



Designing of X46Cr13 Steel Heat Treatment in Condition of Casting Mould

N. Przyszlak^{a,*} , G. Piwowarski^b 

^a Department of Engineering Processes Automation and Integrated Manufacturing Systems, Faculty of Mechanical Engineering, Silesian University of Technology, Konarskiego 18A St., 44-100 Gliwice, Poland

^b AGH University of Science and Technology, Faculty of Foundry Engineering, Department of Engineering of Foundry Processes, 23 Reymonta St., 30-059 Krakow, Poland

* Corresponding author. E-mail address: natalia.przyszlak@polsl.pl

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Abstract

The paper presents issues related to the technology of layered castings manufactured in the system: working part made of high-chromium steel X46Cr13 - base part made of gray cast iron with flake graphite, using the mould cavity preparation technology. Considering the high hardenability of the above-mentioned steel grade, the aim of the research was to optimize the casting parameters of gray cast iron in such a way that it would be possible to perform heat treatment of X46Cr13 steel directly in the casting mould. As part of the research, the geometry of the working and base parts of layered castings was selected, and guidelines for mould technology from the point of view of the moulding sand were developed. In order to control the cooling rate, three matrix of the moulding sand were used - quartz sand, chromite sand and silicon carbide, with the same granularity. The thermal conductivity coefficient of sands made on selected matrix, bound with synthetic resin in the ratio of 30:1, was experimentally determined. Then, the bimetal casting process in a given mass was simulated in the MagmaSoft® (ver. 5.4.1). The purpose of the simulation was to determine the maximum virtual temperature T_m in the thermal center of the outer surface of the X46Cr13 steel insert. From the point of view of the research purpose, the insert was expected to heat up to the austenitization temperature, i.e. at least 950°C.

Keywords: Layered casting, Bimetal, High – chromium steel, Grey cast iron

1. Introduction

Alloy steels, including corrosion-resistant steels, are materials with high mechanical and corrosive properties, and numerous scientific publications indicate that cast bimetals were effectively produced, where the above-mentioned they were constantly constituted the working part, and for the base part, for example, grey cast iron with flake graphite was selected [1-8]. In case of layered castings where steel fulfils a role of the working part of the system, it is worth optimizing the process of their production in such a way that the working layer (made of steel) has the highest possible mechanical properties. In the assumption, if choose a steel

grade that shows high hardenability and properly select casting parameters, e.g. grey cast iron, it will be possible to carry out heat treatment operations such as hardening the steel in the conditions of the casting mould, i.e. integrated with the layered casting production process, and thus an increase in its mechanical properties would be obtained [9-10]. Such a procedure seems to meet the expectations of the modern manufacturing market, focused on saving time and money.

While the hardening of steel carried out under conventional conditions is a well-known and relatively easy operation, its execution directly in the casting mould seems to be more complicated. The occurrence of martensitic transformation requires



heating the steel to the austenitizing temperature T_γ and rapid cooling [9]. If such treatment is carried out in a casting mould, then the selection of casting parameters should be a compromise between the possibility of heating the steel to T_γ and the creation of thermo-kinetic conditions conducive to rapid cooling of the system.

Therefore, the aim of the research was to determine the influence of variable factors of grey cast iron casting (base part of layered casting) on the effectiveness of the hardening process of the X46Cr13 steel insert (working part of layered casting) under the conditions of the casting mould.

2. Experimental procedure

The concept of the measuring stand was developed to determine the possibility of integration of heat treatment of X46Cr13 steel grade with manufacturing of layered casting. It was assumed that the insert (working part), with dimensions 50x50x5 mm was to be placed in the mould cavity just before pouring by the molten grey cast iron (base part) (Fig.1a). Chemical composition of the steel and gray cast iron used, carried out using an optical emission spectrometer with glow excitation LECO GDS 500A are presented in Table 1 and 2.

It was decided that the length and width of the castings would have a fixed dimension of 50x50 mm. The thickness of the working part made of X46Cr13 high-chromium steel was also unchanged. It has been used in this regard made of commonly used and

commercially available steel with a thickness of 5 mm. The castings, however, differed in the thickness of the base part. Based on the literature analysis, it was found that for analogous material configurations, the minimum volume ratio of the base part to the working part should be 8:1 [2,3,5,11-12], as it is a guarantee of obtaining a layered casting with good quality connection of the base part with a working part.

Cooling rate was regulated by application of different matrix of moulding sand: quartz sand (SiO_2), chromite sand (FeCr_2O_4) and silicon carbide (SiC). The final thickness of the base part was selected based on the results of solidification simulations of model layer castings carried out using the MagmaSoft® (ver. 5.4.1). The MagmaSoft® (ver. 5.4.1) was also used to verify whether, with the assumed casting parameters (pouring temperature T_p , cooling rate resulting from the use of different materials for the matrix of the moulding sand λ and the thickness of the base part g), the X46Cr13 steel insert would heat up to the austenitization temperature. Thermoelements were placed in the middle of the outer surface of the steel insert (Fig.1b). The ratio of the thickness of the base part to the working part was assumed as follow: 1:1, 2:1, 4:1, 8:1, 10:1 and 12:1, which in the case of using an insert with a constant thickness of 5 mm translated into the height of the base part, respectively: 5, 10, 20, 40, 50 and 60 mm.

For the purposes of designing the heat treatment, the results of the analysis obtained by means of the computer program for predicting the phase composition ThermoCalc were also used.

Table 1.

Chemical composition of X46Cr13, 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 2.

Chemical composition of grey cast iron with flake graphite EN-GJL-HB 255, wt. %

C	Mn	Si	Cr	Ni	Cu	Al	V	P	S
3,55	0,45	2,15	0,20	0,05	0,10	0,01	0,05	0,20	0,10

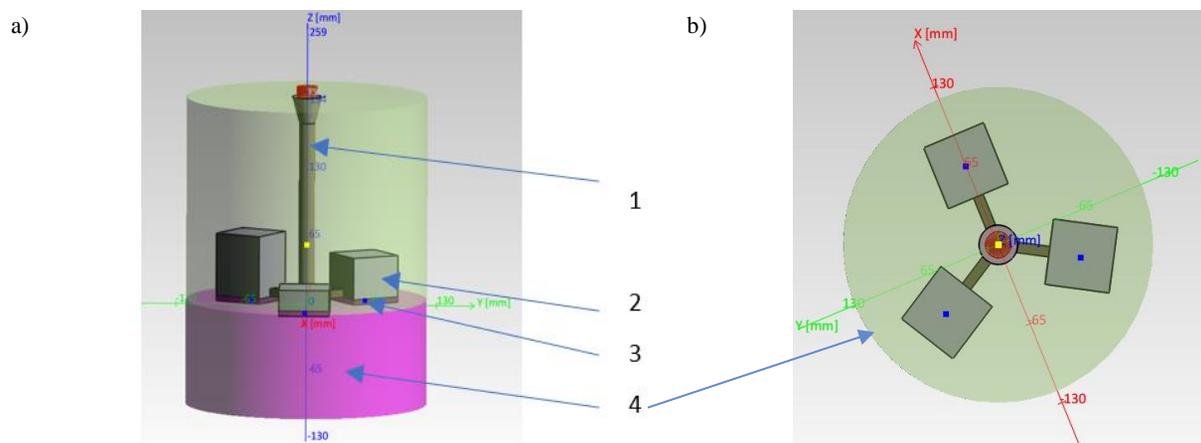


Fig. 1. Virtual model of layered casting: (a) 1- gating system, 2- base part, 3- working part, 4- moulding sand. (b) distribution of thermoelements on external surface of working layer

2.2. Measurement of the thermal conductivity coefficient

As already mentioned, in order to regulate the cooling rate in conditions of casting mould, three different matrix of moulding sand were chosen: SiO_2 , FeCr_2O_4 and SiC . On the basis of the sieve analysis, in accordance with the requirements of the PN-H-11077: 1983 standard, it was found that in the case of all three types of matrix, the dominant fraction of 0.40 mm / 0.32 mm / 0.20 mm allows them to be classified as to the group of coarse sands according to PN-H-11001: 1985. Moreover, due to the fact that in all three matrix the main fraction constitutes more than 80% of the total material, they can be considered as homogeneous matrix. Then, due to the lack of data in this range, it was necessary to determine experimentally thermal conductivity coefficient for masses prepared on the basis of above mentioned materials (SiO_2 , FeCr_2O_4 , SiC), bound with a binder in the ratio of 30:1. The synthetic resin Carbophen 9026 hardened with CO_2 was used as a binder. The material constants of the cast-mould system are presented in Table 3.

For this purpose, open moulds were prepared using three selected moulding sands and a model of a 150x150x15 mm plate was formed in them. Irrespective of the matrix used, an alkaline phenolic resin cured by CO_2 stream was used as a binder, introduced in a volume ratio of 1:30 relative to the matrix. Pt-PtRh10 thermocouples in the amount of 5 were placed in such a way that the first one was located in the axis of symmetry of the plate, and the next ones, with an offset of 7.5 mm each (Fig. 2) and mounted on a special tripod, as shown in Figure 3.

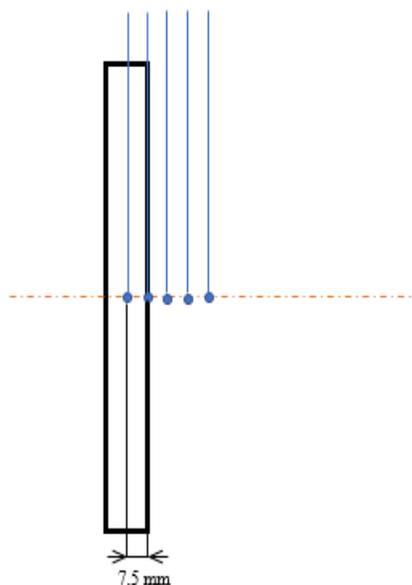


Fig. 2. Scheme of measuring system - distribution of Pt-PtRh10 thermocouples on the cross section of the mould



Fig. 3. Method of mounting Pt-PtRh10 thermocouples in the form. The experimental mould with visible thermocouples mounted in the mould

Table 3.

Material constants and geometrical dimensions of castings and moulds used during calculations.

Property, u	value
Ambient temperature T_{ot} , °C	20,3
Cast dimensions, mm	150x150x15
Moulding box height H, m	0,2
Diameter of the moulding box D, m	0,24
Moulding flask volume V, m ³	0,009
Mass weight on the SiO_2 matrix, kg	16,26
Mass density on the SiO_2 matrix, kg/m ³	1669
Average specific heat of quartz sand C_{SiO_2} , J/(kgK)	1080
Mass weight on FeCr_2O_4 matrix, kg	28,56
Mass density on FeCr_2O_4 matrix, kg/m ³	3282,76
Average specific heat of chromite sand $C_{\text{FeCr}_2\text{O}_4}$, J/(kgK)	800
Mass weight on SiC matrix, kg	16,98
Mass density on the SiC matrix, kg/m ³	1750,5
Average specific heat of silicon carbide C_{SiC} , J/(kgK)	800

The moulds were poured with pure copper from the temperature of 1220°C and the temperature during heating and cooling was recorded. Based on the obtained results, the dependence of the thermal conductivity coefficient λ as a function of temperature for each of the mould materials was determined, referring to the calculations carried out in [13-14]. The thermal conductivity coefficient was determined using the formula (1).

$$\lambda = a \cdot c \cdot \rho \quad (1)$$

where:

a – thermal diffusivity, m^2/s

c – average specific heat, $J/kg \cdot K$

ρ – mould material density, kg/m^3

The specific heat for each mass was read from the tables. Mass densities were calculated as the quotient of mass m and volume V according to the formula:

$$\rho = \frac{m}{V} \quad (2)$$

Thermal diffusivity a was determined from the formula:

$$a = \left(\frac{x}{2u\sqrt{\tau}} \right)^2 \quad (3)$$

x – distance between the thermocouple and the mould

material/liquid metal contact surface, m

τ – time since flooding, p

u – value read from tables for $\text{erf}(u)$

$\text{erf}(u)$ was determined as a quotient of:

$$\theta = \frac{T_x - T}{T_0 - T} = \text{erf}(u) \quad (4)$$

T_x – recorded temperature in mould, $^{\circ}C$

T – Temperature at the mould material/liquid metal interface, $^{\circ}C$

T_0 – ambient temperature, $^{\circ}C$

3. Results

3.1. Measurement of thermal conductivity coefficient in a function of temperature

Figure 4 shows the determined dependencies $\lambda(T)$ for all three moulding sands. As assumed, significant differences in the value of the thermal conductivity coefficient λ in the tested temperature range for each of the masses were noted. It was noted that in relation to the unbound material (without a binder), the tendency of the coefficient λ was maintained. This means that the moulding sand made on the basis of quartz sand had the lowest thermal conductivity in the range of key phase transition temperatures for the tested steel insert, amounting to $\lambda = 0.5 \div 1 \text{ W/m}^{\circ}K$. Approximately twice as high thermal conductivity in the analogous temperature range was determined for the mass based on chromite sand, where λ was in the range of approx. $1.5 \div 2 \text{ W/m}^{\circ}K$. The highest thermal conductivity ($\lambda = 5 \div 20 \text{ W/m}^{\circ}K$) was found for the moulding sand made with silicon carbide. In the case of moulding sand made on the basis of quartz sand and silicon carbide, the

obtained dependencies $\lambda(T)$ are very similar to those presented in papers [15-20].

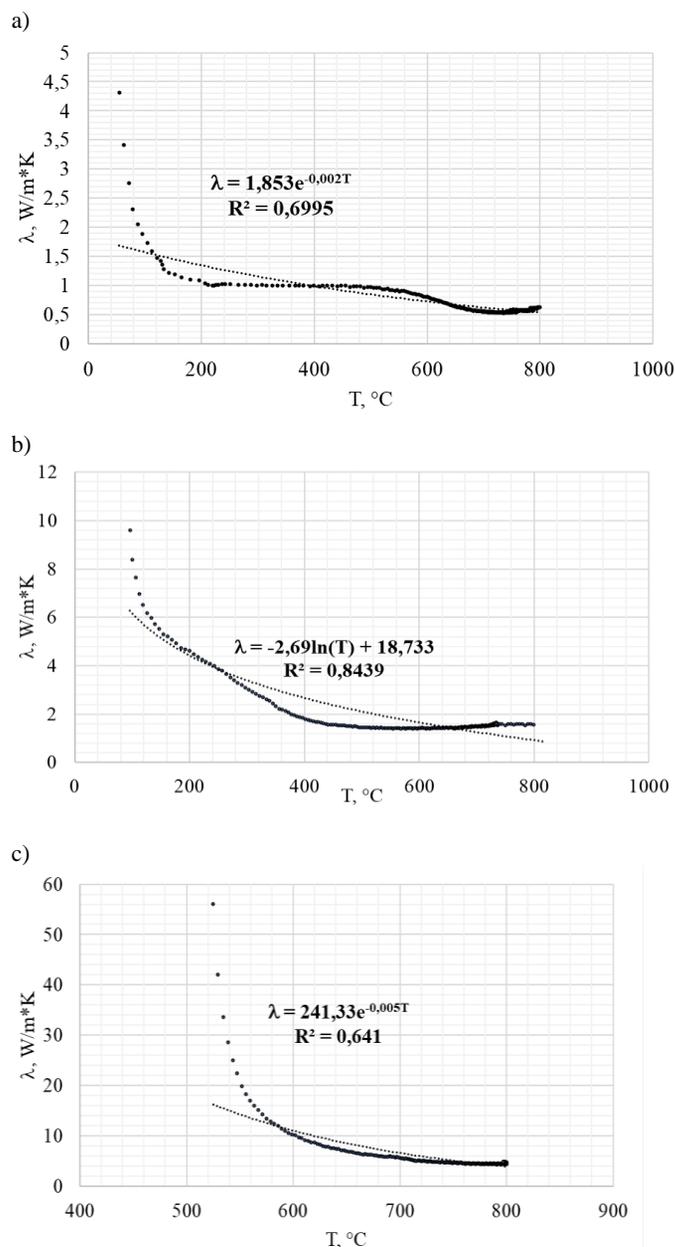


Fig. 4. Thermal conductivity coefficient λ as a function of temperature, determined experimentally for sand based on: (a) quartz sand, (b) chromite sand, (c) silicon carbide, using the Carbophen 9026 binder added in a volume ratio of 1:30

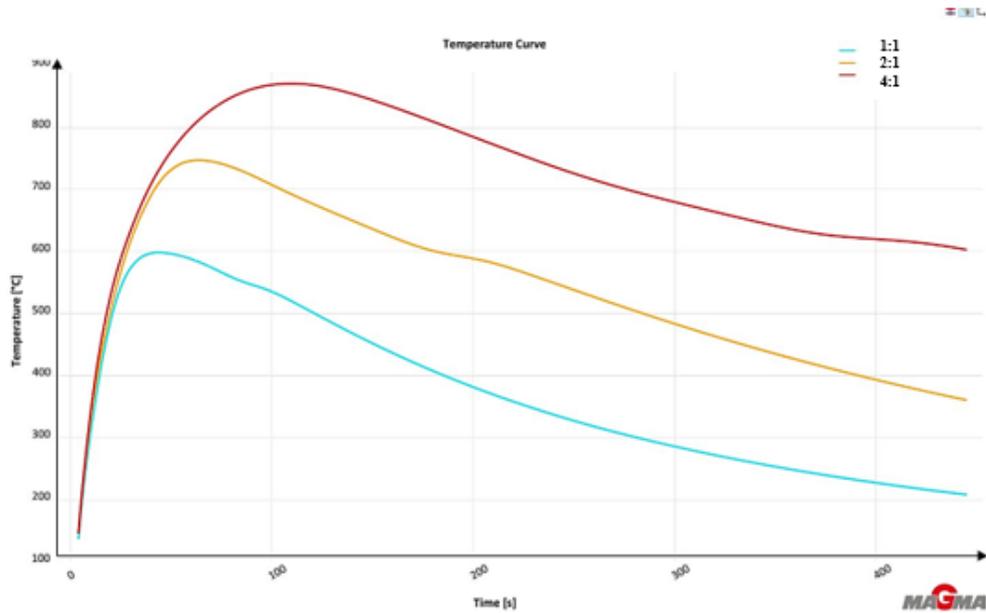
3.2. Simulation results

The database of the MagmaSoft® (ver. 5.4.1) did not have compatible materials in its resources with selected moulding sands, therefore they were added manually, and the dependencies $\lambda(T)$

determined experimentally were introduced in the definition of the material. The analysis of the simulation results showed that in case of the process performed in the sand mould on the matrix of quartz sand (at pouring temperature $T_p=1400^\circ\text{C}$), the X46Cr13 steel insert would heat up to the assumed temperature, i.e. 950°C , when the ratio of the base to the working part would be 8:1, 10:1 and 12:1 (Fig. 5b). However, as shown in Figure 5a, the use of a thickness of the base part $g = 20\text{ mm}$, which corresponds to a ratio of 4:1,

results in heating the insert to a temperature of approx. 900°C . Therefore, bearing in mind that the simulation results require validation in fully real casting conditions, but there is a high possibility that application of the thickness of the base part amounting 20 mm would be sufficient from the point of view of the studies.

a)



b)

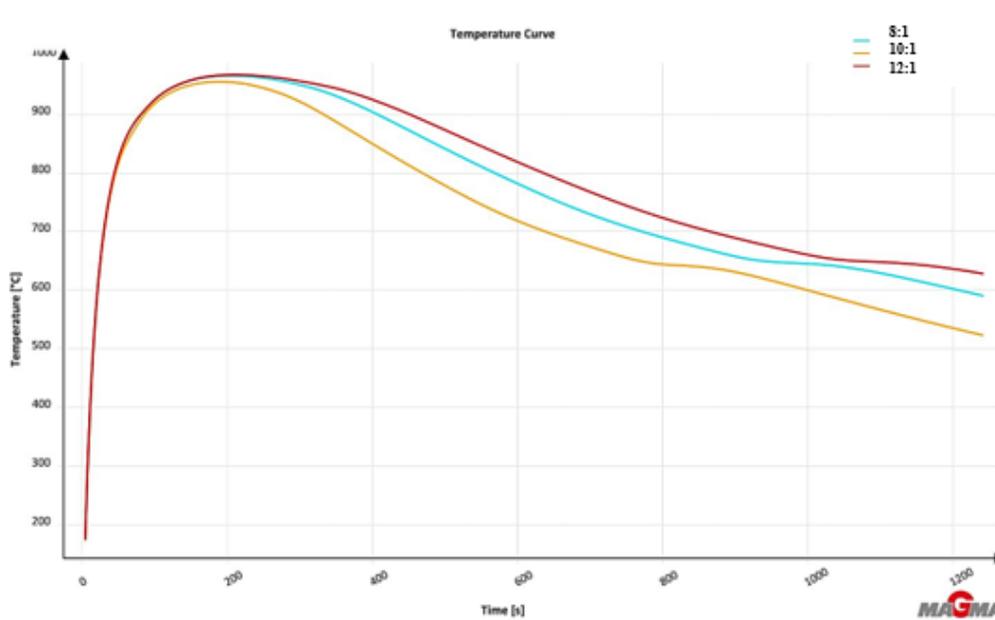


Fig. 5. Dependence of temperature on time during pouring and solidification of a layered casting in the configuration of gray cast iron – high – chromium steel X46Cr13. Base to working part ratio: (a) 1:1, 2:1, 4:1, (b) 8:1, 10:1, 12:1. $T_p=1400^\circ\text{C}$

Then, analogous simulation was performed for the systems made with SiC and FeCr₂O₄. For simplicity, it was carried out for thickness of the grey cast iron amounting 20, 40 and 60 mm. It was observed that the thermal conductivity of the moulding material significantly influenced the temperature reached in the thermal center of the steel insert. Moulding sand based on silicon carbide, dissipates heat too quickly (due to the high value of λ), as indicated by the simulation result (Fig. 7) - the X46Cr13 steel insert did not heat up to the required temperature. In the case of chromite sand (Fig. 8a), the virtual temperature T_p obtained in the heat center of the casting was approx. 800°C, with the thickness of the cast iron part amounting $g = 40$ and $g = 60$ mm. Analyzing the phase equilibrium diagram of the X46Cr13 steel (Fig. 6), it can be seen that austenite occurs in the system above $T = 800^\circ\text{C}$, as a part of the mixture which additionally includes α -iron and Cr carbides. It was assumed that austenite transformation would be possible into martensite, although there would be less of it than if the system exceeded $T = 950^\circ\text{C}$. The increase in the pouring temperature resulted in the temperature T_m in the thermal center of the insert approaching the expected one, which was confirmed in the supplementary simulation (Fig. 8b). This simulation was carried out at $T_p = 1500^\circ\text{C}$.

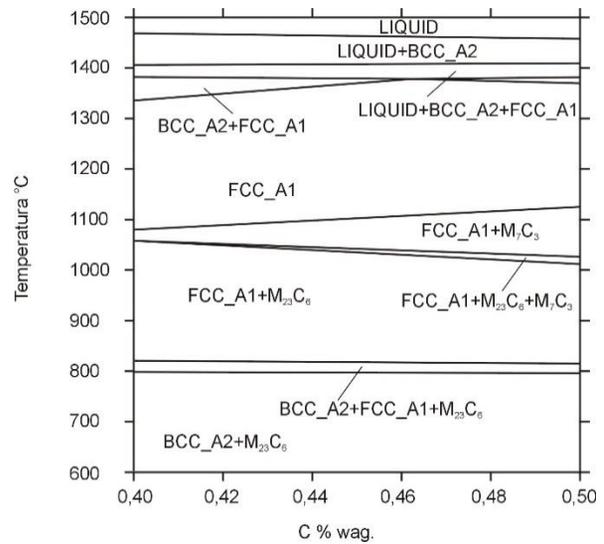


Fig. 6 The phase equilibrium system of X46Cr13 steel determined in the program in Thermo-Calc: LIQUID – liquid, FCC_A1 – austenite, BCC_A2 – ferrite, M7C3 and M23C6 – Cr(Fe) carbide

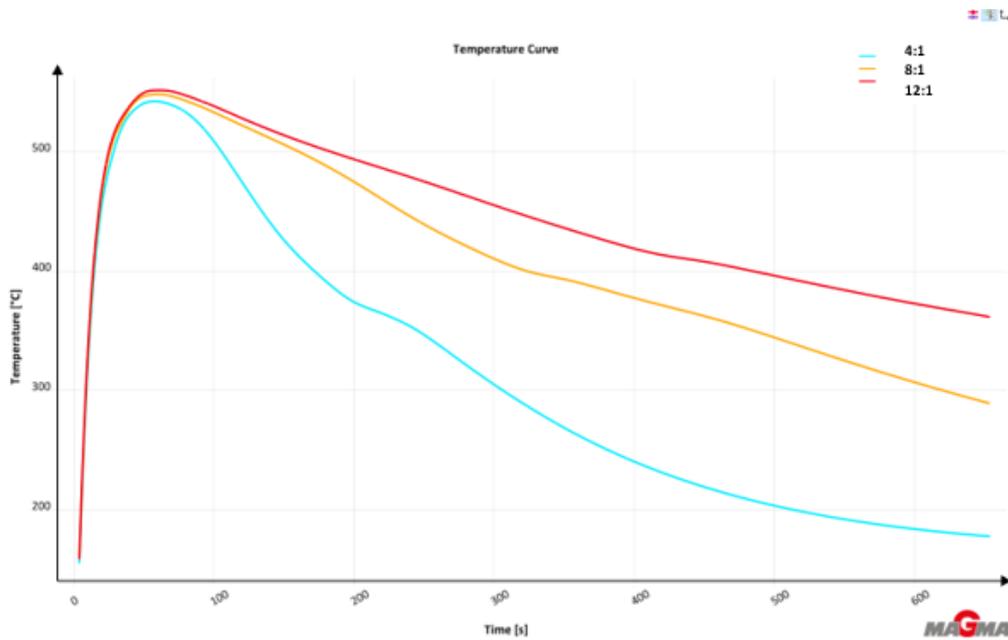
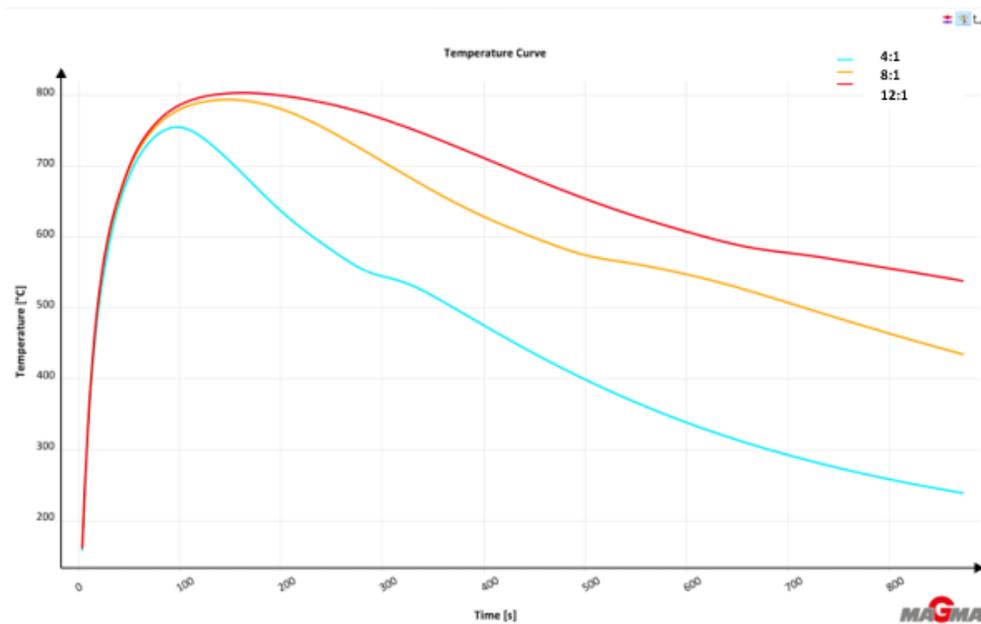


Fig. 7. Dependence of temperature on time during pouring and solidification of a layered casting in the configuration of cast iron - high chromium steel X46Cr13. Base to working part ratio: 4:1; 8:1; 12:1. Moulding sand matrix: silicon carbide. $T_p=1400^\circ\text{C}$

a)



b)

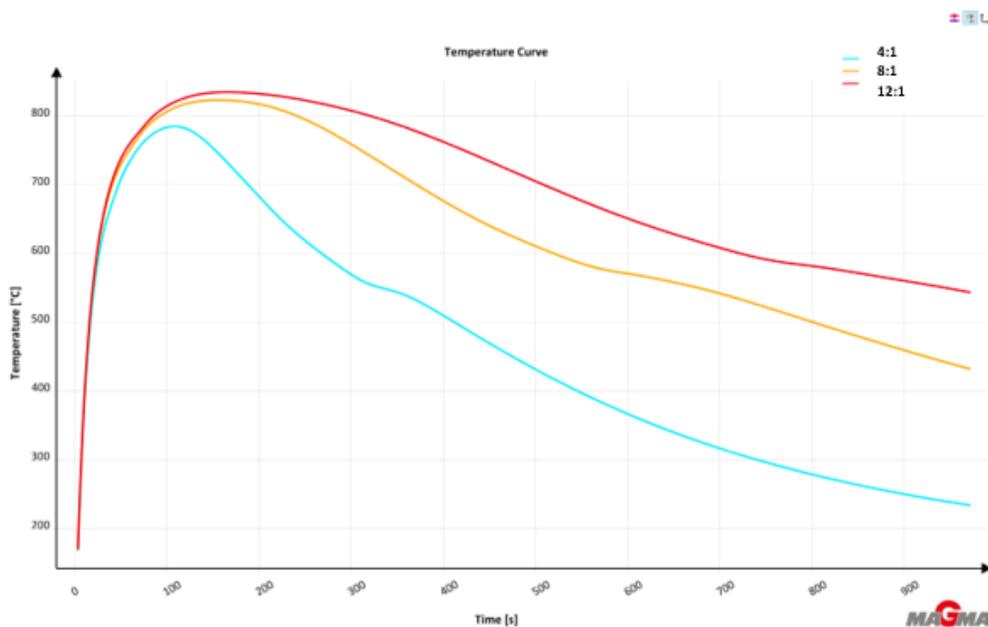


Fig. 8 . Dependence of temperature on time during pouring and solidification of a layered casting in the configuration of cast iron - high chromium steel X46Cr13. Base to working part ratio: 4:1; 8:1; 12:1. Moulding sand matrix: chromite sand: (a) $T_p=1400^{\circ}\text{C}$, (b) $T_p=1500^{\circ}\text{C}$

4. Conclusions

This work provided the following observations and conclusions:

- It has been observed that the MagmaSoft® (ver. 5.4.1) simulation program does not take into account the influence of the so-called transition zones formed at the contact boundary between the steel insert and liquid cast iron. The presence of these zones, the presence of which has been

demonstrated in works [2,3,6,20-26], has an undoubted impact on the heating rate of the insert from the liquid cast iron, and therefore favors obtaining its higher temperature than that predicted in the simulation program. Therefore, it was considered that the minimum ratio of the base part to the working part, which guarantees the austenitization temperature of X46Cr13 steel, is 4:1.

- High thermal conductivity of the moulding sand made on the basis of silicon carbide disqualifies it in the application of the analyzed technology of integrating the heat treatment of X46Cr13 steel with the bimetal production process in the with gray cast iron.
- From the point of view of the aim of the studies, i.e. hardening of X46Cr13 steel grade in condition of moulding sand, based on conducted studies, it is recommended to use sand mould on the matrix of quartz and chromite sand, however the results of the research described in this publication need to be confirmed in real condition.

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