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Experimental-Numerical Model of the Initiation and Propagation of Cracks in Die Inserts

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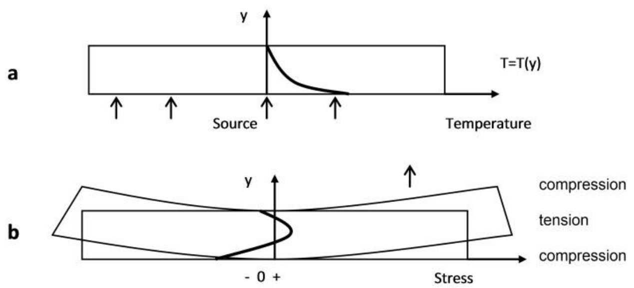
Abstract

The aim of the research presented in this paper was to develop an experimental - numerical model for predicting the life of die inserts. For this purpose, using FEM, the temperature and stress fields in the insert during stable operating cycle of a die casting machine were determined. The study of WCL steel, of which inserts are made, included fatigue tests and tests from the range of fracture mechanics. From the results obtained, a relationship was derived between the number of the die casting machine operating cycles and the propagation speed of cracks formed on the insert working surface.

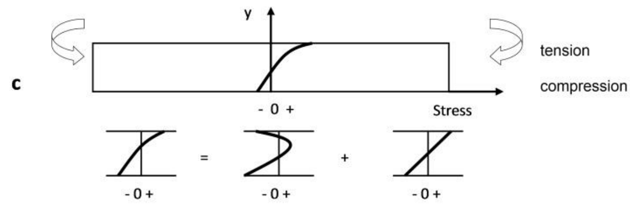
1. Introduction

Inserts installed in dies for the pressure die casting process are operating under the conditions of thermal and mechanical loads changing in cycles and caused by the successively performed operations of metal injection, die opening and spraying of protective coating.

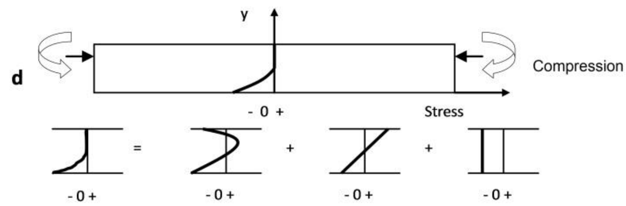


$$\sigma_x = -E\alpha T(y)$$

Fig.1 a-d. Different stress states in a beam heated unilaterally



$$\sigma_x = \frac{12y}{h^3}\int_{-\frac{h}{2}}^{\frac{h}{2}} E\alpha T(y)y\,dy$$



$$\sigma_x = \frac{1}{h}\int_{-\frac{h}{2}}^{\frac{h}{2}} E\alpha T(y)\,dy$$

The non-linear temperature field T = T (y) in Figure 1a gives rise to stress fields which, depending on the mechanical boundary conditions, cause free deflection of the structure shown in Figure1b; stress in this case is described with the following equation:

$$\sigma_x = -E\alpha T(y) \quad (1)$$

or, in the absence of displacements, with equation (2) extended by the members related with the inhibition of deflection and expansion, as shown in Figures 1c and 1d, respectively:

$$\sigma_x = -E\alpha T(y) + \frac{1}{h}\int_{-\frac{h}{2}}^{\frac{h}{2}} E\alpha T(y)dy + \frac{12y}{h^3}\int_{-\frac{h}{2}}^{\frac{h}{2}} E\alpha T(y)ydy \quad (2)$$

In the case of inserts, the stress state shown in Figure 1d prevails. It is described with equation (2) due to the inhibition of deformation by other parts of the die. The contact of liquid metal with the insert of a much lower temperature gives rise to the formation of a field of compressive stresses in the immediate vicinity of the heated surface as a result of the inhibition of its expansion by the adjacent, still not heated, layers, located at a certain distance from this surface. As long as the die halves are closed, the drop of temperature on the insert surface occurs through the conduction-driven heat exchange with the die parts of lower temperature. After opening of the die, this process is continued and, additionally, the process of heat dissipation to the environment begins. Spraying of protective coating, preventing the casting from sticking to the die, and spray cooling of the insert surface cause an enormous drop of temperature in the surface layer and, consequently, generate tensile stresses as a response to the effect of the inner layers of the insert, whose temperature at that moment is definitely higher. As a result of this situation, the subsurface parts of the insert are subjected to alternately acting compressive and tensile forces, which lead to the fatigue of material and, consequently, to the initiation and propagation of subsurface cracks which, according to [1] [2], can be classified as thermal cracks, stress-induced cracks and spallings. Thermal cracks are formed on flat surfaces, usually after several thousand shots, and are independent of the die shape. They depend only on the changing cycles of temperature and properties of the material from which the die has been made. Stress-induced cracks appear in the areas of stress concentration such as notches, undercuts, holes and edges, and are a sum of the combined effect of the changing temperature cycles and die configuration. Spallings are formed as a result of the brittle precipitates getting detached from the die surface. They occur at grain boundaries, reduce the ductility of material and initiate cracks.

2. Numerical model of the process

Thermal fatigue processes occurring in die inserts are complex in nature, and therefore their representation as a FEM model requires a number of simplifying assumptions adopted in calculations, and further experimental verification of some of the parameters. A key issue for the correct calculation is precise determination of temperature changes that occur in insert during the successive cycles of its operation, and therefore, the experimental verification focussed mainly on these changes, examined at selected points. For this purpose, in the previously dismantled ejectors, holes were drilled and in these holes thermocouples were placed. Thermocouples were also placed between the insert and die cavity. Thus distributed thermocouples enabled recording temperature changes at the edges of the insert and in the insert cavity at a distance of 0.5 mm from the metal-die contact surface. The die was installed in the die casting machine with a horizontal squeeze chamber. Studies were carried out on an AK 11 alloy, applying the following test parameters: injection temperature - 680°C, the time lapse from injection to die opening - 5.2 seconds, spray - 2 seconds, the duration of the entire cycle - 30 seconds. The locking force was 150 T with the metal pressure of 70 MPa. For the calculation of thermal stresses varying in time, two numerical models – a temperature model and a stress model - were necessary. The best accuracy of solution in these models was obtained using non-linear elements with reduced integration. The temperature values determined for the internal part of an insert in the nodes of a grid in the subsequent time steps were transferred as loads to the same grid used in the stress model.

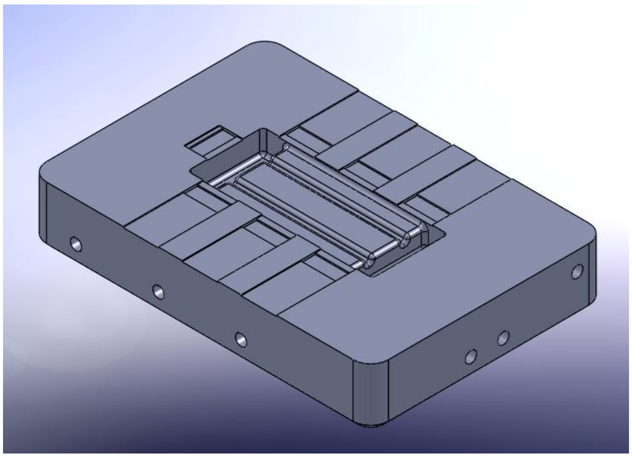


Fig. 2 CAD model of the die insert

3. Temperature – stress analysis

Analysis of the obtained values of the fields of stress and temperature has indicated the possibility of making a conventional division of the insert into three zones A, B and C, starting from the surface and moving deep into the material, where various phenomena reducing the strength of this material take place. Zone C, 25 mm distant from the surface of the division line, where the temperature is in the range of 150°C to 200°C, is dominated by compressive stresses of similar values not exceeding 200 MPa. For this zone it can be assumed that the high-temperature strength is controlled by monotonic creep at a constant temperature and load. In zone B, lying at a distance between 25 mm and 5 mm from the surface of the insert, the compressive stresses are also present but of much higher and changing values. During metal injection they amount to 1200 MPa, decreasing in value at the end of the cycle to 900 MPa. Differences in temperature are comprised in the range of 250°C - 450°C. In this zone, it can be assumed that the dominant influence on metal strength has the cyclic creep phenomenon. Zone A lies at a depth of 5 mm from the surface of the die. In this zone, the periodical changes of temperature are the greatest (260°C - 670°C) and are accompanied by changes in the sign of the thermal stresses. During metal injection, the compressive stresses of 1100 MPa occur, their sign changing when the liquid coating is sprayed, causing stretching of the surface layers. In this zone, the main cause of the die material destruction is the phenomenon of thermal fatigue.

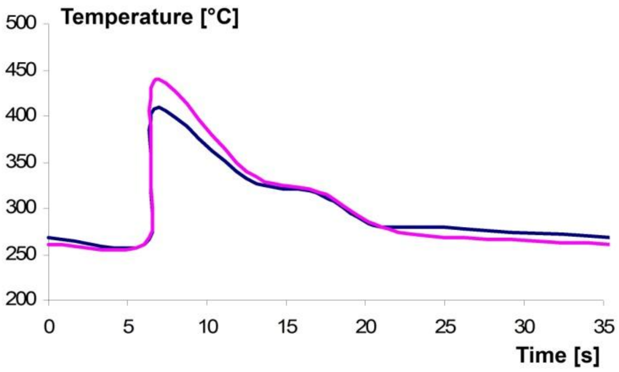


Fig. 3 Recorded experimentally (curve 1) and calculated numerically (curve 2) temperature changes in the die insert during one operating cycle of the die casting machine

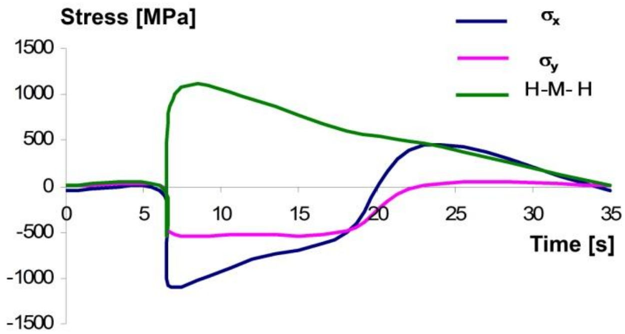


Fig. 4. Calculated by FEM changes in stress components and in reduced stress in the die insert during one operating cycle of the die casting machine

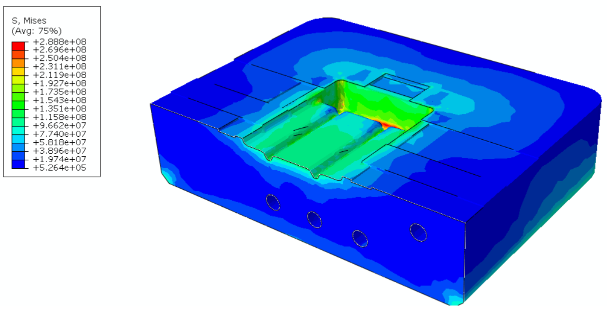


Fig. 5. Field of reduced instantaneous thermal stresses induced by temperature field

4. Model for calculation of the die insert life

Based on the stress and strain values calculated by FEM, the number of the insert operating cycles until the appearance of cracks was determined. The time of the insert operation was divided into the crack initiation period described with Morrow fatigue life equation [4], and the crack propagation period whose stable growth was predicted with Paris equation [5] [6]. For the WCL steel, Morrow equation, completed with experimentally determined constants, assumes the following form:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_{pl}}{2} + \frac{\Delta\varepsilon_{s}}{2} = 0.117\left(2N_f\right)^{-072} + 0.012\left(2N_f\right)^{-0.12} \qquad (3)$$

where:
$\Delta\varepsilon$ – total strain,
$\Delta\varepsilon_{pl}$ – plastic strain,
$\Delta\varepsilon_{s}$ – elastic strain,
$2N_f$ – number of reversals to failure (half-cycles)

The, determined by FEM, deformation of the surface layers of the insert does not exceed 0.0029, so from equation (3) the number of cycles to crack initiation is approximately 60,000. The crack propagation velocity was predicted from Paris equation, for which the constants m = 2.88 and C = 7.9 * 10-12 were experimentally determined:

$$\frac{da}{dN} = 7.9 \cdot 10^{-12}\left(\Delta K\right)^{2.88} \qquad (4)$$

where:
a - the length of a crack,
ΔK – the range of variations in stress intensity factor

Changes in the value of ΔK occurring with the growing crack length were determined numerically, determining the instantaneous values of the strain energy in a dedicated area of the insert material through which the crack propagates. Then, the empirical equation describing the curve of changes in the strain energy - E as a function of the crack area growth – s assumes the form:

$$E = 16.4 s^{2.1} + 2.58 \cdot 10^{-7} \qquad (5)$$

This equation allows calculating changes in the value of the J_I integral as a function of the crack length growth and determining the instantaneous value of the stress intensity factor in the crack tip K_I. Finally, Paris equation, where ΔK is expressed as a function of the instantaneous crack length, assumes the form:

$$\frac{da}{dN} = 1.25 \cdot 10^{-4} \cdot a \qquad (6)$$

After integrating equation (6) we obtain a relationship determining the number of cycles needed for the crack growth by a pre-assumed length:

$$N = 7943 \int_{a_0}^{a} a^{-1.58} da \qquad (7)$$

$$N = -13694 \cdot \left(a^{-0.58} - a_0^{-0.58}\right) \qquad (8)$$

5. Summary

Cyclic changes of stress in the die insert mainly occur on the surface, penetrating inside the material to a depth of 5 mm and this zone should be taken into account when the phenomena of the crack initiation and propagation are to be considered. The predominant stress is compressive stress, but it is the tensile stress of a much lower value, generated during cooling cycles on the surface of the insert, that exerts control over the crack propagation speed. The adopted computational model enabled determining places where there is the greatest likelihood of the occurrence of cracks, enabling also their growth rate to be calculated with reasonable accuracy, taking as a reference the collected data on the extent of wear in real insert, a model of which was considered.
In Table 1 a comparison was made between the numerically calculated number of cycles and the same number measured experimentally for various length of a fatigue crack. From the

comparison it follows that the difference between the values calculated numerically and measured in practice is not really very great, especially that the experimental results are from the measurements made on one specimen only.

Table. 1.
A comparison of the numerically calculated and experimentally measured relationship between the number of fatigue cycles and crack length.

Crack length	Number of cycles	
	measured	computed
from 15 to 16	67000	62700
from 17 to 18	49500	48756
from 18 to 19	46000	43433
from 26 to 27	19000	20566
from 34 to 35	5500	5249
from 41to 42	1530	1227

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