Proceedings of the World Congress on Engineering and Computer Science 2011 Vol I
WCECS 2011, October 19-21, 2011, San Francisco, USA

Numerical Evaluation of Hot Tearing in the Solidifying Casting

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***Abstract*— Hot tearing is a serious defect that appears during the solidification of an alloy. Due to the low recurrence of the phenomena occurring during alloy solidification, such as the evolution of grained structure or stress redistributions, the casting's susceptibility to hot tearing can be estimated only in an approximate way. This work concerns with a new criterion for hot tearing evaluation in castings. An algorithm for the computer simulations of the phenomena accompanying the casting formation is introduced and discussed.**

***Index Terms*—casting, computer simulation, hot tearing, solidification processing**

I. Introduction

The production of castings is an important technology that involves many factors of significant impact on the quality of the finished product. In shape casting, an equiaxial structure is formed. During solidification processes in the solid-liquid areas various types of defects may appear. Among them the shrinkage leads to macro-porosity or/and micro-porosity effects, while the stress reveals the so-called hot tearing in the casting. Hot tearing of solid-liquid areas occurs when the stresses acting on them are able to break the backbone of solid phase, filled with the liquid phase.

Hot tearing of castings was and still is of founders and scientists interest [1,2]. Initially, the problems of hot tearing formation were solved by experimental estimation of the hot tearing susceptibility of foundry alloys. Then, the mathematical models have been developed. Unfortunately, the studies, predominantly focused on the formation of a single crack, were not relevant to industrial practice. The next step in the development of testing methods for hot tearing occurrence was the use of advanced numerical methods, through the computer simulations [3].

Approaches based on computer simulations can be divided into two groups. The first group concerns the analysis of development of a single crack, whereas the second group involves a comprehensive analysis of thermo-mechanical phenomena, accompanying the production process of castings. The analysis of thermo-mechanical phenomena attempts to draw conclusions for assessing the degree of risk of the appearance of defects in continuity in the entire casting or in its selected parts [4]. Such an approach would allow to built up commercial engineering programs. However, such programs do not contain any criteria for hot tearing evaluation in castings. Users have to decide which of the calculated values characterizing the state of stress and /or deformation are appropriate to the rupture-susceptibility evaluation. It should be noted, however, that such an analysis is very time consuming, requires good knowledge of the phenomena in casting formation, skills in simulation of these phenomena and possessing specialized engineering software, usually based on a finite element method.

In this paper, we are focused on the analysis of the susceptibility to hot tearing during an equiaxial structure casting. We propose a new stress criterion to assess the level of risk of rupture in selected fragments of the casting. The evaluation of castings hot tearing with the use of this criterion is possible only after conducting a series of simulation calculations, according to the algorithm proposed here. The result is the information about the degree of rupture risk in selected areas of the casting. Studying the susceptibility to hot tearing by using the method proposed here is time-consuming, but the already achieved calculations' speed will result in applications of the proposed solutions in foundry practice.

II. The Criterion for Hot Tearing Evaluation

Metal alloys often solidify by increasing equiaxial dendrites. It can be assumed that initially each dendrite grows individually. As the dendrites are in contact with each other they form the backbone of the solid phase. Dendrite arms are intertwined with the arms of their neighbors. From this point, there appears tension in the solidifying solid-liquid area, carried by each entangled dendrite arm. Dendrites are separated by layers largely filled with the liquid phase. Such two-phase areas (consisting of the growing equiaxial grains and separating them layers of the liquid phase) in the numerical modeling are represented by hexagonal solid phase grains and the surrounding layers of the liquid phase. The solid phase is presented using regular hexagons, while the liquid phase by means of flattened hexagons. The relevant parts of these two types of hexagons are on the border area, see Fig. 1. The size of both areas (solid and liquid phases) is characterized by participation of the solid phase, calculated at the stage of solidification simulation.

Modeling solidifying casting area enables operating at the micro level of analysis separately for growing grains and for narrowing layers of the liquid phase. Solidifying metal grains almost always are much smaller than finite elements used in calculations and in the macroscopic stress analysis.

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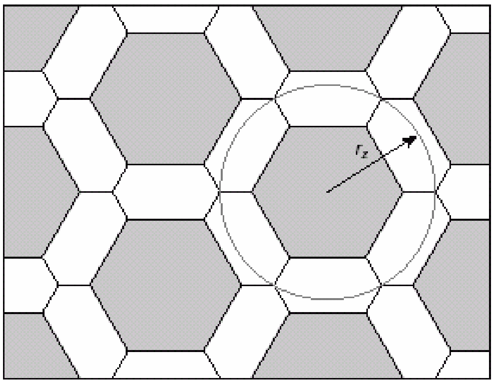

Fig. 1. Model of two-phase area for the alloy solidifying in the form of equiaxial grains.

In the macroscopic analysis, two-phase area is treated as isotropic, ignoring the grain nature of the casting construction. However, since the solidification simulation is carried out based on the coupled model, i.e. macro-microscopic, so after the solidification simulation there can be easily reconstructed the accumulation of grains in two-phase areas, which combined with the analysis of stress at a microscopic level enables to analyze the phenomena that could lead to hot tearing.

The most important causes of stress in the casting are uneven temperature gradients and the resistance posed by the wall of the mold to the shrinking casting. Conditions of heat evacuation from the casting to the mold and to the environment determine the speed of the alloy solidification, i.e. the equiaxial grains growth speed, but also the speed of the stress generated in the casting.

To evaluate hot tearing of the solidifying casting there is proposed a new stress criterion that takes into account the stress-speed ratio of effective stress in the layers separating the congealed particles to the speed of effective strain in these grains. The proposed criterion is expressed by the so-called local coefficient of susceptibility to hot tearing, marked as Θ. This is the criterion, which deals with stress states in micro scale, but these conditions are obtained under the stress states in a macro scale. During the solidification, the changes in geometry (size) of grains and separating layers is obtained from microscopic analysis conducted on the basis of macroscopic modeling. This is possible because in the macroscopic modeling the growth of equiaxial grains is represented by the connection of diffusion phenomena (micro scale) with thermal phenomena (macro scale). The calculation of the local coefficient of susceptibility to hot tearing proceeds in the following time steps, beginning with the participation of the solid phase, in which the backbone of solid phase is formed, until complete solidification. Effective strain rate can be written as:

$$\dot{\bar{\sigma}} = \frac{|\Delta\bar{\sigma}|}{\Delta t}, \tag{1}$$

where: $\Delta\bar{\sigma}$ is the effective stress increment in the time step Δt.

The study shows, however, that much better results are obtained by an introduction of relative effective stresses to the criterion. Therefore it can be written that:

$$\Theta = \frac{|\Delta\bar{\sigma}_l|}{|\Delta\bar{\sigma}_g|}\frac{\bar{\sigma}_g}{\bar{\sigma}_l}, \tag{2}$$

where: l is a sub-layer separation, while g denotes the sub-grain-solidified parts. The quotient of relative increment of effective stress in the layers and the grains tends to zero with increasing share of the solid phase. Thus, in the sake of clarity, the criterion for hot tearing may be transformed to the form:

$$\Theta = -\ln\left(\frac{|\Delta\bar{\sigma}_l|}{|\Delta\bar{\sigma}_g|}\frac{\bar{\sigma}_g}{\bar{\sigma}_l}\right). \tag{3}$$

Application of the criterion (3) requires a computer simulation in the macro scale, and then in the micro scale. At the macro level macroscopic (standard) finite elements are used, while at the micro level – microscopic elements, covering the macroscopic element area. Also, formulating the finite element method is different for both types of simulation. At the macro level it is a traditional formulation, e.g., based on the method of weighted residuals, while at the micro level.-.hybrid formulation was used [5,6].

The local coefficient of susceptibility Θ given by (3) describes the local susceptibility to hot tearing of a small macroscopic area, corresponding to one finite macroscopic element, subdivided into two areas, i.e. grains and layers separating them. Used in equation (3) stress values and their increments are determined for the subdivisions of layers and grains, receiving two tensors which describe the resultant state of stress in all the grains and the resultant state of stress in all the layers of separation, which belong to the analyzed area. Tensors are obtained as a result of the so-called homogenization, based on the integration of the stress function in the above-mentioned subdivision, and then dividing the resulting value by the area of integrated subdivision.

Large values of factor Θ indicate high susceptibility to hot tearing. However, the value of Θ increases with increasing equiaxial grain, as a result of stress growing with an increasing solidification area. Therefore, the criterion Θ does not indicate a specific limit value, above which the casting will crack. Θ factor values are used to indicate the areas of analyzed casting, where most likely appears a damage, i.e. the rupture. Θ criterion can also be used to determine the conditions most conducive to the production of a given type casting.

A. Algorithm for preparatory calculations of Θ

Computation of factor Θ is possible after a complex computer simulations that provide data on which you can only determine (estimate) the susceptibility to the casting hot-tearing. At this stage, a number of preparatory tasks are performed. The steps leading to denoting the casting susceptibility to hot tearing cover the following.

1. Simulation of solidification. For succeeding time steps the temperature field, the distribution of the solid phase participation and the mean radii of equiaxial grains, are determined.
2. Calculating distributions of stress in consecutive time steps.

3. Identification (selection) of subdivided areas for the hot tearing analysis.
4. Division of the macroscopic finite elements into the microscopic-hexagon-hybrid-finite elements in order to obtain the solid-liquid areas.
5. Calculation of the stress in all solid-liquid areas corresponding to the macroscopic finite elements.
6. Calculation of the value of coefficient Θ for each macroscopic finite element in the selected areas.
7. Preparation of the scale of susceptibility to hot- tearing based on the simulations and calculations carried out for all the analyzed variants of the task.
8. Execution of a local distribution coefficient diagrams for susceptibility to hot tearing for different variants of the task.
9. Drawing conclusions.

The first two steps are described in literature [7]. Therefore, only the remaining steps will be described below.

B. Identification of subdivisions

There is no point in conducting the analysis of the susceptibility to hot tearing for all the macroscopic finite elements of the casting. As the practice indicates, the cracks appear only in selected, easy identified, fragments of the casting. To proceed to the identification of such fragments, a group of finite elements and the area around, must be selected beforehand. This selection can be done with the help of the probability of the hot tearing localization. The group of selected macroscopic elements should be slightly greater than the area of the analysis. There should be also a group of macroscopic elements (of a similar number of the elements) selected for analysis in the area least subject to hot tearing. If there is a suspicion about the possibility of hot tearing appearance in other parts of the casting, then another group of elements should be created and analyzed. For the casting shown in Fig. 2, three groups of elements were selected.

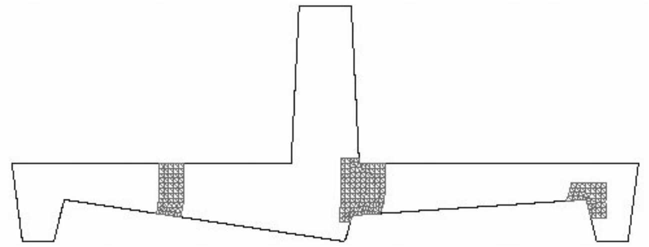

Fig. 2. Location of selected groups of macroscopic elements for the analysis of hot tearing.

The major group is located in the central part of the casting and includes elements collected under infusion and forming a notch around the bottom of the casting. This is the group at high risk of hot tearing. In the group of elements located on the left, in the casting arm, there is no danger of hot tearing. Rupture should not occur either, by design, in the third group, comprising the area around a 'notch' connecting the right shoulder with the casting 'head' located at its end.

Comparing the areas selected for the analysis with the size of the entire area of the casting (Fig. 2) shows that the number of elements selected for analysis is relatively small in comparison with the number of finite elements in the whole casting.

C. Figures division of the macroscopic finite elements into the microscopic finite elements

Macroscopic finite elements belonging to the group of the elements analyzed from the point of view of susceptibility to hot tearing are divided into hybrid, microscopic finite elements [6]. The hybrid finite element mesh is generated based on the characteristic dimension of the grains (grain radius), determined in the solidification simulation. The formed mesh can also be taken into account in further analysis of two areas of material properties: densely tangled dendrites (solid phase) and the layers separating them in a solid-liquid state [8].

The number of microscopic finite elements is determined by the surface area of a macroscopic finite element. Whatever its original shape, the hybrid elements mesh is always built on a rectangular plan (similar to a square) with an area equal to or close to the macro element area. Such an approximation of projecting a macroscopic element to microscopic elements is dictated by the polygonal shape of hybrid elements.

In the areas of separating layers there is not only the liquid phase, but also the solid phase in the form of dendrite arms. Therefore, the participation of the grains area in the region of the whole solid-liquid area can be written as:

$$q = \frac{A_g}{A} = \frac{f_s(1-u)}{1-uf_s}, \quad u \in \langle 0,1 \rangle, \qquad (4)$$

where: u is the part of the solid phase share in the separating layers, while f_s is the share of the solid phase. The course of q, depending on the share of the solid phase, including a displacement of half share of the solid phase to the area of layers (u = 0.5) and assuming that all of the solid phase is in the grain area (u = 0), is shown in Fig. 3.

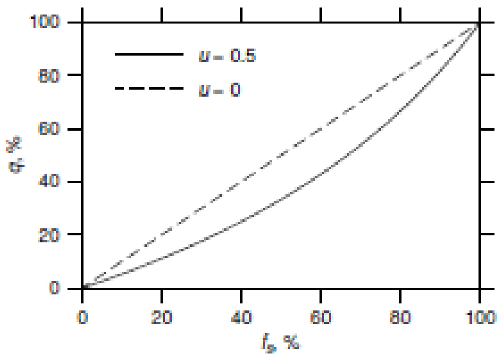

Fig. 3. The course of the function q for different u values.

Grain growth due to the increase in solid phase participation in the analyzed solid-liquid area was implemented through the appropriate displacement of the finite element mesh nodes, according to the relation:

$$x = x_C - \sqrt{\frac{q}{q'}}(x_C - x'), \qquad (5)$$

where: x is the coordinate of the node, x_c is the coordinate of the so-called measure of the solid phase increase, while the symbol ' denotes the current location of the node and the output share of the grain area.

D. Calculation of the stress in microscopic areas

The macroscopic calculation yields a number of instantaneous fields. Among them, the temperature profile, the characteristic grain's size and the stress field are relevant for further simulations.

In the selected area the macroscopic finite elements are isolated from the rest of the elements mesh of the casting. The parameters describing the state of the macro elements are used as input for further calculations leading to the determination of the susceptibility to hot tearing. The equiaxial grain radius assigned to the macro element is used to determine the dimension of the hybrid finite elements. The solid phase participation function $f_s(t)$ and the temperature profile $T(t)$ are used to control the growth of the grains area and the change in material properties in successive time steps. The appropriate boundary conditions are formulated with the help of the stress tensor $\sigma(t)$, see Fig. 4.

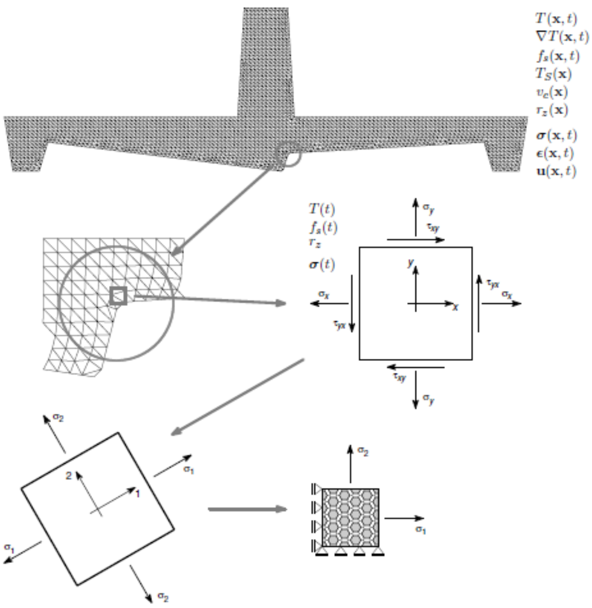

Fig. 4. The division of macroscopic finite element into microscopic (hybrid) finite elements and the way of support and load of the analyzed area.

Due to the lack of symmetry for loading the system, the stress tensor is converted into an equivalent tensor of main stresses. As the result of this approach it is possible to analyze only a quarter of the system, suitably mounted on symmetry axes and charged by the main stress. For the purpose of numerical modeling of the solid-liquid center cracking it was necessary to separate the macroscopic properties as the properties of the two subdivisions and appointed in an experimental way before. The "amount" of the subdivision is determined by the share of its surface area q in the whole solid-liquid area. Thus, the value of material property W is:

$$W = qW_g + (1-q)W_l, \tag{6}$$

where: W_g is the value of material properties for the solid phase area (grains), while W_l is the value of material properties for the area of separating layers. Furthermore, it has been assumed that the material properties in the subdivisions are in a relationship expressed as:

$$\frac{W_l}{W_g} = p, \qquad p \in \langle 0,1 \rangle. \tag{7}$$

Unlike pure metals, alloys solidify over a range of temperatures. Thus, (7) involves the distribution $p = p(T)$ of material properties that can be defined as follows

$$p(T) = \frac{T_L - T}{T_L - T_S}, \tag{8}$$

where: T_L and T_S are the liquidus and the solidus temperatures, respectively. These temperatures determine the range of the solidification temperatures. Substituting (7) to (6) we obtain the relationship describing material properties for the solid phase:

$$W_g = \frac{W}{p + (1-p)q}. \tag{9}$$

The microscopic finite element mesh, covering the analyzed solid-liquid area, is charged by the macroscopic state of stress. The boundary conditions are updated on grains arising from the simulation at the macro level. Material properties of sub-grains and separating layers are also determined with the use of the current temperature values. The calculations are carried out from the 'appearance' of stress, i.e., when the share of the solid phase exceeds a critical value (e.g. 25%) until complete solidification.

E. Calculation of the value of Θ for the macroscopic finite element

The values of the local coefficient of susceptibility to hot-tearing Θ are calculated according to (3). Since different areas of the casting solidify at different time intervals it is convenient, due to further analysis, to present the course of Θ in the function of the solid phase share. Sample graph presenting such a course is shown in Fig. 5. Presentation of results in the function of the solid phase share enables a direct comparison of the coefficient value Θ of all the solved task variants.

F. Drawing up the scale of Θ

In order to compare values Θ for different tasks, different conditions for pouring and solidification have been drawn up the scale of susceptibility to hot tearing, based on the critical value Θ_{cr}. It was assumed that the scale is dependent on the participation of the solid phase. The critical value Θ_{cr} is determined from the maximum values Θ for all the variants of the simulation for the solid phase participation, ranging from 50 to 95%, in steps of 5%. On the basis of the received values the function determining critical values of Θ in the function of the solid phase may be constructed. This function is the basis for determining the degrees of the susceptibility to hot tearing.

ISBN: 978-988-18210-9-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

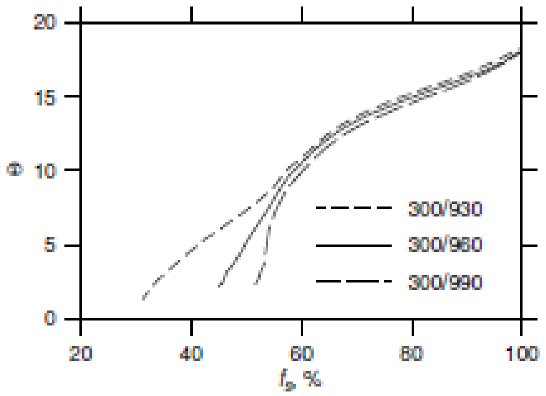

Fig. 5. Sample courses of Θ for given casting conditions (temperature of the mold/casting temperature).

Thus one should decide whether further analysis of susceptibility to hot tearing will run for four degrees. As high (the highest) degree adopted values Θ larger and equal to Θ_{cr}, as the average – values from $0{,}9\Theta_{cr}$ to Θ_{cr}, as low degree – values from $0{,}8\Theta_{cr}$ to $0{,}9\Theta_{cr}$. For values Θ below $0{,}8\Theta_{cr}$ the lack of susceptibility to hot tearing is accepted.

G. *Execution of diagram of Θ distribution*

Proposed in the previous section, the scale is the basis for drawing up diagrams (maps) of the coefficient Θ distribution for the main group of elements and for the control groups (Fig. 2). The maps are drawn up for certain selected values of the solid phase participation (Fig. 6).

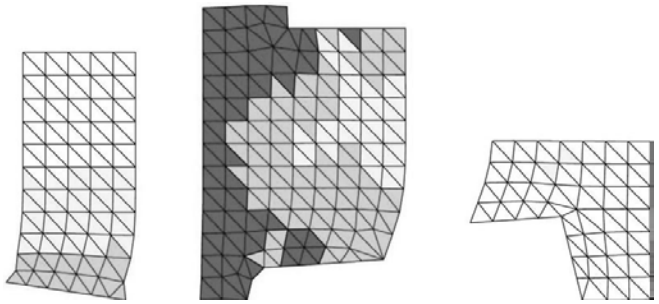

Fig. 6. Sample map of the coefficient Θ distribution of susceptibility to hot-tearing (a darker color means a greater susceptibility to hot tearing).

Since the coefficient Θ distribution maps are only comparative, there are compared elements with the same share of the solid phase in a single casting. So they do not represent any real situation, i.e. those which may occur in the solidifying casting. Such maps are made to indicate that while the main group values Θ indicate the possibility of hot tearing, in the control groups the coefficient values Θ are so small, that they are not at risk from cracking.

H. *Conclusions from the simulations*

After preparing maps of the coefficient Θ distribution some relevant, for the casting practice, conclusions arise. These conclusions may involve the casting hot tearing at different stages of solidification. What is also important, is the evaluation of infusion conditions, which determine the temperature of the mold or flooding temperature, to ensure obtaining sound castings.

III. Example of Application of the New Criterion

Application of the proposed criterion for the hot tearing evaluation has been illustrated by the simulations and analysis of the casting made of Al-2% Cu alloy, solidifying in a metal form. For all simulations, the initial mold temperature was set to 300 K. The variable parameter was the pouring temperature, that was equal to: 930 K, 960 K and 990 K, respectively. Distributions of the local coefficient of susceptibility to hot tearing for the major group and control groups are presented in Fig. 8. The upper distributions were made for the pouring temperature 930 K, the middle - for 960 K and the lower distributions for 990 K.

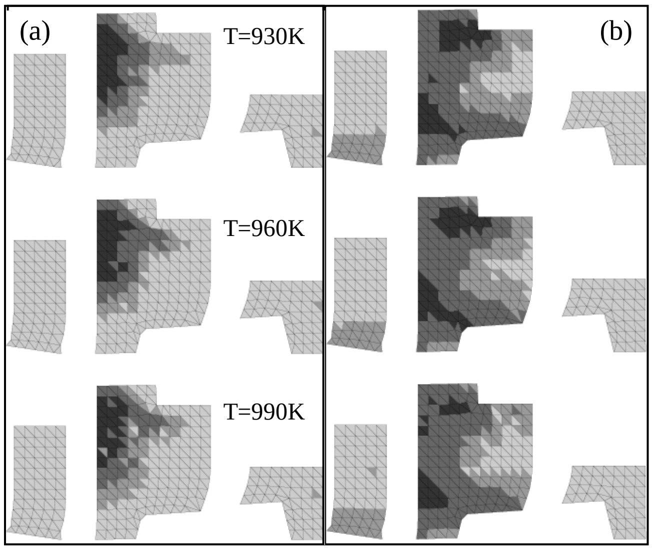

Fig. 8. The distribution of Θ for the solid phase share of 60% (a) and of 95% (b) in each macroscopic finite element.

The analysis shows that in all the cases, there is a high risk of the rupture of hot casting. It is therefore concluded that the initial mold temperature is too low. The obtained results were confirmed by experimental research. The hot tearing occurred for an initial mold temperature of 300 K, while raising the temperature to 600 K guaranteed to receive a sound casting.

IV. Summary

The proposed new stress criterion for hot tearing evaluation in castings is a local criterion, covering the area of a single macroscopic finite element. The application of this criterion for compact groups of finite elements, in selected casting areas, allows for a global evaluation of the casting susceptibility to hot tearing. The analysis of the susceptibility to hot tearing can be carried out jointly for several ranges of the initial and the boundary conditions. From the point of view of the rupture risk this analysis yields the most advantageous variant of the casting.

Application of the proposed criterion is time-consuming because it requires a lot of preparatory work and computer simulations. However, modern computing systems are powerful enough, so that our criterion can be taken into account and yield valuable results.

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