# ORIGIN AND SPREADING OF CRACKS DUE TO THERMAL FATIGUE IN CASE OF METAL MOLDS

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For heating T of the die material is valid where the thermal diffusivity of the die material is exercised by deciding method. The stress of the die material by heating from the die casting liquid metal depends mainly on physical properties of the die material when the value of the calculated stress does not exceed the yield point. Also derived with help of dislocations write the die life till the origin of cracks in cycles eventually the share of this die life on total die life in dependence on mechanical and physical properties of the die material and well explain increasing die life at higher thermal diffusivity of the die material as also at heat treatment of the same die material on the lower strength. The derived relation for the spreading cracks length in dependence on number of cycles agrees with the results of the transferred tests.

**KEYWORDS**

*die casting, cracks, metal moulds*

## 1 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.). [Gaspar 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. [Ruzbarsky 2014, Pasko 2014].

## 2 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 Fig. 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 Fig. 2.

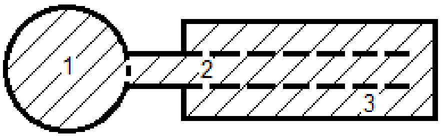

**Figure 1:** The advancement of the simple plate die filling

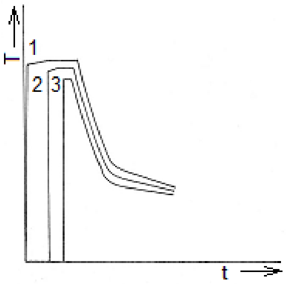

**Figure 2:** The cast of die individual parts in dependence on time

During contact with liquid metal for die casting it is possible to assume by [Vinarcik 2003, Majernik 2016] direct contact of die with liquid metal and almost instant heating of the die surface to the temperature *T* by the following relation

$$T = \frac{2.B.T_2+T_1}{2.B+1} \tag{1}$$

where: $B = b_2/b_1$
$b_1$ – $\lambda_1 c_1 \rho_1$ 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 [$J^2.kg.m^{-4}.K^{-2}.s^{-1}$]
$\lambda_1$ – thermal conductivity of the die [$W.m^{-1}.K^{-1}$]
$\lambda_2$ – 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 [$J.kg^{-1}.K^{-1}$]
$\rho_1$ – specific mass of the die [$kg.m^{-3}$]
$\rho_2$ – 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*. Fig. 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 aluminum 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%.

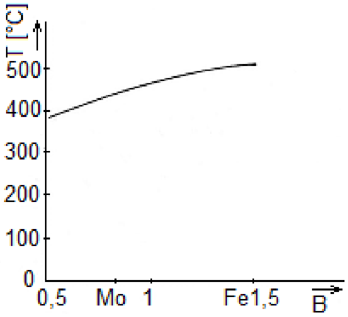

**Figure 3:** Dependence of the die surface temperature on the ratio of the die casting and the die thermal diffusivities

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:

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

where:

*c₂* – 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 mold surface. According to (2) the temperature spreading into the depth of a mold 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 mold 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)

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

where:

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 mold surface) the following can be reached (Fig. 4):

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

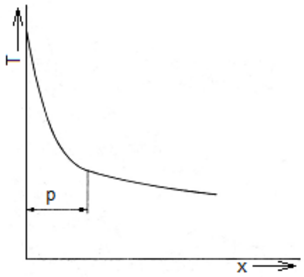

**Figure 4:** Temperature in the depth *x* under the die surface

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

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

where:

*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 mold 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 mold and in the layer under the tensile stress can be observed. If during cooling of a mold 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 Fig. 5 shows. The values of stresses in single parts of the mold 1, 2, 3 are according to (6) or (6.1) directly proportional to the temperatures difference $\Delta T = T - T_1$. 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 as it is shown in figure 6. Prior to compression the surface layer is stressed on pull and the layer under is stressed on pressure. Fig. 6 shows both the course of the surface layer stress in a full line and the layer under the surface in an interrupted line (the same is shown in Fig. 5) in case of which during a single cycle of the cast the stress changes the sign. 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 mold life.

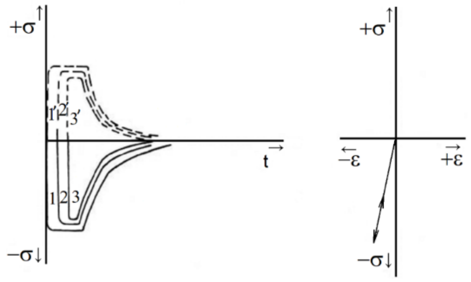

**Figure 5:** The diagram of stresses multiplying in single parts of a mold (if plastic deformation does not occur in the surface layer)

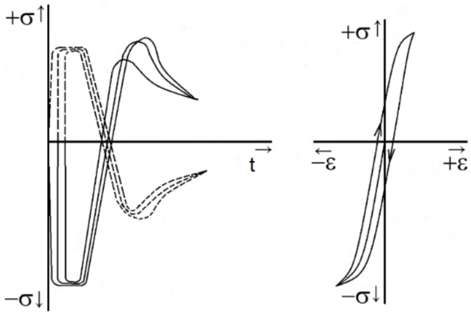

**Figure 6:** The diagram of stresses multiplying in single parts of the die (if plastic deformation occurs in the surface layer)

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 $\sigma$-$\sigma_p$

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

where:

*A* – energy [kg.m$^2$.s$^{-2}$]

$k_1$ – constant [m$^3$]

$\sigma$ – stress of the material [Pa]

$\sigma_p$ – 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:

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

where:

$\bar{N}$- 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 $\sigma$ 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:

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

where:

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

From here the number of cycles $i_0$ before the occurrence of a crack

$$i_0 = e^{\frac{1}{\sigma-\sigma_p}.\left(\frac{Rm-\sigma}{E}+\frac{Rm-Re}{E_1}\right)} \tag{10.2}$$

After substitution from (6.1)

$$i_0 = e^{\frac{1}{k.(E.\alpha.\Delta T-\sigma_p)}.\left(\frac{Re-E.\alpha.\Delta T}{E}.\frac{Rm-Re}{E_1}\right)} \tag{10.3}$$

In the region of the highest $\sigma$ in case of which $\sigma_p$ is possible to be neglected contrary to $\sigma$, the relations (10.2) and (10.3) are thus simplified

$$i_0 = e^{\frac{1}{k\sigma}.\left(\frac{Rm-\sigma}{E}+\frac{Rm-Re}{E_1}\right)} \tag{10.4}$$

$$i_0 = e^{\frac{1}{k.E.\alpha.\Delta T}.\left(\frac{Rm-E.\alpha.\Delta T}{E}+\frac{Rm-Re}{E_1}\right)} \tag{10.5}$$

In case of fragile materials the following is applicable

$$i_0 = e^{\frac{1}{k.E}.\left(\frac{Rm}{\sigma-1}\right)} \tag{10.6}$$

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

$$e^{\frac{Rm-Re}{\sigma}} = 3.5\frac{Rm-Re}{\sigma} \tag{11}$$

consequently after substitution into (10.4)

$$i_0 = \left(3.5.\frac{R_m - R_e}{\sigma}\right).\frac{1}{k.E} \tag{10.7}$$

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 $L_k - L$

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

where:

*k* - constant of proportionality.

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

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

By dividing the lengths *L* and $L_k$ by the area circumference *O* the specific values are achieved as follows:

$$\frac{L}{O} = l \tag{14.1}$$

$$\frac{L_k}{O} = l_k \tag{14.2}$$

then

$$R_m.s.dl = k.(l_k - l)di \tag{14.3}$$

after integration and arrangement

$$l = l_k.\left(1 - e^{-\frac{i_1 - i}{k.R_m}}\right) \tag{14.4}$$

$$l = l_k.\left(1 - e^{-\frac{i_1 - i}{i_k - i_1}}\right) \tag{14.5}$$

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

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

Where:

*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:

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

where:

$\sigma$ – 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],

$l = L/L_k$

## 3 EXPERIMENTAL RESULTS

According to [3] the calculated value on the mold surface in case of die cast of aluminum 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 aluminum alloys is presented [Ruzbarsky 2016, Ruzbarsky 2014] in Fig. 7. The calculated values according (3.1) correspond with the measured ones.

According to [Majernik 2015] during operation tests the occurrence of the cracks on the mold 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 center 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.

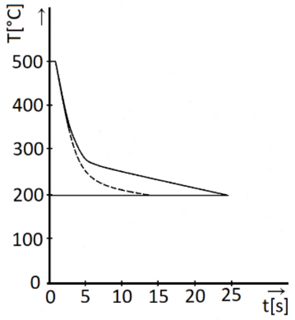

**Figure 7:** The time course of cooling the plate die casting from aluminum alloys

In Fig. 8 the state after 300 cycles is represented in dots and after 1500 cycles in full lines. Gradually, the length of cracks was recorded and plotted in the values divided by the sample circumference in Fig. 9. It is an analogy of the theoretical course according to the relation (14.3).

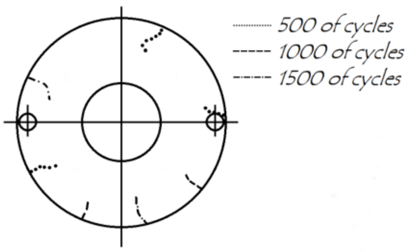

**Figure 8:** The surface state after 300, 1200 and 1500 cycles

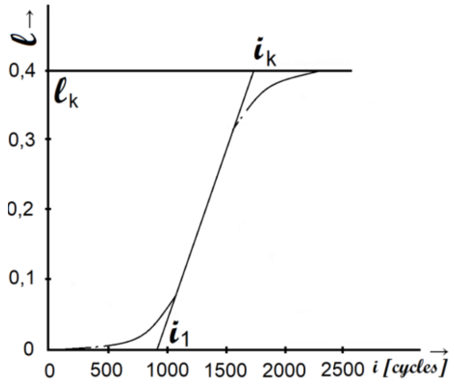

**Figure 9:** The length of cracks plotted in the values divided by the sample circumference

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 Fig. 10 the further cracks occur after 25 and 100 cycles.

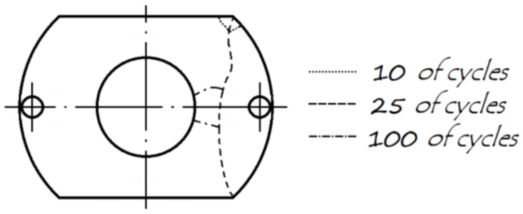

**Figure 10:** Origin of the cracks after 10, 25 and 100 cycles

The length of cracks was recorded and plotted in values divided by the sample circumference in Fig. 11 in dependence on number of cycles *i* (14.3).

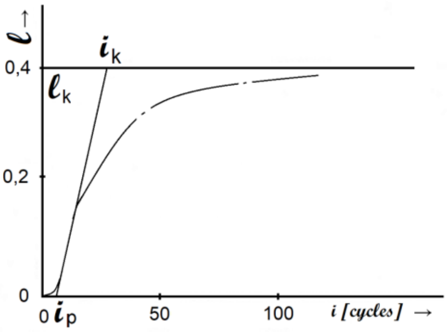

**Figure 11:** The length of the cracks plotted in the values divided the sample circumference dependence on the number of cycles

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. 12).

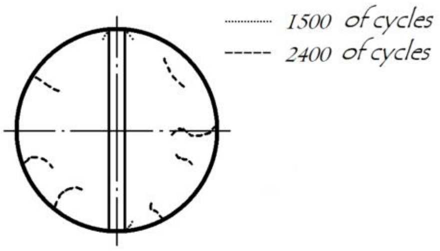

**Figure 12:** Origin of cracks after 1500 and 2400 cycles

In Fig. 13 the dependence of the cracks length divided by the sample circumference on the number of cycles i was plotted. The course corresponds to the relation (14.3).

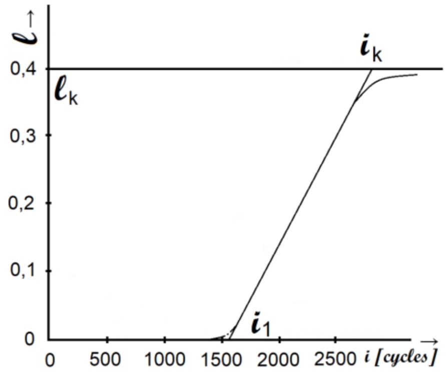

**Figure 13:** The length of cracks plotted in the values divided by the sample circumference in dependence on the number of cycles

To make a comparison – Fig. 14 shows the dependence of the cracks length in case of circular samples with diameter of 12.7 mm from materials *H11*, *H13*, *H21* and steel Maraging and in Fig. 15 from steel *D11* heated in the inductor to *670°C* and blown by the pressure air. The courses in figure 14 correspond to the initial degree and in Fig. 15 to the entire development (14.3).

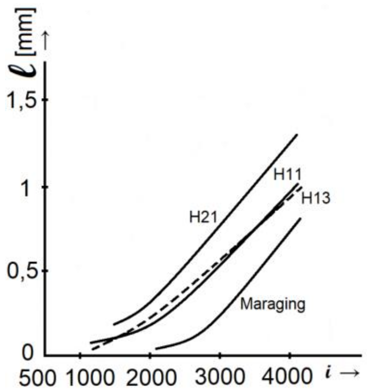

**Figure 14:** The dependence of the length of cracks in case of circular samples from materials *H11*, *H13*, *H21* and from steel Maraging

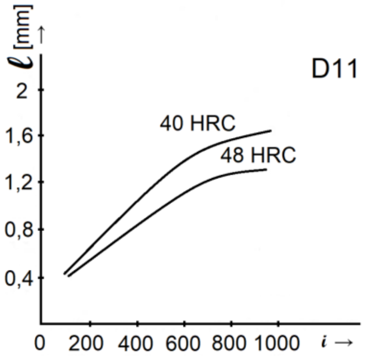

**Figure 15:** The dependence of the cracks length in case of circular samples from steel *D11* heated in the inductor on *670°C* and blown by the pressure air

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.

In Fig. 16 plotted are the Wohler's curves for $i_1$ and $i_{k1}$ for the material of ISO STN 422420 standard and in Fig. 17 for 12 060 according to the information of the tests and from [6]. The developments correspond to the relations (10.5) or to the relations (10.1).

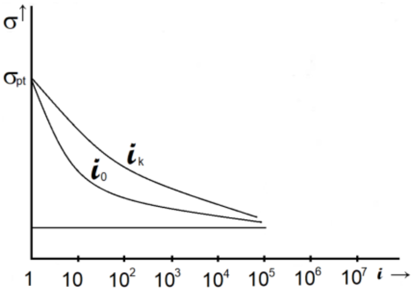

**Figure 16:** Wohler´s curves for $i_1$ and $i_k$ for the material STN 422420

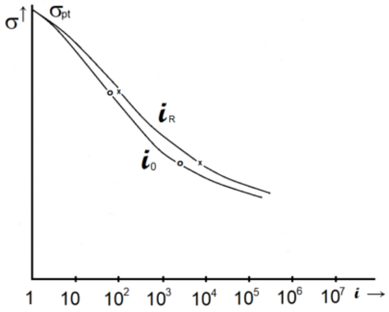

**Figure 17:** Wohler's curves for $i_1$ and $i_k$ for the steel 12 060

## 4 CONCLUSIONS

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) to (10.7) 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.

The derived relation for spreading of crack length in dependence on number of cycles (14.2) and (14.3) accord with the results of the transferred tests, with the results of tests from references as well as with the standard practice.

## ACKNOWLEDGMENTS

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