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Development the Methods for Preventing Hot Cracking With Use Analysis of Temperature Fields

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Abstract. The reasons for formation of hot cracks in steel castings having difficult geometric shape of a revolution body are discussed in the paper. Mathematical model for the calculation of metal castings solidification and analysis of temperature conditions, which determines the conditions of hot cracking formation are proposed. The advantage of developed model is ability to use only results of thermal analysis without special calculation of stress-strain state. Criteria for evaluating of thermal conditions for directional solidification and heat dissipation in mold is developed, what allowing to correct technology of casting for defects prevention.

1. Introduction

Hot tearing in complex steel castings is well-known and urgent problem [1] for foundry production. Shrinkage strain in solidifying steel become very different from temperature strain for most metals, the initial stresses are developed in casting immediately upon its crystallization in the mold [2]. Due to complexity and difficulty of practical of experiments with study of process of curing shaped castings in the literature there are only a limited number of experimental studies [3] about temperature curing conditions, what complicates the development of physical and mathematical model of hot cracks formation.

Tasks of development analysis of thermal shrinkable strain of solidifying casting includes features which usually are absent at separate calculation of temperature field or development of strain, and are described by us in works [4-6]. Techniques for an assessment of the temperature conditions of solidifying influencing defects formation for the fittings preforms of the oil and gas industry are offered in these works. In article [7] we have considered in detail the problems of power interaction between the solidifying metal of casting and mold.

The corps details (fig. 1) which have big external diameter in comparison with thickness of the detail walls have been chosen as objects for research in this work. Such design is always a problem for technology development of her production as to ensuring of quality it is necessary to apply at once all complex of technological methods which includes the following tasks: completion of the detail design (use of shrink-resistant edges, technological stock, plate's ribs and so forth); development of technological means for creation of the volume or directed casting metal solidifying; development of special model and industrial equipment, methods for providing a necessary pliability of materials of the casting mold and cores.

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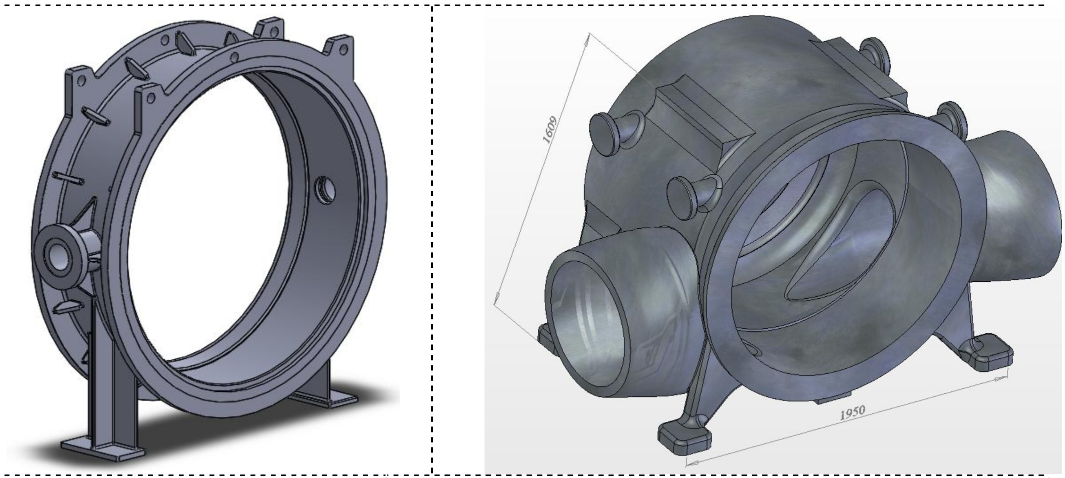


(a) (b)

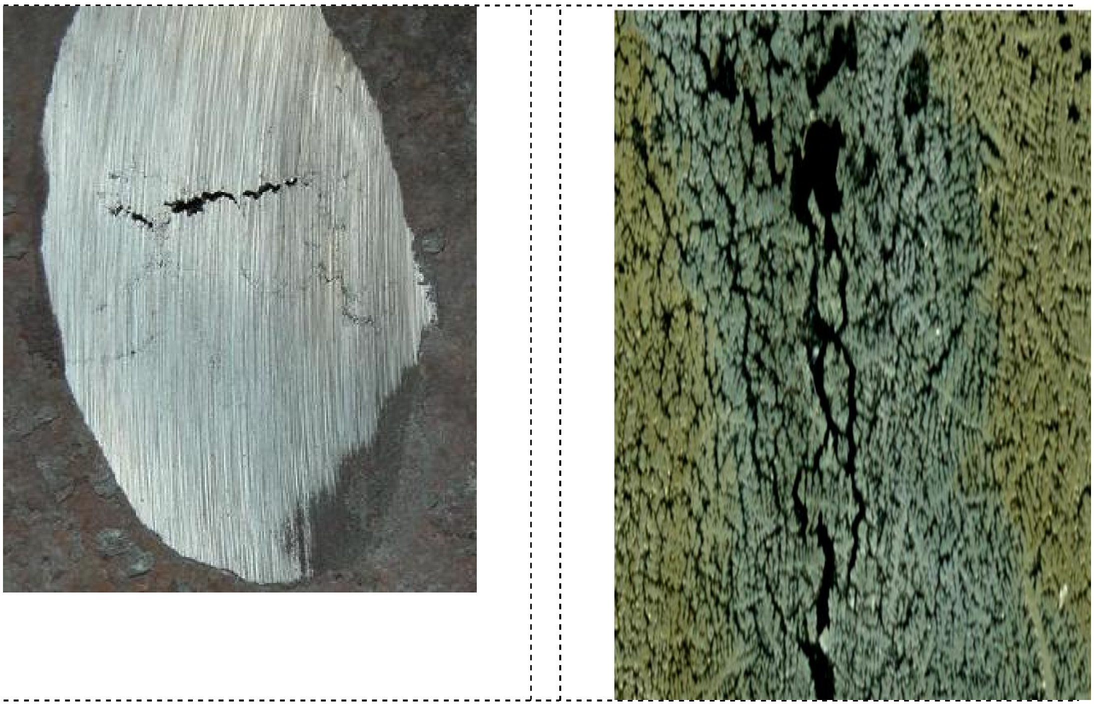
Figure 1. Objects of research – corps steel castings: (a) corps of valve disk rotary lock with orifice of 800mm; (b) corps of the natural gas supercharger with orifice of 1200mm

Even application of vacuum-film mold technology which is the safest in terms of emergence of hot cracks not always solves a problem. Casting feed by liquid metal occurs through the feeders directly in the corps flange, and for high-quality improvement of feed the special thickenings are structurally made. Thus, walls of casting enough quickly solidify because of small cross section, and the flange exists long time in strongly warmed state under thermal influence of feeder, speeds of metal solidification can differ several times for wall (plate) and flanges.

2. Research methods

The strong temperature gradient in solidifying steel casting of corps on one hand is favorable to creation of volume or directed solidification, but on other hand existence of several centers of crystallization is a source of their competition, and at realization of the complicated metal shrinkage the intermediate zone which shrinkage is insufficiently compensated by liquid metal is formed. Such zone is presented in fig. 2. At decrease in metal temperature below the solidus point metal loses the plasticity, but doesn't gain sufficient durability yet, and due to uneven shrinkage between areas of the corps flange and wall there is a hot tearing.

Considering a real macrostructure (fig. 2.) of a hot crack in the casting wall (steel ISO 200), the existence of a crack between a zone of columnar dendrites and area of the equiaxed crystals was observed distinctly. The last one has been strongly warmed as a result of feed from feeders. The casting wall with columnar dendrites has smaller section and is cooled more intensively from mold and core. For forecasting of hot cracks formation was developed techniques of numerical modeling which reproduce all thermal process of metal solidification. Further the grid of final elements in the form of tetrahedrons is generated, for such operation any available generator FEM can be used.



(a) (b)

Figure 2. A hot crack in casting of corps valve disk lock: (a) crack disposition on radial transition of the through passage section to a flange; (b) crack macrostructure, x10

Standard methods for calculating of heat conduction problems cannot be used for the simulation of solidification metal of casting in mold, because it does not take into account a number of physical processes, such as a phase transition or release of latent heat of crystallization.

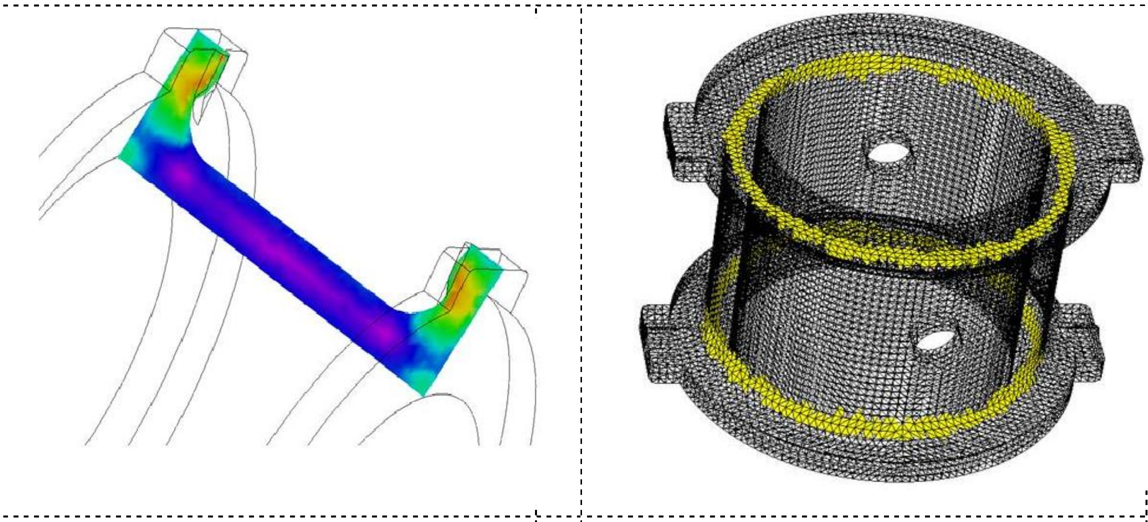
For computer realization of calculation of cooling of casting in mold the special calculation procedure was developed where the equation of thermal balance for i-element of the grid splitting is as follows:

$$\sum_{j=1}^{m} k_{i,j}^{n}(T_i^n - T_j^n)F_{i,j}\Delta\tau = C_i G_i (T_i^n - T_j^n) \quad (1)$$

where k – heat transfer coefficient between elements i and j; m – quantity of not-adiabatic sides of an element (m=4); F – the area contact between elements i and j; C_i и G_i – specific heat capacity of the element material and its weight; $\Delta\tau$ – time step; n – time index.

On contact of an i-element with an j-element the heat transfer coefficient is determined by a formula: $k_{i,j} = 1/(L_i/\lambda_i + L_j/\lambda_j)$, where L – the distance from the center of gravity of an "i" - element (with the heat conductivity coefficient λ) to the next element in the direction of the thermal stream movement. Preliminary all elements of FE grid are indexed (on belonging to materials and on boundary conditions of a heat transfer) that allows to change parameters of heat conductivity, a thermal capacity, etc. properties in process of calculations. For determination of heat and physical properties of materials which participating in a heat transfer their temperature dependences which are stored as piecewise linear dependences in the special database are used. As a result of calculations are temperature fields in metal, mold and core was formed on each time step. The Scheil-Gulliver model adjusted for the non-equilibrium of crystallization process was used as model of crystallization which allows to consider more precisely emission of latent heat of crystallization. Speed of solidification process was calculated as a ratio of a total time of element (i) solidification to the temperature range of solidification $V_i = \frac{T_{liq} - T_{sol}}{\tau_i}\left[\frac{^oC}{\sec}\right]$

As soon as temperature of metal has decreased lower than temperature of alloy liquids, there are conditions for firm phase formation according to the phase diagram. The process of crystallization begins and firm phase - g_S occupies some fraction $0 < g_S < 1$ from the metal volume which gradually increases with advance of the front of solidification. For the conditional "equilibrium" state of solidification comes to an end with achievement of solidus temperature and full solidifying of metal $g_S = 1$. For the case of equilibrium crystallization this range depends on the structure of an alloy and the inclination of the liquids line on phase diagram. Development of equilibrium crystallization process - $g_s(T)$ is described by the famous "lever rule". But in actual practice the temperature range of metal crystallization will also depend on the non-equilibrium factor – $g_s = 1 - \left(\frac{T_f - T_{liq}}{T_f - T} \right)^{\frac{1}{1-k}}$ first of all connected with local speed of solidification which for complex casting will have difficult distribution gradient of temperature (fig.3).



(a) (b)

Figure 3. Temperature gradient in the section of solidifying steel casting – (a) and computational area by criterion of danger of hot cracks formation – (b)

3. Results and Discussion

Existence of the powerful gradient of speeds of metal cooling leads to a situation when one local area of casting has completely solidified (passage section of the corps of the disk lock valve) at the same time it has managed to realize own shrinkage at the expense of still pliable liquid area. The casting zone with a low speed of cooling can't freely realize shrinkage without power consequences any more. Existence of the area which is in intermediate region between a zone of fast and slow solidifying is dangerous in aspect of the hot cracks formation. Distinction in cooling speeds, and hence in rate of solidification in turn seriously determines degree of feed by liquid metal for various local zones of casting. Such distinction in speeds of solidifying can be critical in terms of formation of thermal shrinkage of metal which at a strong gradient will lead to a hot tear in field of transition from one local zone to another. For casting of corps of rotary lock the dangerous zone on thermal gradient border (fig. 3(b), it is highlighted in the color) was revealed that corresponds to practice. Hot cracks usually hit such castings through on radial transition from cylinder to flange.

The analysis of thermal deformations calculated according to non-stationary temperature fields causes a number of complications for understanding of the mechanism of the complicated metal shrinkage. The incompressible nature of plastic deformation creates restriction in each element of FE grid. When the number of the restrictions arising because of incompressibility surpasses the number of degrees of freedom, blocking takes place as there is no possible decision for this case. The reduced order of calculated iterations for hydraulic components of tension (sphere tensor) can be the decision that can lead to inadequate results. The effect connected with it follows from an order of fields of thermal tension in the elements of FE grid. If nodal temperatures are interpolated for obtaining of temperature values in the element, they are used for determination of thermal tension, the field of thermal tension has the same order, as well as the field of movements in the element. The full deformation calculated from partial derivative movements, 10 times less. This incompatibility can also lead to problems at the decision. The need to avoid the fields of incompatible deformations is well-known, and in our case we always has within calculation a set of materials with various and changing in time elastic properties, and in case of the superficial accounting of such features the considerable mistakes can appear. The basis for the analysis of the stress-strained state of metal castings during hot cracks formation is the information on temperature fields [9] and microstructure [10] formation. The modeling of hot tearing formation during DC casting can be identified as a particular task [11,12].

However, the solution task about development of tension and deformations demands the special approach based on load mechanical model of interaction of solidifying metal casting with the sand mold offered by us in works [6, 7].

4. Conclusion

To prevent hot cracks formation it is possible at the stage of design process to carry out the modeling of solidification and to make the relevant amendments to technology of casting. The proposed criterion for assessing of the risk of hot cracking formation can be formulated as follows: the availability of areas in the casting containing several unrelated thermal centers as well as the presence of a strong gradient of cooling rates. Under such gradient it is possible to consider a difference in solidification speeds at distance not less than two minimum thickness of casting walls or existence of two or more thermal centers with a cooling speed difference in 30÷50 of °C/sec.

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