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QUANTITATIVE EVALUATION OF THE EFFECT OF TECHNOLOGICAL FACTORS ON ORIGINATION OF HOT CRACKS IN “TRACK LINK” CASTING

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casting, stress-strain state, got cracks, sand-loam mould, thermal field, pouring temperature, mix yielding, casting wall thickness.

ABSTRACT

The paper examines the problem of rejected material appearance during fabrication of shaped casting “Track link” manufactured on the base of Mechanical and Repair Complex that is a part of Magnitogorsk Iron and Steel Plant (MMK) in Magnitogorsk. Hot cracks are considered to be the main cause of rejects for such castings. These cracks are arising due to force interaction between casting and mould, as a result of development of shrinkage processes during cooling of a casting. The main methods of evaluation of hot brittleness of a cast billet are displayed, the scientists from Russian and foreign scientific schools that have conducted researches in this area are mentioned. The technology of fabrication of the casting “Track link” is considered in the work. It is noted that the casting material (steel 110G13L) is characterized by low mechanical properties at high temperatures, large casting shrinkage and low heat conductivity; thereby these material parameters can be concluded to be a cause of high hot brittleness.
Thermal interaction between casting and mould is examined using the numerical methods for solving the problems of heat conductivity. Influence of geometry and technological factors (such as wall thickness, pouring temperature, yielding of foundry mould) on development of stress-strain state of cast billet wall is determined. The dynamics of varying of arising stresses depended on geometry variation as well as on technological factors of casting fabrication (pouring temperature and mix yielding) is shown. Quantitative evaluation of the effect of each separate factor is calculated. It is displayed that wall thickness of a cast billet has the most strong effect on its stress-strain state. Recommendation for varying of wall thickness of a cast billet by 3 mm is given. It led to calculated lowering of stresses by 27.62% and, consequently, to absence of metal rejects caused by hot cracks during fabrication of pilot series of castings.

Introduction

Decrease of metal rejects caused by hot and cold cracks, as well as by buckling, is considered as one of the most important factor having the effect on resource and energy saving and, consequently, on the cost of foundry production. Rejects caused by hot cracks are ones of the most hardly predictable among the above-mentioned defects. Braking of free linear shrinkage of castings by mould or mould core are considered as the main cause of origination of hot cracks in shaped castings. As a result, critical tensile strains appear. Prevention of hot cracks origination remains the actual problem for foundrymen, despite of simplicity and complete understanding of the mechanism of origination of such stresses. Usage of unyielding moulds and mold rods, necessity of decrease of casting wall thickness can lead to forming of critical stresses and, respectively, crack origination in a cast billet.

Mechanical properties of the system “casting – mould” in general should have the decisive influence on the alloy ability to form crystallization cracks, as well as on ability to any other destruction. Thereby it is necessary to pay the main attention during analysis of hot brittleness to examination of mechanical properties and regularities of elastic and plastic deformation and destruction of the alloys in solid-liquid state [1]. Analysis of hot brittleness can’t be reduced to examination of only mechanical properties of the casting material. Especial attention should be paid to the thermal processes of fabrication of a cast billet. Heat and mass transfer in a sand-loam casting mould (SLM), shrinkage processes, temperature softening of sand-loam mix are connected with the effect of thermal flow of a casting and finally have the effect on stress-strain state of a cast billet [2].

Theoretical aspects of the problem

Hot brittleness of castings in foundry production is practically evaluated using special technological samples. Development of such samples, i.e. designing of special castings with simple shape, where hot cracks origination is susceptible to varying of alloy grades and technological parameters, have been conducted by H. F. Hall, J. Middleton, H. Fredriksson and many other scientists [3–7]. High expenses and hard workability of such method are the deficiencies of this technique, so such samples are used only for definite identified casting groups. Additionally, the differences in thermal and force processes of casting and sample fabrication allow to speak about this method only as about the indirect evaluation of hot brittleness of cast billet.

The criterion evaluations of crack resistance of a casting are known; they are built on the analysis of mechanical characteristics, temperature conditions of its fabrication etc. (A. P. Trukhov, Yu. S. Gomelskiy, L. S. Konstantinov, N. A. Feoktistov, G. F. Balandin, B. B. Gulyaev, Yu. A. Stepanov et al. [8, 9]). The indirect features of evaluation of the stress state of a cast component are considered.

Strength calculations of a casting should be considered as the most exact prediction methods for crack origination. These calculation methods are rather prospective because they allow to deepen the knowledge about hot crack origination and about the effect of technological factors during casting fabrication.

This paper presents the calculation method for analysis of shrinkage stresses during manufacture of the casting “Track link”.

Analytical materials and methods

Let’s consider influence of shrinkage processes on forming of stress-strain state the casting “Track link”. Its fabrication is conducted in the dry sand-loam mould (SLM). 5%-containing kaolin clay (C_2) is a binder, and steel 110G13L is casting material. The chemical composition of this steel is as follows (%): C: 0.9–1.5; Si: 0.3–1; Mn: 11.5–15; Ni: до 1; S: up to 0.05; P: up to 1.12; Cr: up to 1. Steel pouring temperature makes 1520 °C, liquidus temperature is 1425 °C and solidus temperature — 1370 °C. Wall thickness of the examined casting $\delta = 0.02$ m and the coefficient of linear expansion of 110G13L steel is equal to $18 \cdot 10^{-6}$ 1/°C.

This steel is also characterized by such disadvantage as high ability to hot crack origination, connected with its low mechanical properties at high temperatures, large linear and volumetric shrinkage and low heat conductivity.

Discussion on the results

The process of casting fabrication in a foundry mould is accompanying by forming of hot cracks in the link wall (**fig. 1**), that are the main material reject for such casting.

To exclude the arising rejects, the effect of geometrical dimensions and technological parameters (such as pouring temperature, yielding of moulding mixture) on forming of the stress-strain state of casting “Track link” has been examined in the area of violation of the cast billet wall.

It was noted that yielding of moulding mixture has substantial effect on arising stress state in a casting wall; in its turn, it depends on thermal state of the casting [10]. Thermal interaction inside the system “casting — mould” has been evaluated via numerical solution of the heat conducting problem.

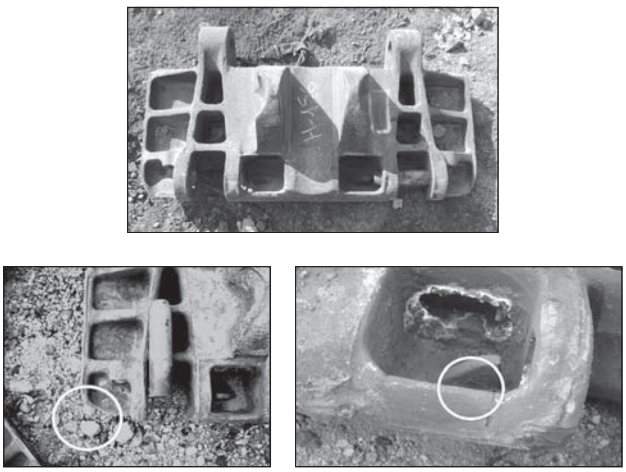

Fig. 1. Hot cracks in the wall of casting «Track link»

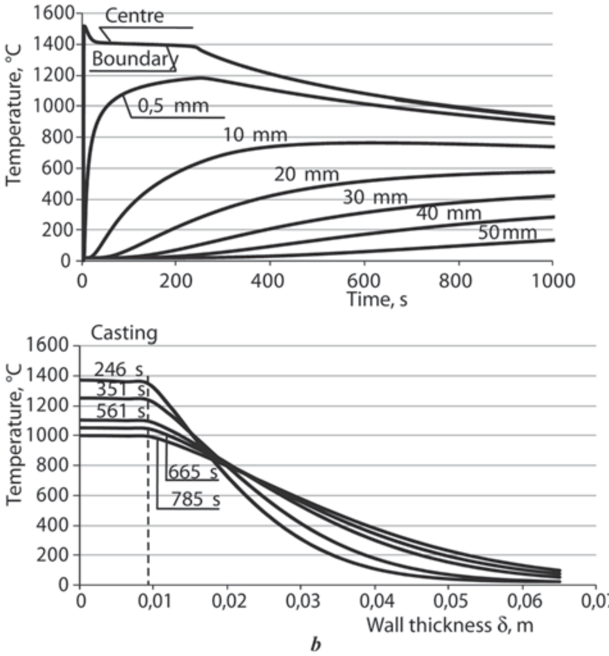

Fig. 2. Variation of the thermal field in the system “casting – mould”:
a — variation of the thermal field of the mould, boundary and centre of the casting in dynamics;
b — temperature distribution in the cross section of the object “casting – mould”

The dynamics of thermal field varying in the system “casting — sand-loam mould” is reflected on the **fig. 2, *a***, where temperature variation in the center and boundary of the casting wall is shown, as well as the temperature curves of moulding mixture corresponding to 0.5; 10; 20; 30; 40 and 50 mm distance from the boundary of the casting wall. Variation of the thermal field in cross section of the examined object has been investigated since the moment of complete solidification of the cast billet wall and is displayed on the **fig. 2, *b***. The obtained data about thermal state inside the system “casting – mould” have been used for determination of mechanical parameters during calculation of shrinkage processes in solving the problem on the stress-strain state of the cast billet.

To provide the quantitative evaluation of casting wall deformation, arising as a result of its force interaction with the layer of moulding mixture, the following expression has been used [11]:

$$\varepsilon = \frac{\Delta T \alpha}{1 - \Delta T \alpha}\left(1 - \frac{E_{cast} k \ell''}{E_{cast} k \ell'' + 2\ell' \delta_x \sum_{i=1}^{n} E_i}\right), \qquad (1)$$

Where ε — relative deformation of casting, units; α — coefficient of alloy linear expansion, °C^{-1}; ΔT — difference of temperatures corresponding to the average wall temperature before and after casting shrinkage, °C; E_{cast} — young’s elasticity modulus of casting, MPa; k — wall

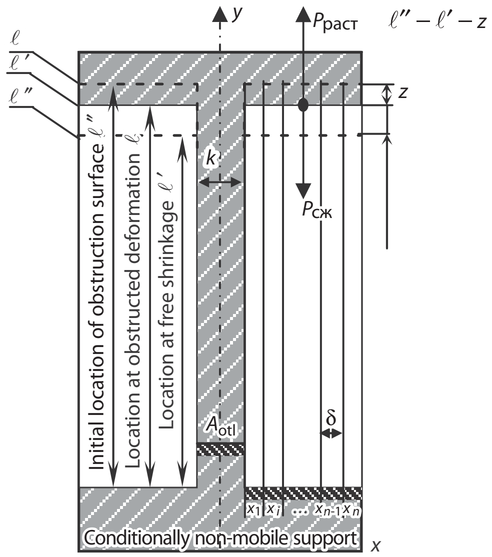

Fig. 3. The scheme for calculation of deformation in the system "casting – mould" at obstructed shrinkage

thickness of casting, m; ℓ' — length of compressed layer after free deformation, m; ℓ'' — length of compressed layer before free deformation, m; δ_x — thickness of mixture layer, m; E_i — young's elasticity modulus of *i*-layer of moulding mixture, MPa.

If we use (1) expression to describe the processes in the plastic area of casting deformation, tangential elasticity modulus is accepted instead of Young' elasticity modulus E_{cast}.

Force interaction between casting and mould are presented schematically on the **fig. 3**. It is shown there that braking of casting shrinkage by the plane l occurs as a result of its wall cooling; thereby extending deformation arises, which is expressed by the difference of $\ell''- \ell'$ planes location. These planed reflect revealing of obstruction element in free shrinkage and its current location.

Using the Hook's law

$$\sigma = E\varepsilon \qquad (2)$$

and the expression for deformation resistance in the dry layer of moulding mixture σ_i, MPa,

$$\sigma_i = 7{,}54\cdot10^{-8}T_i^3 - 7{,}67\cdot10^{-8}T_i^3\varepsilon + 0{,}48\varepsilon^2 - \\ -1{,}2\cdot10^{-4}T_i^2 - 1{,}3\cdot10^{-7}T_i^2\varepsilon^2 + 1{,}21\cdot10^{-4}T_i^2\varepsilon - \\ -4{,}4\cdot10^{-4}T_i\,\varepsilon^2 - 0{,}0432T_i\varepsilon + 4{,}6\varepsilon + 0{,}04T_i, \qquad (3)$$

where T_i — temperature of moulding mixture, °C; ε — relative deformation of the mixture layer, %, the yielding effect of compressing layer of a casting mould on cracks arising in the casting wall has been determined. Yielding effect has been expressed through the sum of elasticity moduli of *i*-layers of moulding mixture $\sum_{i=1}^{n} E_i$ (rigidity of compressing layer of moulding mixture). These layers were taken under the obstruction element (see fig. 3). It should be mentioned that stresses caused by obstructed shrinkage can be also determined via (2) expression due to brittle destruction during hot crack arising in the wall of cast billet.

Using the expressions (1) – (3), the authors have calculated development of stresses in the casting wall during its cooling (**fig. 4, *a***). This calculation has been conducted via the following algorithm: prediction of the thermal field of "casting – mould" system; determination of mechanical parameters of the system objects; calculation of yielding of the compressing layer of moulding mixture; determination of extending deformation of the casting wall. Calculation was based on using of the average temperature value of cast billet wall in the direction of its thickness.

It was established during consideration of the effect of geometrical parameters of cast billet (expressed by wall thickness δ) on the stress state, that increase of wall thickness leads to essential lowering of stresses for the same values of casting wall temperature (1100, 1200 and 1300 °C). Increase of δ by 10 mm leads to lowering of arising stresses by 54 % in average (**fig. 4, *b***).

The melt pouring temperature is the most important technological factor having the effect on stress-strain state of the system "casting – mould". Analysis of the effect of melt overheating temperature has displayed that variation of pouring temperature in the framework of 1470–1520 °C has slight effect on shrinkage stress (**fig. 4, *c***). In this connection, yielding of moulding mixture is considered as a substantial factor having the effect on stress-strain state in the system "casting – mould". Mixture yielding is one of the technological parameters that can be used actively during fabrication of cast billet via varying the content of component composition of sand-loam mixtures [14]. Quantitative evaluation of yielding value has conducted in this research by summarizing of Young's elasticity moduli of the layers of moulding mixtures $\sum_{i=1}^{n} E_i$ that have been taken under shrinkage obstruction element. Fig. 4, *c* shows the relationship between stress state of a casting wall and variation of rigidity of compressing layer in moulding mixture. Calculation has been done for the values of casting wall temperature equals to 1100, 1200 and 1300 °C. The results of this calculation have displayed that yielding variation $\sum_{i=1}^{n} E_i$ under shrinkage obstruction element from 4700 to 2500 MPa has led to lowering of stresses by 24.9 % (see fig. 4, *d*).

To compare the effect of investigated technological factors, the relationships (4) (see fig. 4, *b–d*) have been transferred to the coordinates $\sigma - \xi$, where ξ means the value of relative variation of the technological parameter in the range from 0 to 1:

$$\chi_{0(1)} = 0{,}1\xi\chi_{init} + 0{,}95\chi_{init}\,, \qquad (4)$$

where ξ — the value of relative variation of the technological parameter in the range from 0 to 1,obtained for the interval ± 5 % of the initial value of the varying technological factor; $\chi_{0(1)}$ — the values of technological factors corresponding to $\xi = 0, \xi = 1$; χ_{init} — the initial value of the technological factor in the researched variation interval.

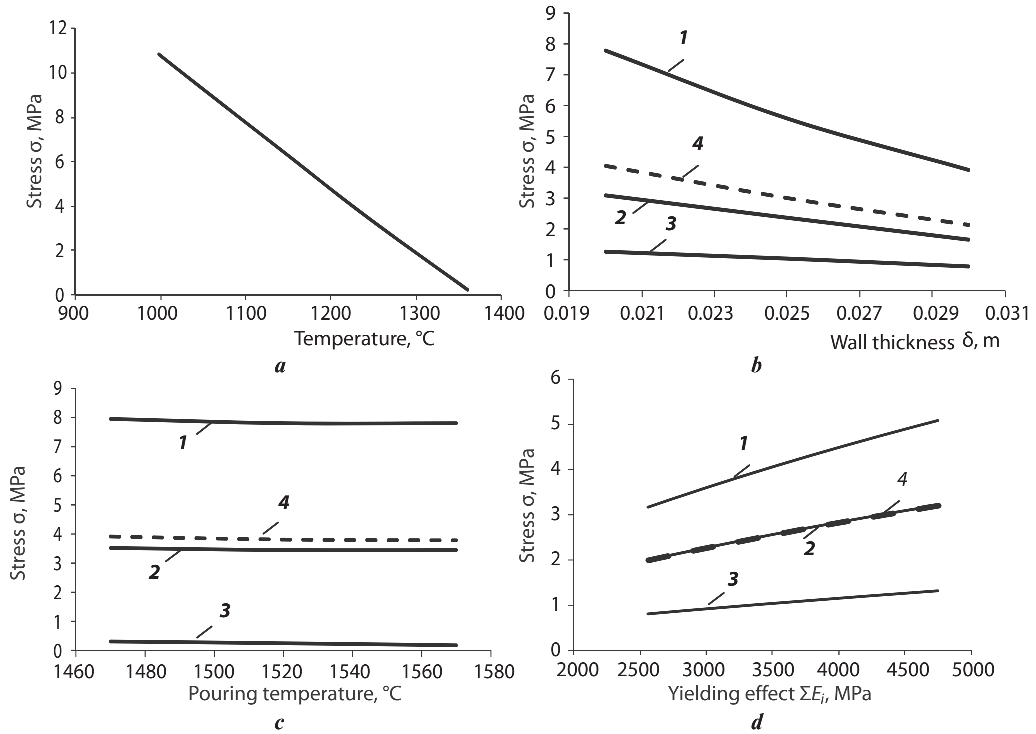

Fig. 4. Dependence between shrinkage stresses and:
a — casting wall temperature; *b* — casting wall thickness at its temperature (*1* — 1100 °C; *2* — 1200 °C; *3* — 1300 °C; *4* — average stress value); *c* — steel pouring temperature; *d* — moulding mixture yielding

The values of technological parameters $\chi_{0(1)}$ corresponding to $\xi = 0$, $\xi = 1$, as well as the values of arising shrinkage stresses are obtained using the expression (4). It allowed to receive the following regression equations in the relative range of variation of the value of technological parameter ξ:

$$\sigma_\delta = -0,48\xi + 3,3, \quad (5)$$

$$\sigma_T = -0,17\xi + 3,93, \quad (6)$$

$$\sigma_{\Sigma E_i} = 0,24\xi + 2,53\,. \quad (7)$$

Derivatives of the obtained functions (5) — (7):

$$\frac{d\sigma_\delta}{d\delta} = -0,48\,, \ \frac{d\sigma_T}{dT} = -0,17\,, \ \frac{d\sigma_{\Sigma E_i}}{d\Sigma E_i} = 0,24$$

characterize the rate of growth of shrinkage stresses depending on variation of the technological factor. If we shall deduce the value of derivatives to 1, we shall get the histogram of the technological factors having the effect on stress-strain state of "Track link" casting wall (**fig. 5**).

Analysis of the obtained results based on variation of the casting wall thickness in the range 0.02–0.03 mm, variation of pouring temperature between 1470–1570 °C and variation of mould yielding from 2500 to 4700 MPa has displayed that casting wall thickness has the most effect among these parameters. Yielding and pouring temperature have substantially less influence, thereby varying of wall thickness with its increase is the most efficient way to decrease residual stresses of the casting "Track link".

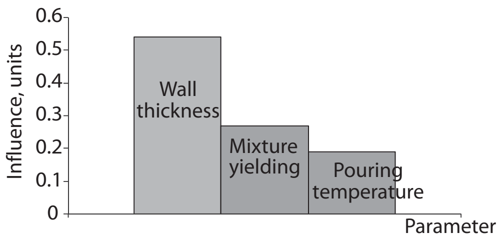

Fig. 5. Influence of technological parameters on the stressed state of the casting

The industrial experiment included fabrication of 30 castings with increased wall thickness (from 20 to 23 mm) has shown that metal rejects caused by hot cracks have not been observed. At the same time calculated stress was decreased by 27.62%.

Conclusions

The results of this work can be formulated in the following conclusions:

- The force interaction between the casting "Track link" and the mould is analyzed.
- The effect of pouring temperature, casting wall thickness and moulding mixture yielding on arising shrinkage stresses are examined.
- The quantitative evaluation of the effect of each of the investigated factors on the value of arising stresses is given,

and it is shown that variation of geometrical parameters of the casting wall is the most important among these factors.

• Increase of wall thickness of the casting "Track link" by 3 mm has diminished the value of shrinkage stresses by 27.62 % (it was established via calculations); in its turn, it leads to decrease of possibility of forming of metal rejects caused by hot cracks.

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LARGE INGOT. MAIN ACHIEVEMENTS, MOST IMPORTANT SCIENTIFIC AND TECHNICAL PROBLEMS, PERSPECTIVE DEVELOPMENT DIRECTIONS*

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Key words:

large ingot, chemical heterogeneity, structural heterogeneity, crystallization, thermal-physical parameters, critical transition brittleness temperature.

ABSTRACT

The paper describes qualitative variation of thermal-physical parameters of solidifying large ingot and the following consequences of this variation. The chemical elements presented in the ingots, their classification and effect on operating parameters of finished products are described as well. The tendency to rise of ingot metal purity and positive influence of this tendency on the value of brittle-tough transition in steel is presented.

Today we can speak about several general fundamental relationships that allow to consider a large ingot as an object of management and to solve the problems of engineering and control at the most responsible stages of its forming in IT terms.

Physical-chemical and hydrodynamic appearances occurring during crystallization are mainly determined by thermal-physical situation in a solidifying ingot. The appearing dynamic thermal state can be completely described by 3 values: temperature gradient G, linear rate of crystallization V and cooling rate ε. Only two of these values are independent for ideal isotropic medium, consequently

$$\varepsilon = G \times V, \text{°C/c} \quad (1)$$

Variation of the main thermal-physical parameters depending on the average diameter is presented on the

* A. N. Romashkin, E. V. Makarycheva, S. I. Markov, A. G. Lebedev, V. A. Dub, A. G. Balikoev participated in this research.