown that the width of this zone decreases with increasing difference in the chromium content in the matrix of the working layer and the base and expands with increasing the pouring temperature and mass of steel and cast iron. It was determined that increasing the pouring temperature and the mass of the steel base and the working layer leads to a decrease and the chromium content in the matrix of the working layer and the base to an increase in the average rate of the change of the chromium concentration in the transition layer. These data are useful for optimizing the technology of obtaining high-quality bimetallic castings.

Keywords: steel, cast iron, temperature, transition layer, pouring, distribution, chromium, diffusion.

Introduction

At manufacturing bimetallic castings the influence of the temperature of the solidified steel base and cast iron at its pouring over the solidified base, the ratio of the mass of liquid cast iron to the specific area of the steel base surface and the composition of the flux were studied [1; 2]. Another factor that significantly influences the quality of the diffusion bond between the steel base and the cast iron working layer of bimetallic castings is the distribution of elements in the transition layer between steel and cast iron. Chromium has the most effective influence on the quality of the transition layer among elements such as carbon, silicon, manganese and chromium, which diffuse from cast iron into steel [3].

The distribution of the concentration of the diffusing element in the material is determined by the time (τ) and the diffusion coefficient (D) according to the following relationship

$$x = \sqrt{D \cdot \tau}\ , \tag{1}$$

where x – distance, over which an element with a diffusion coefficient D diffuses in time τ.

The diffusion coefficient (D) depends on the physical and chemical properties of the metal and the diffusing elements, characterizes the rate of diffusion and increases exponentially with increasing the metal temperature, according to the Arrhenius law.

$$D = D_0 \exp(-E / RT)\ , \tag{2}$$

where D_0 – pre-exponential factor;
E – activation energy, which are associated with the physical and chemical properties of the metal;
R – gas constant;
T – absolute temperature.

The casting accumulated heat during pouring the base and the working layer. The heat of a body (Q) depends on its mass (m) and temperature (t), as well as the heat capacity of the material (c) according to the following relationship [5]:

$$Q = m \cdot c \cdot \Delta t, \tag{3}$$

where Δt – temperature changing.

Equation (3) shows that with a change of the casting heat as a result of a change in the mass of the base or working layer, the temperature of the transition layer will be changed, causing the changes of the diffusion coefficients of the elements and their distribution in the transition layer.

During the pouring process of the working layer onto the solidified steel base, stress fields arise over the contact surface as a result of uneven heating and phase transformations, non-uniform distribution of elements and shrinkage. In the case of different atomic radii of the diffusing elements and iron, microscopic deformations and stresses arise around them. The stress field around a diffusing atom in a solid solution promotes attraction of the atom to dislocation. In this case, the flow of the matter will be the sum of the flows arising under the action of the concentration gradient and the field of non-uniform stresses (deformations). As a result, it may turn out that the total diffusion flow will be directed towards not a lower, but a higher concentration, and the case of ascending diffusion will be realized [4].

At present there is no information about the influence of such process parameters as the difference in the chromium content in the matrix of the working layer and the base, the mass of the casting, the base and the working layer, the temperature of pouring steel and cast iron, as well as the time interval in which the casting is in the temperature range of intensive diffusion of elements on the average width of the transition layer, where the chromium content changes between the base and the working layer, and the rate of such change. So, the paper aims to study the influence of the parameters above.

Materials and methods

Research was carried out on bimetallic castings of steel 25L – cast iron 300Kh12G5 and steel 70GL – cast iron ChKh22, the chemical compositions of which are given in Table 1.

Table 1

Chemical composition of alloys of bimetallic castings

No	Parts of casting	C	Si	Mn	Cr	V	Ti	S	P
		wt.%							
1	Base (steel 25L)	0.26	0.36	0.63	0.29	-	-	0.040	0.035
	Work layer (cast iron 300Kh12G5)	2.80	0.70	4.85	14.5	-	-	0.050	0.080
2	Base (steel 70GL)	0.73	0.35	1.35	0.20	-	-	0.042	0.040
	Work layer (cast iron ChKh22)	3.00	0.60	2.00	22.0	0.25	0.20	0.070	0.075

The experimental bimetallic castings with overall dimensions of 160x100x40 mm, 120x100x40 mm, 80x100x40 mm and 40x100x40 mm were obtained by sequential pouring of layers into a liquid glass casting mold (CO_2 process) through autonomous gating systems. The thickness of the poured layers was regulated using level markers so that the ratio of the masses of the base alloys and the working layer of the bimetallic casting was of 1:1, 1:3 and 3:1. The alloys were smelted in IST-0.16/0.25-I1 induction melting furnaces.

The heating and cooling temperatures of the bimetallic castings were determined using PPR 6/30 platinum-platinum-rhodium thermocouples and WAD-AIK-BUS four-channel analog input modules via the RS-485 interface with channel-by-channel galvanic isolation. The temperatures were recorded in computer using the WAD-RS 232/RS 485-BUS interface converter with galvanic isolation. The basic error reduced to the converter range is 0.3% for thermocouples and 0.1% for voltages. The thermocouples were installed in the contact zone of the alloys of bimetallic pairs at a distance of 10 mm from the outer surface of the casting. The temperatures were recorded from the moment of pouring the working layer until the transition layer reached of 700 °C, assuming that the main diffusion of elements occurs in this temperature range. The microstructure was studied on 20x20x10 mm samples cut from experimental bimetallic castings using a MIM-10 optical microscope. Structural components were revealed by the chemical etching of the samples in an alcohol solution with a mass fraction of nitric acid of 2-4%. After etching, the samples were washed in water or alcohol. The local chemical composition, redistribution of chromium in the transition zone of contact and diffusion interaction of the steel base and the cast iron working layer were studied using a REMMA-102 and JEOL JSM-35CF electron microscope and INCA Energy 350 (Oxford Instruments) energy dispersion analyzer.

The sample numbers, characteristics of the experimental bimetallic castings and the parameters of their production are presented in Table 2.

Table 2

Sample numbers, weight and pouring temperature (t_p, °C) of castings

No	Parts of casting	Weight, kg			t_p, °C		No	Part of casting	Weight, kg			t_p, °C	
		casting	base	work layer	steel	cast iron			casting	base	work layer	steel	cast iron
3	1	2.43	1.23	1.20	1653	1386	26	2	3.64	1.84	1.80	1590	1414
4		1.22	0.62	0.60	1653	1386	27		2.43	1.23	1.20	1590	1414
7		2.47	0.62	1.85	1611	1409	30		3.69	0.92	2.77	1571	1419
8		1.22	0.30	0.92	1611	1409	31		2.47	0.62	1.85	1571	1419
11		2.47	1.85	0.62	1615	1424	32		1.22	0.30	0.92	1571	1419
12		1.22	0.92	0.30	1615	1424	33		4.93	3.70	1.23	1580	1429
							34		3.69	2.77	0.92	1580	1429
							35		2.47	1.85	0.62	1580	1429

Multiple correlation analysis was carried out according to the methodology in [6]

Results and discussion

The results of determining the change in the temperature of the contact transition zone during the process of pouring the working layer and cooling the bimetallic castings are shown in Fig. 1. The numbers of the curves in Fig 1 correspond to the casting numbers given in Table 2.

a)

b)

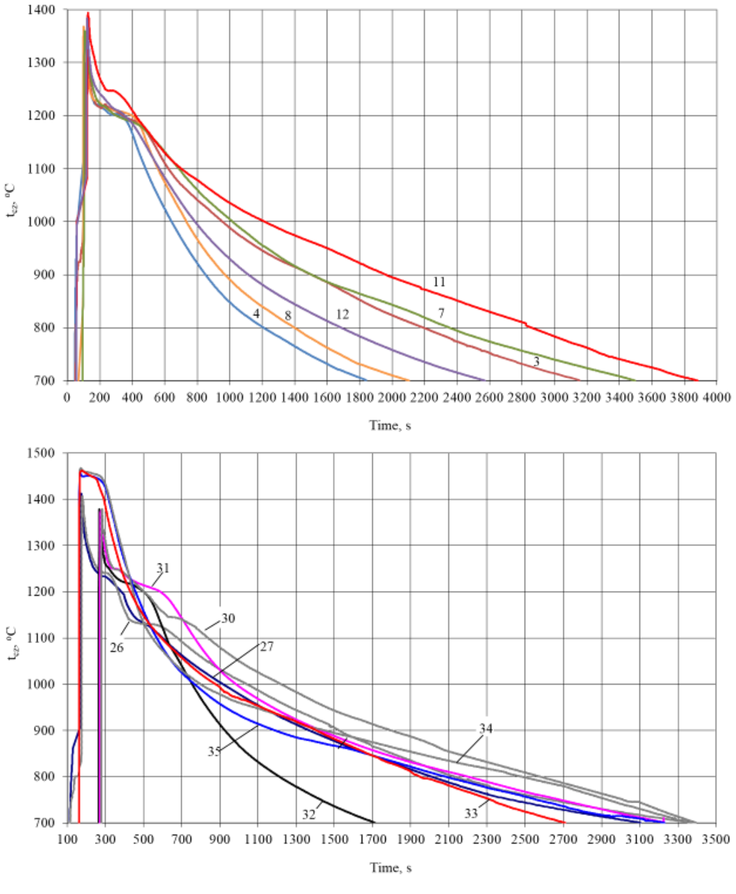

Fig. 1. **Temperature changing of the contact transition zone during the pouring process of the cast iron 300Kh12G5 (a) and ChKh22 (b) working layer on the steel base of steel 25L (a) and 70GL (b) and cooling of bimetallic castings**

From Fig. 1 it is evident that, depending on the manufacturing conditions, the time of chromium diffusion from the working layer to the base of the bimetallic casting from the moment of pouring to 700 °C varies from 1713 to 3883 seconds, i.e. by 2.3 times, which predetermines the formation of a transition zone of the chromium concentration from the working layer to the base of various widths.

During the formation of the cast iron working layer, carbides are released and, depending on the technological parameters of production, the chromium content in carbides varies from 24.14 to 45.10 wt.%, and in solid solution – from 7.35 to 11.12 wt.% (Table 3).

Table 3

Average content of chromium in solid solution (Cr_{ss}) and carbides (Cr_c) of the cast iron working layer of bimetallic castings

Casting number	3	4	7	8	11	12	26	27	30	31	32	33	34
Cr_{ss}	8.9	9.0	10.6	7.4	9.6	10.4	9.9	10.3	11.0	9.7	11.1	10.7	10.0
Cr_c	29.7	45.0	34.9	24.1	37.2	27.3	45.1	30.8	27.9	42.9	29.9	26.6	37.7

Distribution of chromium in the contact transition zone is shown in Fig. 2. The numbers of the curves in Fig 2 correspond to the casting numbers given in Table 2.

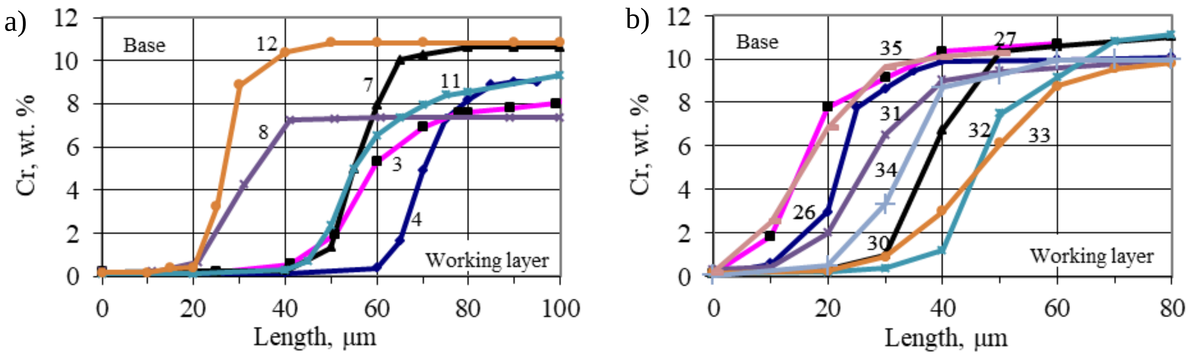

Fig. 2. **Distribution of chromium in the contact transition zone after pouring cast iron 300Kh12G5 (a) and ChKh22 (b) working layer on a steel base of steel 25L (a) and 70GL (b) and cooling of bimetallic castings**

Taking as independent factors such technological parameters as the difference in the chromium content in the matrix of the working layer and the base ($Cr_{mwl\text{-}b}$, wt.%), the mass of the casting (m_c, kg), the base (m_b, kg) and the working layer (m_{wl}, kg), the pouring temperature of steel (t_{steel}, °C) and cast iron (t_{ci}, °C), as well as the time of casting at the temperature above 700 °C (τ_{c700}, s) determined the effectiveness of their influence on the average width of the transition layer in which the chromium content changes between the base and the working layer (B_{Cr}, µm).

Multiple correlation analysis showed that the technological factors, with a probability of 95%, influence the average width of the transition layer in which the chromium content changes between the base and the working layer as follows:

$$B_{Cr} = 1435.4 - 9.515 \cdot Cr_{mwl-b} - 1325 \cdot m_b - 0.832 \cdot t_{\mathrm{steel}} + 0.8443 \cdot m_b \cdot t_{\mathrm{steel}} + 0.009 \cdot m_{wl} \cdot t_{\mathrm{ci}}, \qquad (4)$$

$$R = 0.973; \ \delta = 5.1\%.$$

where R – multiple correlation coefficient;
δ – relative approximation error, %.

Assessment of the effectiveness of the influence of the factors of equation 4, according to the Student's criterion (t_{St}) [6] showed that the parameters related to the mass ($t_{St(mb)} = -7.6$) and the pouring temperature ($t_{St(tsteel)} = 6.3$) of the base ($t_{St(mb \cdot tsteel)} = 7.7$) have 67.7% influence on the change in the average width of the transition layer of chromium. The influence of the difference in the chromium content in the matrix of the working layer and the base ($t_{St(Crmwl\text{-}b)} = -5.1$), as well as the mass and temperature of pouring the working layer ($t_{St(mwl \cdot tci)} = 5.2$) is, respectively, 16.1 and 16.2%.

Using the average value of the studied parameters as a basis, formula 5 estimated the influence of the technological factors on the average width of the transition layer of chromium. The results of the calculations are shown in Fig. 3 (a, b). The data show that with an increase in the difference in the chromium content in the matrix of the working layer and the base from 7 to 11% Cr, the width of the zone decreases from 88.6 to 50.5 μm, that is, by 43%. When the steel casting temperature increases from 1570 to 1650 °C, the transition zone expands from 54.2 to 78.2 μm, that is, by 44%. An increase in the casting temperature of cast iron from 1380 to 1430 °C practically does not affect the size of the transition zone, since its size increases by 1%.

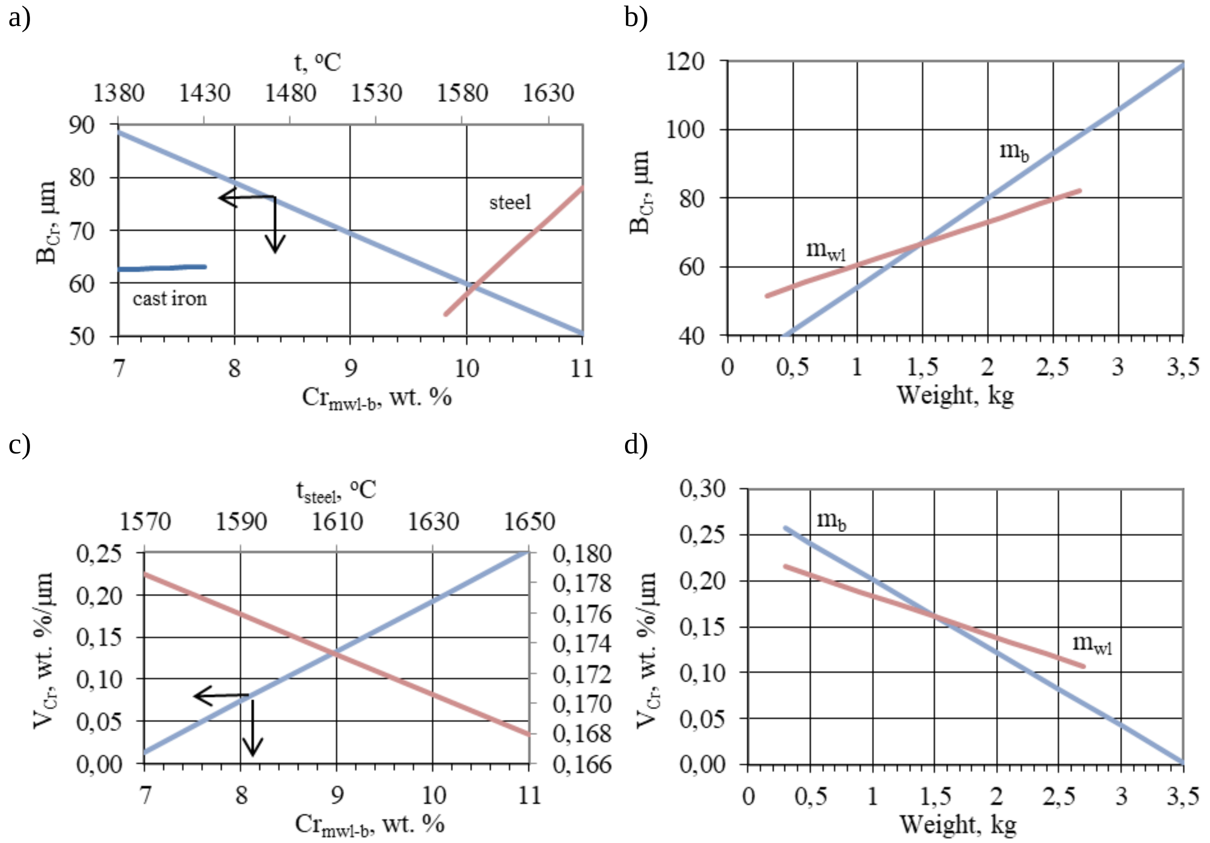

Fig. 3. **Influence of difference in the chromium content in the matrix of the working layer and the base (Cr_{mwl-b}, wt.%) (a, c), pouring temperature of steel (t_{steel}, °C) and cast iron (t_{ci}, °C) (a, c), mass of the base (m_b, kg) (b, d) and working layer (m_{wl}, kg) (b, d) on the average width of the chromium transition layer (a,b) and the rate of chromium concentration changing in the transition layer (c,d). Base parameters: Cr_{mwl-b} = 9.69 kg; m_b = 1.34 kg; m_{wl} = 1.2 kg; t_{steel} = 1599 °C; t_{ci} = 1415 °C**

The influence of the mass of cast iron is more significant, since when it increases from 0.3 to 2.7 kg, the transition zone expands from 51.6 to 82.0 μm, that is, by 59% (Fig. 3 b). The mass of the steel base has a more effective effect. Calculations show that when it increases from 0.3 to 3.5 kg, the transition zone increases from 36.2 to 118.6 μm, that is, by 3.3 times (Fig. 3 b).

From the graphs shown in Fig. 3 c it is evident that an increase in the temperature of the steel base pouring from 1570 to 1650 °C leads to a decrease in the average rate of change of the chromium concentration in the transition layer from 0.179 to 0.168% μm^{-1}, i.e. by 6%. The influence of the difference in the chromium content in the matrix of the working layer and the base (Cr_{mwl-b}, wt.%) is more significant. When it increases from 7 to 11% chromium, an increase in the average rate of change in the chromium concentration in the transition layer is observed from 0.0132 to 0.253% μm^{-1}, i.e. 19 times.

Analysis of the influence of the base and working layer masses (Fig. 3 d) shows that with their increase, respectively, from 0.3 to 3.5 kg and from 0.3 to 2.7 kg, the average rate of the change in the chromium concentration in the transition layer decreases from 0.257 to 0.003% μm^{-1} and from 0.215 to 0.107% μm^{-1}, i.e. by 88 and 2 times, respectively.

Summarizing the presented results, it can be stated that by targeted changes in such technological factors as the mass and temperature of pouring the steel base, the difference in the chromium content in the matrix of the working layer and the base, the mass and temperature of pouring the working layer, it is possible to control the size of the chromium transition zone from cast iron to steel and the average rate of the change in the chromium concentration in the transition layer. In this case, the factors that have the most expressed effect are the mass and temperature of pouring the base.

Conclusions

It was established that the size of the chromium transition zone from cast iron to steel in the transition layer is affected by such technological factors of bimetallic castings production as the mass and the pouring temperature of the steel base, the difference in the chromium content in the matrix of the working layer and the base, the mass and the pouring temperature of the working layer.

It was shown that the width of the chromium transition zone decreases with an increase in the difference in the chromium content in the matrix of the working layer and the base and expands with an increase in the pouring temperature and the mass of steel and cast iron.

It was established that an increase in the pouring temperature and the mass of the steel base and the working layer leads to a decrease of the chromium content in the matrix of the working layer.

The mathematical model of the influence of the mass and the pouring temperature of the steel base and the working layer, as well as the difference in the chromium content in the matrix of the working layer and the base on the size of the chromium transition zone from cast iron to steel has been developed.

Analysis of the mathematical model has established that the most effective influence on the width of the chromium transition layer is exerted by the mass and temperature of the steel base, the contribution of which is 67.7% and 60.2%, respectively.

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., 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., V.K. All authors have read and agreed to the published version of the manuscript.

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