SPREADING OF CRACKS DUE TO THERMAL FATIGUE IN METAL MOLDS

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Abstract: The article deals with the formation and spread of cracks from thermal fatigue in metallic forms. For a detailed examination of the problem, it is necessary to describe the thermal side of the process and the mechanism of mechanical stressing of the material. For the heating of the material is valid where the thermal diffusivity of the material is exercised by the decision method. The stress of the material by heating from the die casting metal depends mainly on the physical properties of the material when the calculated stress does not exceed the yield point. Also, with the help of dislocations write the life to the origin of the cracks in the cycles eventually the share of this lifetime on the total lifetime in dependence on the mechanical and physical properties of the material. During operation tests the occurrence of the cracks on the mold surface was initiated by the inclusion or concentration of stress in the knurling effect of fine grooves after grinding. Other cracks occurred in the undersurface layer and their direction was statistically accidental.

Keywords: die casting, cracks, metal moulds

INTRODUCTION

The issue of technological factors of die casting, which plays an indispensable role in the production of lower weight category casts, mainly from aluminium, magnesium and zinc alloys, is nowadays a subject of numerous studies on a global scale (the USA, Japan, EU, Australia, etc.). (Gašpar et al., 2014). The moment of the origin and spreading of cracks along the die cavity surface is very important for life of these expensive tools especially in case of die casting and most expressively for cutting of metals and alloys with higher melting temperature (Ružbarský et al., 2014, Vinarcik, 2003).

THEORETICAL ANALYSIS

The cause of heating of the function die is the liquid metal with which it is in contact during casting and solidifying. The figure 1 represents the advancement of a simple plate die filling (1- front against filling chamber, 2-gate and filling stream of metal in die cavity, 3-other parts of the die cavity). In such sequence the individual parts of the die 1, 2, 3 are heated as it is shown in figure 2.
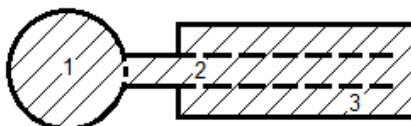

Fig. 1. The advancement of the simple plate die filling
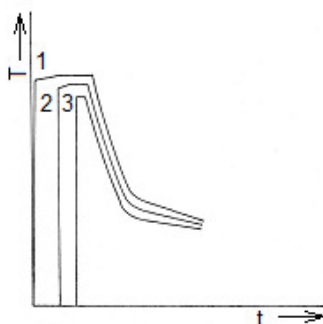
Fig. 2. The cast of die individual parts in dependence on time

During contact with liquid metal for die casting it is possible to assume by (Lo et al., 2004, Klouda et al., 2017, Paško et al., 2014) direct contact of die with liquid metal and almost instant heating of the die surface to the temperature T by the following relation

$$T = \frac{2.B.T_2 + T_1}{2.B + 1} \qquad (1)$$

with: $B = b_2 / b_1$

$b_1 - \lambda_1 c_1 \rho_1$ thermal diffusivity of the die [J^2.kg.m^{-4}.K^{-2}.s^{-1}]
$b_2 - \lambda_2 c_2 \rho_2$ thermal diffusivity of the die casting [J^2.kg.m^{-4}.K^{-2}.s^{-1}]
λ_1 – thermal conductivity of the die [W.m^{-1}.K^{-1}]
λ_2 – thermal conductivity of the die casting [W.m^{-1}.K^{-1}]
c_1 – specific heat of the die [J.kg^{-1}.K^{-1}]
c_2 – specific heat of the die casting [J.kg^{-1}.K^{-1}]
ρ_1 – specific mass of the die [kg.m^{-3}]
ρ_2 – specific mass of the die casting [kg.m^{-3}]
T_1 – temperature at cast [K]
T_2 – temperature of metal at cast [K]

Under other unchanged conditions the most convenient materials for dies are those with high thermal diffusivity with regard to their ability to reach lower die surface temperature T. Figure 3 shows the dependence (1) of die surface temperature T on the ratio of thermal diffusivities for die casting and die B for $T_1 = 200\,°C$ and for aluminium alloys cast $T_2 = 650\,°C$. In case of steel for dies with 5% of Cr the $B = 1.48$ and $T = 500\,°C$ and in case of molybdenum the $B = 0.82$ and thus $T = 435\,°C$ which represents the decline in heating by 22%.
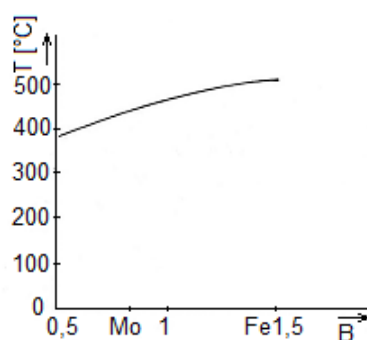

Fig. 3. Dependence of the die surface temperature on the ratio of the die casting and the die thermal diffusivities

With regard to the further and further streaming of metal along parts of the die 1 and 2 (Fig. 1) during die filling these parts get heated to higher temperature produced by a long contact with large quantity of liquid metal in the filling chamber. After casting, the prolonged periods of solidification can be observed at these places due to the same reasons. Similar prolonged solidification as well as so-called "warm places" occur in case of accumulation of material in a

cast. Moreover, the cores are subjected to high thermal strain due to being heated from all sides.

For solidification of die casting it is possible to assume the constant gradient ΔT against the die. Then the following is applicable:

$$-c_2.m_2.\Delta T_2 + c.m_2.\Delta T_2 = k.S.\Delta T.dt \tag{2}$$

with: c_2 – specific heat of the die casting [J.kg^{-1}.K^{-1}]

m_2 – mass of the die [kg]

T_2 – temperature of the die casting [K]

c – latent heat of crystallization in case of solidification of the die casting [J.kg^{-1}.K^{-1}]

S – contact area of the die casting and the die [m^2]

t – time [s]

After the integration of the left side from T_{02} to T_2 and of the right side from 0 to t it goes out

$$T_2 = T_{02} - \frac{k.S.\Delta T.t}{c_2 - c} \tag{2.1}$$

During cooling of the die casting the following is applicable:

$$-c_2.m_2.dT_2 = k.S.(T_2 - T_1)dt \tag{3}$$

in case of which the die temperature T can be considered to be the constant at least during the first moments. After separation variables and integrations from T_{02} to T_2 and from 0 to t it goes out.

$$T_2 = T_1 + (T_{02} - T_1).e^{-\frac{k.S}{c_2.m_2}.t} \tag{3.1}$$

It means that during cooling the temperature of a cast declines exponentially and intensely in dependence on time with regard to a thin wall of the casts (high ratio of S/m_2) and to the aforementioned positive contact of a cast with the die surface caused by the pressure (high value k). Taking into consideration (1) has also the temperature of the die surface prior to expelling the die cast (in figure 2 vertical line) when the die surface temperature is so low that the further cooling of the die surface during attendance and locking of the machine is not that intense.

The die surface stress is related to distribution of the temperature of a cast into its depth at least in layers which are in the proximity of the mould surface. According to (2) the temperature spreading into the depth of a mould in the course of first moments after casting corresponds with theoretical one in case of the semi-infinite field, since the limit of heat transfer "still does not recognize the mould outlines" and cannot reach them.

According to (1) the following is applicable for the heat penetration p [m]

$$p = 4\sqrt{\frac{\lambda_1}{c_1.\rho_1}.t} \tag{4}$$

And for solidification the penetrating p equals to a double of the cast thickness. For the course from temperature T according to (1) up to the temperature which was prior to casting in depth p the following is applicable according to (4)

$$K.S.(T_2 - T) = \lambda_1.S\frac{dT}{dx} \tag{5}$$

with: K – constant [W.m^{-2}.K^{-1}]

After substitution from (1)

$$\frac{K}{\sqrt{2.B}}.(T - T_1) = -\lambda_1\frac{dT}{dx} \tag{5.1}$$

By integration from 0 to x and from T to T_x (temperature in depth x under the mould surface) the following can be reached (figure 4):

$$T_x = T_1 + \left(T - T_1.e^{-\frac{K}{\sqrt{2.B.\lambda_1}}x}\right) \tag{5.2}$$

Heating of the mould surface to temperature T from the liquid metal and the temperature difference $\Delta T = T\text{-}T_1$ in contrary to reference temperature T_1 are crucial for stress of the mould material. By heating the surface layer of the mould the stress σ occurs

$$\sigma = \int_0^{\Delta T} E.\alpha.dT \tag{6}$$

with: E – modules of elasticity [Pa]
     α – coefficient of thermal expansibility of the die [K^{-1}]
With regard to the opposing dependence of E and of α on the temperature it is possible to consider that their influence is mutually compensated and consequently the following is applicable:

$$\sigma = E.\alpha.\Delta T \tag{6.1}$$

At higher temperatures of the mould surface T the calculated stress according to (6) or (6.1) exceeds the yield point and consequently, the actual stress exceeds the yield point only inconsiderably and the rest of extension is compensated by the plastic deformation compressing. Thus the compressive stress occurs in the surface layer of the mould and in the layer under the tensile stress can be observed. If during cooling of a mould the plastic deformation is avoided in the surface layer the sense of the stresses does not change yet they are only unceasingly reduced as the scheme in figure 5 shows. The values of stresses in single parts of the mould 1, 2, 3 are according to (6) or (6.1) directly proportional to the temperatures difference $\Delta T=T\text{-}T_1$. If the plastic deformation occurs in the surface layer, then during cooling corresponding to the compressive stress of the surface layer the state free from stress is reached and at further cooling the sense of the stresses changes. Prior to compression the surface layer is stressed on pull and the layer under is stressed on pressure. At the same time the figure shows the course of the stress presented by a hysteresis sling the settling of which can be observed after hundreds and in case of stresses to higher temperatures after tens of cycles, i.e. one thousand of a mould life.
For the shift of the dislocations and for the generation of a high-tension region inevitable is energy A proportional to the number of the accumulated dislocations d in this micro region and to the difference of stresses $\sigma\text{-}\sigma_p$

$$A = k_1.(\sigma - \sigma_p).d \tag{7}$$

with: A – energy [kg.m^2.s^{-2}]
     k_1 – constant [m^3]
     σ – stress of the material [Pa]
     σ_p – fatigue limit [Pa]
     d – the number of dislocations
N refers to atoms in the high-tension field and d is the number of dislocations sufficient to generate the high-tension region. Consequently, the following ensues from the theory of combinatory:

$$i = \binom{N}{d}d! \tag{8}$$

By arrangement the following is achieved

$$i_0 \frac{N!}{(N-d)!} \tag{8.1}$$

Since d is almost by a single order lower contrary to N, the following simplification can be produced:

$$(N-d)!.\bar{N}^d = (N_1)^N \tag{9}$$

with: $\bar{N}$- average of N
If further at average N_1

$$N! = (N_1)^N \tag{9.1}$$

Then after substitution into (8.1) the following is achieved:

$$d = \frac{\ln i_0}{\ln N_1} \tag{8.2}$$

By substitution into (7)

$$A = k_1 . (\sigma - \sigma_p) . \frac{\ln i_0}{\ln N_1} \tag{7.1}$$

On the other hand, energy A is proportional to the difference of the material stress in the yield point R_e and the competent stress σ derided by the material modulus of elasticity E and the difference of the material stress on the breaking strength R_m and in the yield point derided by the average modulus of elasticity E_1 with regard to the deformation that by the certain number of cycles i_0 must be transferred unless the material is ruptured.

$$A = k_2 . \left(\frac{R_m - \sigma}{E} + \frac{R_m - R_e}{E_1} \right) \tag{10}$$

If the right sides of the equations (7.1) and (10) are made to be equal, the following is achieved:

$$k_2 . \left(\frac{R_m - \sigma}{E} + \frac{R_m - R_e}{E_1} \right) = k . (\sigma - \sigma_p) . \ln i_0 \tag{10.1}$$

with: $k = \frac{k_1}{k_3 . \ln N_1}$ and it depends on kind of material.

Within the range of $R_m / \sigma = 1 \div 1{,}5$ with maximum error of +10% the following can be written for σ near R_m

$$e^{\frac{R_m - R_e}{\sigma}} = 3.5 \frac{R_m - R_e}{\sigma} \tag{11}$$

When the first crack is observed after the number of cycles $i_1 = i_0 + \Delta i_0$ (in case of which i_0 refers to relatively low number of cycles) the crack spreads along the length and at the same time further cracks occur.

If the function of working from the cycle i to the further cycle $i + 1$ is considered as quasi-continuous, then the differential of force dF causing the rise of further advance an element of the length dL is from one side as follows

$$dF = R_m . s . dL \tag{12}$$

And from the other side differential force dF forming the further length of the crack is proportional to the differential of the further cycles di and the remaining length to its limit value $L_k - L$

$$dF = k . (L_k - L) . di \tag{13}$$

with: k - constant of proportionality.

If the expressions (12) and (13) are considered as the equal ones, the following is achieved:

$$R_m . s . dL = k . (L_k - L) . dL \tag{14}$$

During spreading of cracks in case of mechanical fatigue the following is applicable:

$$\frac{dL}{dt} = A(G^2 - G_p^2) \tag{15}$$

with: L – length of the crack [m]

    A – constant

    G – controlling force of the crack [N]

    G_p – threshold controlling force of the crack when it comes to stopping spreading of the crack [N]

In case of the controlling force of the crack the following is applicable:

$$= \frac{\sigma^2 . l_k}{E} . \tan \frac{\pi}{2} . \frac{L}{L_t} \tag{16}$$

with: σ – stress [Pa]

    L_t – total length of the crack [m]

E – material modulus of elasticity [Pa]

L_k – final length of crack before static fracture [m], $l = L/L_k$

EXPERIMENTAL RESULTS

According to [3] the calculated value on the mould surface in case of die cast of aluminium alloys $T = 540\,°C$ corresponds to the measured value of $T = 544\,°C$ relatively precisely. The time course of cooling of a measured plate form of a cast from aluminium alloys is presented (Dahlberg, 2004; Davidson et al., 2006) in figure 4. The calculated values according (3.1) correspond with the measured ones.

According to (Midor and Žarnovský, 2016; Mortsell et al., 2003) during operation tests the occurrence of the cracks on the mould surface was initiated by inclusions or concentration of stress in a knurling effect of fine grooves after grinding. Other cracks occurred in the undersurface layer and their direction was statistically accidental.

In order to verify the occurrence and spreading of cracks the fragile materials were tested in case of which it is possible to assume the small necessary number of cycles. The first tests were transferred by soaking the circle of the diameter *60 mm* with the hole of the diameter *15 mm* in the centre from the cast iron ISO STN 422420 standard. The soaking was performed into the melted salt with the temperature of *1000 °C* during the period of *30 sec.* and afterwards the soaking into water (*20 °C*) was performed. The reviewing of the sample surface was transferred visually after every 100 cycles.
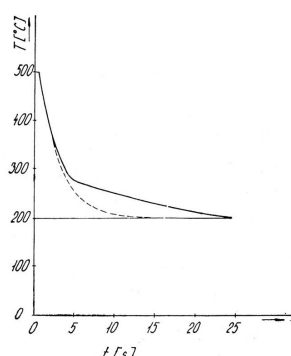

Fig. 4. The time course of cooling the plate die casting from aluminium alloys

In figure 5 the state after 300 cycles is represented in dots and after 1500 cycles in full lines.
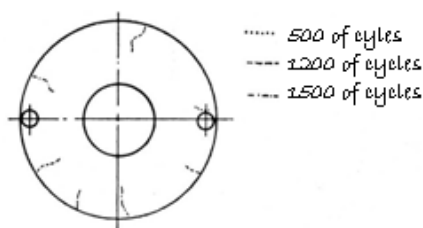

Fig. 5. The surface state after 300, 1200 and 1500 cycles

With regard to troublesomeness of a sample being soaked into the salt bath the stricter examination was chosen. The sample was cut on both sides to width of *42 mm* and was heated in a high frequency inductor to *1200 °C* and cooled in water (*20 °C*). Already after 10 cycles the first cracks could be observed. In figure 6 the further cracks occur after 25 and 100 cycles.
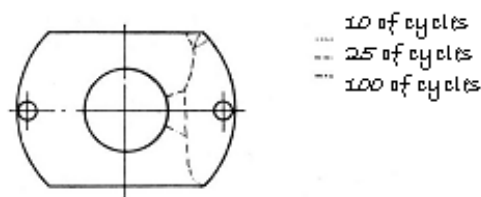
Fig. 6. Origin of the cracks after 10, 25 and 100 cycles

Further the sample with the diameter *20 mm* from the low carbon steel 12 060 was made. It was tested in the inductor by warming on *1100°C* and by soaking into water (*20°C*). With regard to a large scale the temperature was lowered to *800°C*. After 1500 cycles the crack occurs and spreads rapidly and the further cracks occur as well (fig. 7).
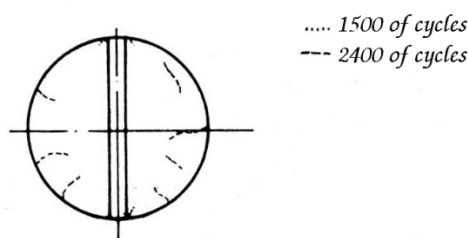

Fig. 7. Origin of cracks after 1500 and 2400 cycles

The cracks are like the isostatic lines corresponding to development of main stresses. They are perpendicular to each other and always perpendicular to the outline. With the exception of the evidently defective places the cracks are bound especially to the outside and interior edges and to the surroundings of the middle area.

The origin of cracks was not possible to be followed but the points of tangent intersection of dependence of the cracks length on the number of cycles in its inflection point with the zero cycles *i* axis can be considered to be the curve equidistant to the curve of cracks origin shifted by the relatively low value of cycle number i_0 and with the line of crack final length i_k the curve i_{k1} of total life.

CONCLUSION

For heating of *T* of the mould material the relation (1) is applicable in case of which the thermal diffusivity of the mould material is employed.

The relation (6) or (6.1) expresses the stress of the mould material by heating from the die casting liquid metal mainly in dependence on physical properties of the mould material unless the value of the calculated stress exceeds the yield point of the material.

The relations from (10.1) derived with the aid of dislocations describe the mould life prior to the origin of cracks in cycles or the contribution of this mould life to the entire mould life in dependence on mechanical and physical properties of the mould material and they provide sufficient explanation of increasing of the mould life in case of higher thermal diffusivity of the mould material as well as during heat treatment of the same mould material to the lower strength.

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