ARCHIVES
of
FOUNDRY ENGINEERING

ISSN (1897-3310)
Volume 7
Issue 3/2007

191 – 198

37/3

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Validation Studies of Temperature Distribution and Mould Filling Process for Composite Skeleton Castings

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Received on 25.04.2007; Approved for printing on: 27.04.2007

Abstract

In this work authors showed selected results of simulation and experimental studies on temperature distribution during solidification of composite skeleton casting and mould filling process (Fig. 4, 5, 6). The basic subject of the computer simulation was the analysis of ability of metal to fill the channels creating the skeleton shape and prepared in form of a core. Analysis of filling for each consecutive levels of the skeleton casting was conducted for simulation results and real casting. The skeleton casting was manufactured according to proposed technology (Fig. 5). Number of fully filled nodes in simulation was higher than obtained in experimental studies. It was observed in the experiment, that metal during pouring did not flow through the whole channel section, what enabled possibilities of reducing the channel section and pointed out the necessity of local pressure increase.

Keywords: Skeleton castings, Composite, Simulation, Casting, Solidification

1. Introduction

Because of great possibilities for porous materials application in today industry [1÷6] it is advisable to find low-cost methods of its manufacturing. The main advantage of presented in this work technology for porous material manufacturing is the elimination of special equipment needed for preparation of similar materials, for example metallic foams. The basis of presented technique is the specially formed core responsible for geometrical features of skeleton casting.

Skeleton castings are the intermediate of solutions metal materials between the monolithic casting and metallic foam. Skeleton castings should compete with the other ones used [5,6] in the industry of porous materials.

The process of producing the skeleton casting mainly depends on the creation of the core that has designed geometry. The hypothetical process of creating such core was presented in the studies [7,8].

Studied skeleton casting belong to the group of materials with open cells due to their construction. It also contributes to open possibilities for multi-phase materials manufacturing with non-monolithic spatial structure. This can be obtained by connecting the skeleton with cell cavities filling material in a composite process. As a filling material different types of materials can be used, for example: other alloys, polymers, or ceramics.

The use of the cores requires creating the maximum gap between the cells to enable the extraction of the core from the area of the casting. Geometry of potential cells of skeleton casings [7,9,10] was presented in the Fig. 1. Geometry shown in the Fig. 1c and 1g was used to produce the experimental castings. The profitable features of this geometry are: perpendicularity of cell connectors, their circular sections and the simplicity of creating the core. Manufacturing of the casting according to given geometry, is connected with its appucation as a consequence with the selection of specific proportion between the section of the circular connector and the cell dimension.

Proposed geometry of the core enables liquid metal flow with minimal hydraulic flow resistance in order achieve the maximum capability of filling the space of the mould cavity in the same time preserving apparent density of the casting. Moreover, the skeleton having equal structure along tree main axes is profitable because of equal strength in all directions.

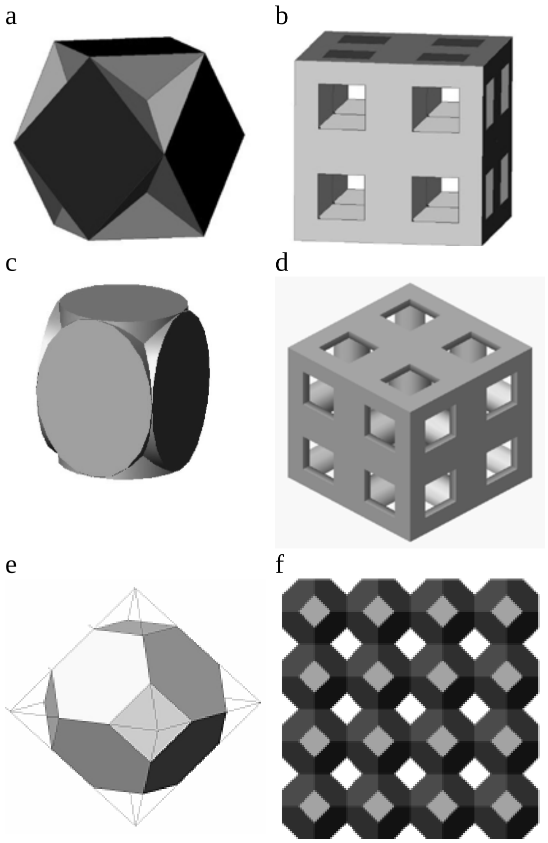


Fig. 1. Skeleton casting structure: a), c), e) - geometry of metal skeleton; b), d), f) – cell structure of skeleton casting

2. Selection of materials and technological conditions for numerical simulation

The aim of conducted simulations was the choice of thermal and geometrical parameters for the needs of designed calculations of the skeleton castings and the estimation of the guidelines for the technology of manufacturing. Two components of the process of filling the mould cavity and its solidification were taken into account.

Cooling of the castings in range of temperature solidification (t_L – t_S) was taken into consideration as solidification or crystallization process. The process of crystallization is usually discussed with taking into account nucleation and the rise from the liquid phases of individual crystals and primary crystallization of the casting. These processes depend on over – cooling of liquid metal. The processes of solidification are studied in macroscale as the increase of the solid phase in the time of cooling (t_L – t_S). There are caused by conducting the heat out from the cast to the form. There are many aspects of theory of composites solidification. It is brought about the various factors that affect the mechanism of solidification, the various components, their mutual proportions, different physical and chemical properties and also their interactions in liquid state and during solidification.

The composite consists of metallic matrix m and ceramic reinforcement p, which have different coefficients of thermal conduction (λ_m, λ_p), different specific heat (c_m, c_p) and various densities of masses. The different composites have different fraction of ceramic particles V_p to casting volume V ratio.

Hypoeutectic AlSi7Mg alloy with the addition of 0,4 % antimony, which is designed for manufacturing of the skeletons, can be the target alloy of the matrix. Due to the proposed technique, the liquid composite is the result of in situ reaction from the gaseous phase with the production of the particles of oxides – mainly aluminum oxide. In the simulation corundum was accepted as the material of reinforcing particles. Its properties are, as follows:

$$\lambda_p = 3{,}7 \text{ W/m·K}$$
$$c_p = 1070 \text{ J/kg·K}$$
$$\rho_p = 3940 \text{ kg/m}^3$$

with volume fraction:

$$V_p=4\%$$

where ‘p’ concerns the reinforcing particles.

The specific properties of matrix of AlSi7Mg alloy are:

$$\lambda_m = 168 \text{ W/m·K}$$
$$c_m = 1200 \text{ J/kg·K}$$
$$\rho_m = 2554 \text{ kg/m}^3$$

and heat of crystallization is:

$$L= 394 \text{ kJ/kg}$$

where ’L’ means heat of crystallization and the index ‘m’ concerns matrix.

Liquid composite, prepared in this way, will be used for manufacturing of the skeleton castings [7,11,12].

The average values of these coefficients [13] were used for calculations thermal properties of the composites k:

- thermal conductivity:

$$\lambda_k = \lambda_c \cdot \frac{2\cdot\lambda_c + \lambda_p - 2\cdot V_p\cdot(\lambda_c - \lambda_p)}{2\cdot\lambda_c + \lambda_p + V_p\cdot(\lambda_c - \lambda_p)} \qquad (1)$$

for tested composite: λ_k=158 W/m·K

- specific heat:

$$c_k = \frac{V_p\cdot\rho_p\cdot c_p + (1 - V_p)\cdot c_c\cdot\rho_c}{\rho_k} \qquad (2)$$

for tested composite: c_k= 1134 J/kg·K

- density

$$\rho_k = V_p\cdot\rho_p + (1 - V_p)\cdot\rho_c \qquad (3)$$

for tested composite : ρ_k=3108,4 kg/m^3

and heat of crystallization

$$L_k=378 \text{ kJ/kg} \qquad (4)$$

3. Numerical simulation

The basic subject of computer simulation was the analysis of ability of filling the channels of core by liquid metal. Broad use of skeleton castings demands forecasting, by the means of simulation, of filling the mould cavity, hence there is the verification of the results of the simulation through the experimental tests. Below the assumptions and results of the initial simulated calculations and geometry of experimental casting are presented. The qualitative nature of conductor analysis is emphasized by the tests of simulations. The combination of the calculations of simulations and the experimental tests will enable defining the influence of geometrical technological parameters on the process of filling mould cavity and solidification of skeleton casting.

Physical models describing metal flow in the mould cavity and in the inlet system generally do not consider the connection of rising flow resistances with the tendency to oxidation of the stream of metal which is divided into the modules. However, the programmes take into consideration the rising share of solid phase already during filling the mould cavity. Hence use of hypoeutectic alloy can bring the results of the simulation closer to casting composite dispersion based on eutectic matrix. Selection of equivalent thermal properties describing the composite can be discussed. The influence of the exemplary amount of the particles (4 %) on solidification processes seems not to be distiuct in quantity but it is surely important in quality. The influence on casting is difficult to estimate and compare with the typical alloys, however. Presented researches are the preliminary studies.

Oxides, occurring as the layer on the solid phase on the stream front and make difficult the process of revival of the stream in a high degree what was caused by the progressing crystallization of the matrix in the channels of the skeleton casting.

The initial assumptions took into account manufacturing the casting of the basic bottom getting system. The subject of the research was defining the minimal technological metalostatic pressure that provided filling a mould. Providing the tests at different metalostatic pressure to achieve the function dependence was presumed. The different level of filling the mould cavity in the function of metalostatic pressure would be the result. The level of filling the mould cavity at the consecutive levels of the experimental casting was observed for initially accepted height of the inlet circuit. The results obtained in the experiments were compared with the results of the analogous simulation of the mould cavity. The shape of the model casting with its core and getting system was presented in Fig 2. The simulation was conducted with use 'NovaFlow & Solid' software.

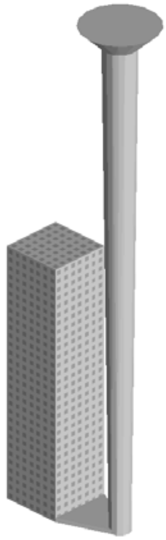


Fig 2. The view of the model cast with its core and getting system

The typical properties of core and mould sands [7,11,12] were established.
The temperature of pouring was 670^0C and the temperature of the mould and the ceramic core was set to 80^0C.

4. Manufacturing the experimental skeleton casting

Castability was the main factor in selection of chemical composition of metal.

The alloy with minimal range of solidification temperature, it means eutectic AlSi11 alloy, was used for experimental tests. Its properties:

$$\lambda = 130 \text{ W/m·K}$$
$$c = 1190 \text{ J/kg·K}$$
$$\rho = 2500 \text{ kg/m}^3$$

and crystallization heat:

$$L = 389 \text{ kJ/kg}$$

The chemical composition of AlSi11 alloy was presented in the Table 1.

The liquidus temperature of the tested alloy was 584^0C and its solidus temperature was 577^0C.The minimal intended scope of the solidification temperature of the alloy was 4K.

Table 1. The chemical constitution of AlSi11

Pierw.	**Al**	**Si**	**Mg**	**Mn**	**Cu**	**Ni**	**Zn**	**Sn**
Skład %	82,95	10,50	0,10	0,50	2,50	0,30	3,00	0,15

Antimony was used to improve the castability of the alloy. Antimony gives very high castability to the alloys without gassing it. The addition of Sb in the amount of 0,4 % mas was applied [4]. Moreover, antimony improves wettire during composite creation from liquid phase.

The main inlet is twice as high as the casting in the presented getting system. The experimental castings were prepared in the form shown in the Fig. 3.

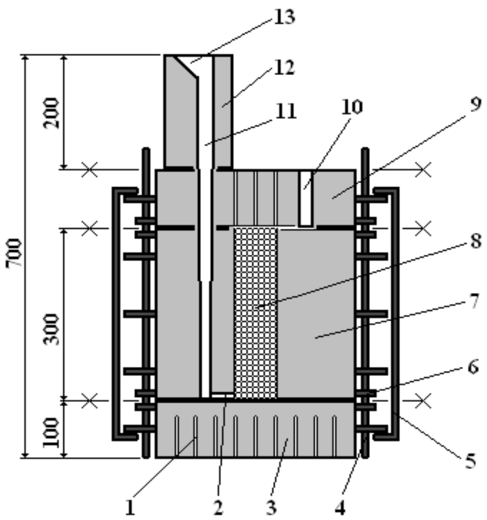


Fig. 3. Mould for skeleton casting: 1 – degassing channels, 2 –ingate, 3 – lower part of the mould, 4 – lifting pins, 5 – clamp, 6 – grip, 7 – central part of the mould, 8 – mould cavity and ceramic core, 9 – upper part of the mould, 10 – over flow, 11 – getting system, 12 – pouring part, 13 – pouring basin

The differences of thermal properties of the simulated and real castings:

$$\Delta\lambda = 28 \text{ W/m·K}$$
$$\Delta c = 56 \text{ J/kg·K}$$
$$\Delta\rho = 604 \text{ kg/m}^3$$

Relative error between thermophysical properties of the simulated material and the composite are:

$$\Delta\lambda_{\%} = 18\ \%$$
$$\Delta c_{\%} = 4{,}7\%$$
$$\Delta\rho_{\%} = 19{,}4\%$$

Presented differences of the properties were taken as enough to estimate metalostatic pressure needed for proper composite skeleton casting manufacturing.

5. Studies results

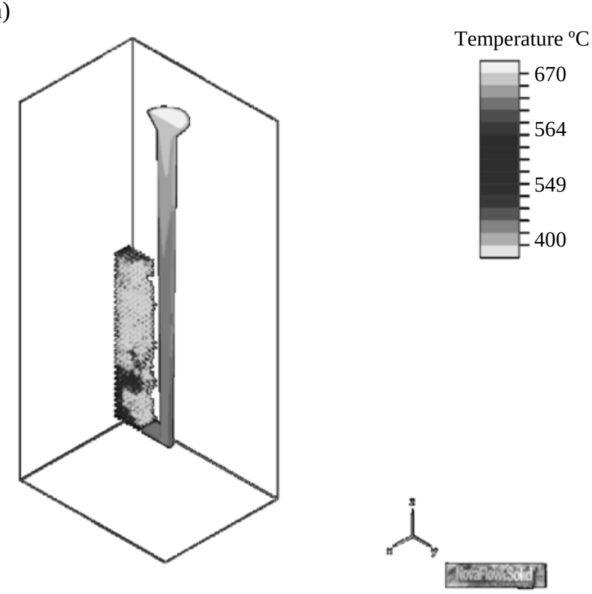
5.1. The results of computer simulation

High cooling rate of metal that flows through the channels in the core is present. It has been shown by the distribution of the temperatures in casting volume. Filling of the mould cavity is not equal what results in the large differences of the temperatures in cooling down the casting (Fig.4 a, b).

Presented graphs specifically show the clusters of liquid phase agree with the places of the most intensive metal flow. The simulation clearly points at the places where incomplete filling occurs. Liquid dispersion, even not flowing through the whole section of the connectors, can fill the nodes that are the places where metal streams meet. The simulated filling of mould cavity with metal in the adequate areas of the nodes and the connectors was shown in the Fig. 5 and 6.

The estimated average volume of filling the mould cavity is $V_{average}$= 92 % for the whole simulated Al casting.

a)



b)

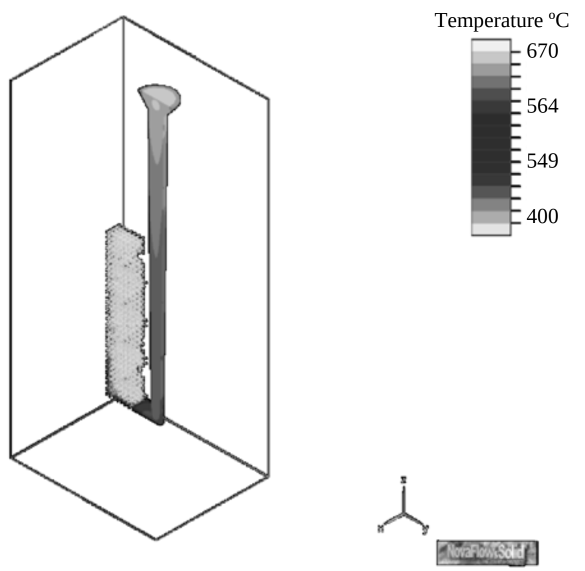


Fig. 4. The results of filling and temperature distribution during casting and cooling the virtual cast. The scale is adequate to the established local temperature of the cast

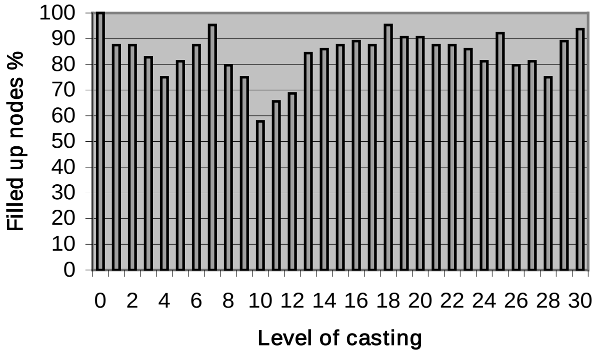


Fig. 5. The number of the filled up nodes at the individual levels of the skeleton casting that has been obtained through the computer simulation

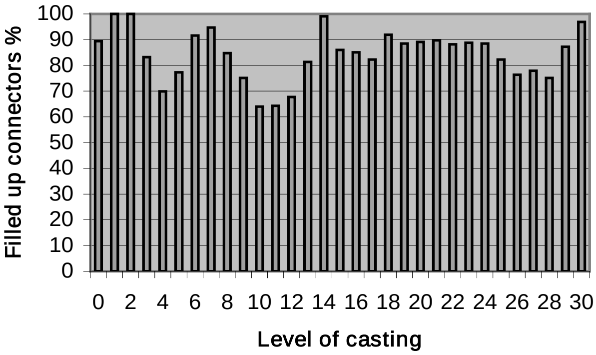


Fig. 6. The number of the filled up connectors of the skeleton casting that has been obtained through the computer simulation

5.2. Experimental results

The obtained aluminium cast was shown in the Fig 7. The asymmetrical non-filling of the mould cavity is presented. The lack of many nodes at the side surface of the casting in the upper part of it and the lack of many connectors directed perpendicularly to the axis is the result of diminishing of flowing quantity of the metal alloy and the height of the cast.

The estimated average filled volume of the mould cavity is $V_{average}$= 57 %.

Obtaining incompletely filled castings enabled relating the parameters of filling with the ability to fill the mould cavity. Metalostatic pressure has the important influence on repeatability of geometry. It worsens due to the fall of pressure at the higher levels of the cast, although the general outline of the cells is seen. The revival of the stream of flowing metal produces the improvement in filling the mould with metal [7] and is one of the factors affecting filling of mould cavity. It indicates the need for aiding the process of filling the mould cavity with liquid dispersion. 'Not filled up' connectors with the concave front have not been found in the real casting. It indicates at good taking gases out from the elementary volumes of the core (pressure of the flowing metal was higher than pressure of gasses expanded with the rise of temperature). Real filling of the mould cavity with metal in the areas – adequately of the nodes and connectors, is shown in the Fig. 8 and 9.

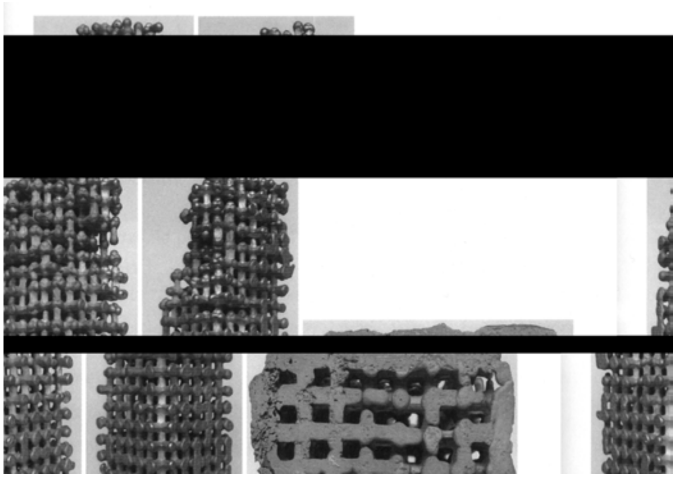


Fig. 7. Example of Al skeleton

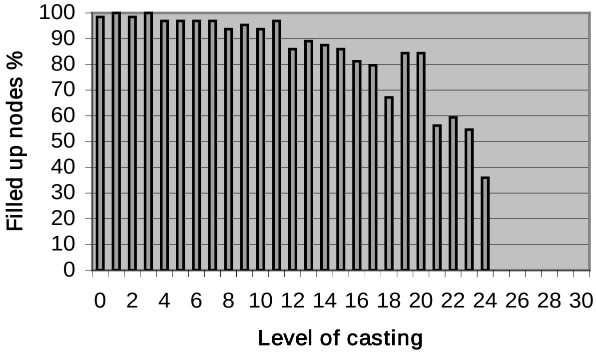


Fig.8. The number of filled up nodes at the individual levels of the real skeleton casting

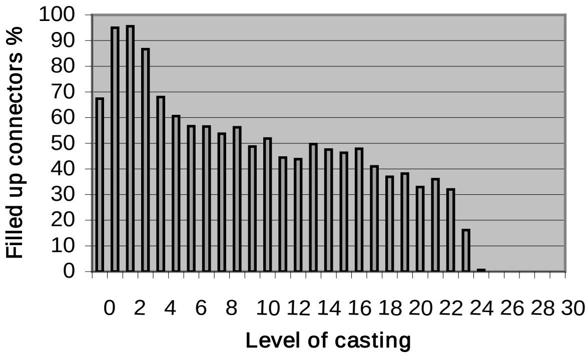


Fig.9. The number of filled up connectors of the real skeleton casting

5.3. Simulation and experimental results comparison

Filling of the nodes and metal connectors at the individual levels of the skeleton casting was analyzed. The total number of the nodes in the casting was 1920 and of the connectors was 5280 what gave filling of 86,9% for the nodes and 81% for the connectors in the results of the simulation. Together it resulted as 82 % of filling the volume of the casting. Modulus of solidification of a node is greater than that of a connector. Filling of the node is technologically easier. The inner nodes can momentary be reinforced by 6 nodes. The minimum amount of the connectors reaching to the node is 3. Locally increased flow resistance resulted in blocking the flow can be supplied from only one node. The connector links only two nodes. That is why the efficiency of filling the nodes is greater than of the connectors what was confirmed by the results of the simulation and the tests.

The comparison of filling in real and simulated conditions was done. The results of the analysis of filling the metal nodes and connectors for the individual levels were shown in the Fig. 10 and 11.

The results of the simulated analysis generally overstate the values of the numbers of flooded connectors and nodes.

The number of filled up nodes diminished at the higher levels in the real casting, even though any node has not been filled up above the 26 level. The nodes were filled up to the 30 level of the casting in the simulation. It was stated in the experiment and in the simulation that metal did not flow through the whole section of the connectors what showed the possibility of diminishing the sections of the channels but it equally pointed at the technological necessity for local pressure increase. The natures of the changes of filling till the 14 level are similar. The number of filled up nodes up to the 14 level is higher in the real casting than it is ensued by the simulation.

Starting from the 26 level any filling of any node can be noticed in the real casting. The difference between the numbers of the filled up connectors at the individual levels of the skeleton casting have been obtained by the simulation and in the real cast is shown in the Fig. 10. Noticed dependence was attributed to proportional variability that is illustrated by the line of the trend in the Fig. 12 and 13. The results of the analysis of filling up the connectors of the skeleton casting were assumed as the basic in the choice of correcting coefficient in the simulated calculations in which the height of the casting is the indicator of metalostatic pressure in the getting system.

Taking into account obtained results it should be expected that due to the rising height of the cast for the assumed geometrical and thermal system the inaccuracy of predicting filling the mould cavity would linearly increase in accordance with the inclination coefficient of the line of the trend k=9,1 (Fig. 12 and 13).

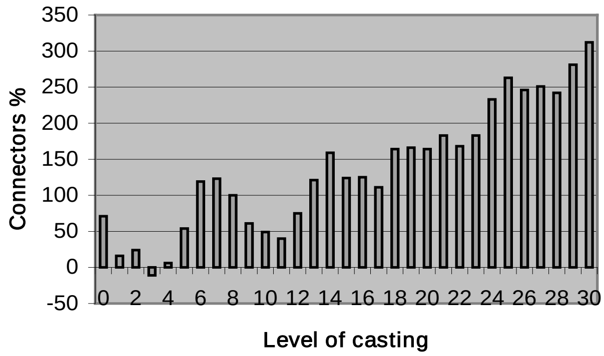


Fig. 10. The differences in filling of connectors at the individual levels of the skeleton casting. The participation of the numbers of filled up connectors in relation to the total number of the numbers at the individual levels of the skeleton casting

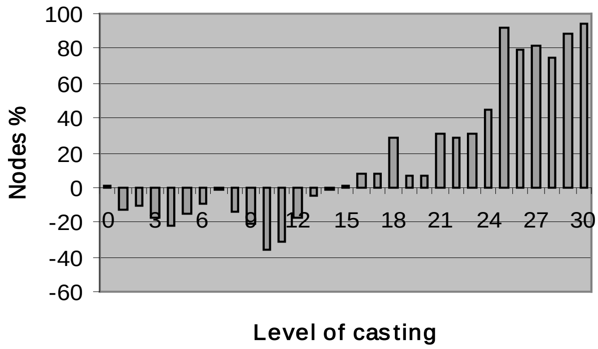


Fig. 11. The differences in filling of nodes at the individual levels of the skeleton casting. The participation of the number of filled up nodes in relation to the number of the nodes at the individual levels of the skeleton casting

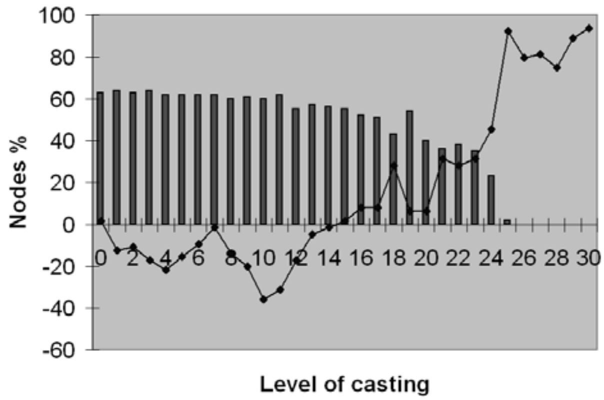


Fig.12. Graph of inaccuracy of forecast filling of the nodes and the line of the trend k

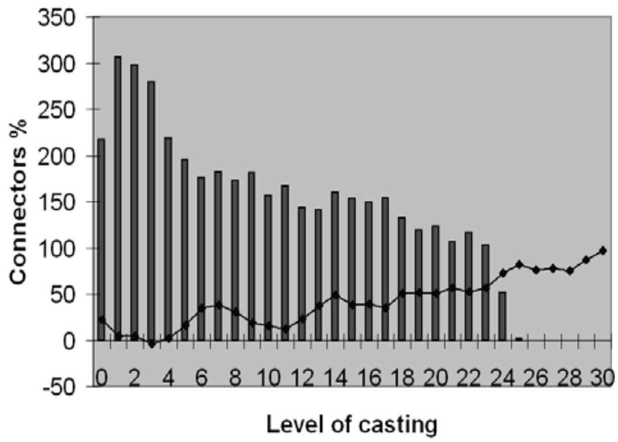


Fig.13. Graph of inaccuracy of forecast filling of the connectors and the line of the trend k

6. Conclusion

Based on conducted studies following conclusion were formulated:

1. The physical model accepted to fill the traditional mould cavities in the simulation software turned out not to be useful in correlation to the skeleton castings instead of established more favourable heat conditions. It is necessary to provide the proper correcting coefficients that will take into account the increased resistances of the flow.
2. It was stated that dependence of the error of predicting due to metalostatic pressure in the getting system of the skeleton casting is approximately linear.
3. The future research should follow two directions that should closer the conditions of casting to the traditional ones:

- The choice of the values of metalostatic pressure up to the value providing the similar results of the simulation and the experiment. That is why it is profitable to increase the height of the getting system up to about 50%.
- The application of the getting system that is justified technologically, for example, it could be multi-level one that might lead to diminishing the grade of dividing the stream of liquid metal into the units. It might also bring filling the mould of skeleton casting closer to the traditional casting.

4. The correcting coefficients should be determined with distinction between the classes of the castings with the different inner constructions and the different shapes.
5. It is necessary to conduct the next simulations with changeable geometry at different initial casting conditions.
6. It seems to be advisable to use Bernoulli's law of the continuity of stream including Kirchhoff's laws of the flow with reference to the stream of metal, that is divided into the units, taking into account increasing value of flow resistance in the function of time and diminishing temperature of the alloy in the calculations of the designed getting system.
7. Forced local revival of the stream achieved due to the combined assisted physical and chemical interactions should be the technological factor of the higher filling of mould cavity.

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