INFLUENCE OF THE STRUCTURE AND OF THE TEMPERATUREFIELD ON THE FORMATION AND PROPAGATION OF THERMAL FATIGUE CRACKS

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High temperature cycles are the reason for the thermal fatigue crack formation in the surface of die casting dies. The number of cycles until the start of damage is proportional to that time necessary for creep rupture - measured at the maximum stress and the maximum temperature in the surface of a die - and indirectly proportional to the time the skin of the die is loaded at the maximum temperature. The dependence of the thermal fatigue on the temperature will be determined by the activation energy of creep.

INTRODUCTION

In many constructions thermal fatigue cracks often arise and they are the premature reason for breakdown. For example in railway wheels, forging dies, break-disks of cars, hot rolling roles, turbine blads very often such defects are to be observed. The history of origin and the appearence of thermal fatigue cracks depends always on the actual state of stresses and temperature of the construction unit. This paper is restricted to the study of thermal fatigue cracks in die casting dies. Excluding "bad" constructions, wrong heat treatment and inappropriate handling during working, thermal fatigue is the only reason for failure.

TESTING EQUIPMENT

In order to study the crack initiation and the crack growth, a thermal fatigue equipment was built. It is possible to simulate the processes when die casting dies are loaded, for example by erosion,

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corrosion and alternating temperatures. It is known (1) that the influence of die casting pressure is more than one order of magnitude smaller than the influence of alternating tempereture. All specimens of hot working steels simulating the die casting dies were dipped alternating in two bathes, one heating (simulating the die casting alloy) and one cooling (simulating the die lubricant). The period of the hold time can be controlled and regulated by an electronic control device.

CONSIDERATIONS ON THE MECHANISM OF DAMAGE

Different thermal expansions are caused by temperature differences and lead to stresses which result in thermal fatigue cracks. At high temperatures of about 0,5 of the homologeous temperature two mechanisms of damage are possible. The one is fatigue by cyclic straining of the material, the other can be creep under high tension or pressure.

After loading a specimen by some temperature cycles in the former described test device cracks appear after a low number of cycles. These cracks arise at the grain boundaries but also inside the grains. Furthermore strong deformations at the surface can be observed. Hence it follows that the stresses produced by temperature cycles exceed the hot yield strength near the surface of the specimen. The hot yield strength of the tested hot work tool steels used here is about 400 MPa at 650°C.

Also fatigue (2) and creep (3) tests were performed with a hot work tool steel (X 40 CrMoV 51) at stress and temperature levels, typical for the die casting process. It can be shown that for cycles typical for die casting the most important damage mechanism is creep and not fatigue. Following an analysis by Danzer and Sturm (4) the number of cycles till to the appearence of macroscopic visible cracks can be estimated. Under the assumption that creep damage is the main mechanism for damage, the number of cycles until the first macroscopic cracks can be estimated

$$N_f = \frac{t_f(\sigma_{max}, T)}{t_e} \qquad \text{..............(1)}$$

The time until creep rupture t_f depends at the one side on the effective stress following a Norton law and at the other side on the temperature following an Arrhenius function. T means the temperature in a small surface layer and σ_{max} stands for the maximum stress in this layer.

In order to work out this equation (1) it was necessary to make many simplifications. Further the effective stress in the surface is not very easy to be evaluated. The life time prediction of crack initiation by the number of cycles N_f is therefore only an approximation. But it is possible to estimate the influence of the loading parameters by means of this formula. There is a specific temperature dependence of N_f in relation to the temperature-dependence of the time to creep rupture t_e which shows a dependence of the activation energy Q_c in form of an Arrhenius function.

Tests have shown (3) that the activation energy for creep reaches-according to the stress level-values from 500 to 680 kJ/mol. If as a result of equation (1) creep appears as the dominant damage mechanism than N_f should be proportional to $\exp(Q_c/RT)$. At a maximum temperature of the die casting dies of about 650°C a decrease of the temperature of only 25°C results in an increase of six times of the life time. This behaviour could be clearly confirmed by tests in our testing equipment for temperature cycles previously described.

Fig. 1 shows a section of the end plane of specimens after 70, 420 and 3000 cycles in a dipping bath of 700, 725 and 750°C. It can clearly be observed that damage increases with increasing temperature and the number of cycles. The ascending diagonals from the left show specimens with comparable damage. This result can also be quantified by an Automatic Image Analyzer. At a specified area of the specimen the ratio of the projected opened crack area to the whole specified area works as a measure of the damage rate.

Fig. 2 shows the damage over the number of cycles according to the specimens at the right column of Fig. 1 (750°C). Surprisingly an increase of damage in dependence on the number of cycles shows a linearity in this case. The observed scatter of the measured values is less caused by the experimental procedure but mainly by an inaccurate evaluation procedure. Fig. 3 exhibits the evaluation of all specimens from Fig. 1. The parameter of the straight line according to the increase of damage with increasing number of cycles is a function of temperature.

Fig. 4 shows the correlation of the time to failure (number of cycles N_f - symboled by ▼) necessary for the formation of thermal cracks with the temperature. This results are now compared with the time necessary for creep rupture - symboled by □ -and the temperature. The proportionality factor in this figure is choosen in such a way that an overlap of the two curves in the exhibited part of Fig. 4 occurs. It is evident that - within the slope"accuracy" in measurement - the two curves are equivalent. This means that the activation energy of creep is the same as the activation energy of the formation of thermal cracks. But it is impossible to describe the formation of thermal cracks by high-temperature-fatigue data published up to now (3). Considering change of the temperature of 25°C, the strain amplitude alters about 10 %. This would change the number of cycles N_f until the appereance of visible cracks by max. 15 % only. The negligible effect of temperature on fatigue can clearly be excluded as the dominant mechanism of damage.

The fact that creep is the main mechanism will be confirmed by the damage in die casting dies. All those parts near the sprine: which exhibit a higher temperature during die casting process show there a premature formation of thermal cracks although the temperature difference amounts only few C-degrees. An increase of temperature of about 9°C devides the time (time until crack formation) according to the determined activation energy by 2!

Furthermore all these parts of a die casting die which have a reduced flow of heat due to their geometry have to stay therefore for a longer time under high temperature levels, showing as a consequence a higher damage rate. Equation (1) has proved to be a simple and practicable aid to estimate damage in die casting dies.

Using equation (1) the rate of stresses in the surface of the die casting die can be estimated by measuring the life time. Characteristic life times of the dies are some ten thousand cycles, a typical value for t_f is one second. Due to equation (1) $t_f = N_f \ t_e$. This are some ten thousand seconds, corresponding about 10 hours. The creep resistance for 10 hours is therefore a typical value for the stresses which will be expected in the surface of the die casting die. σ_{max} will be at 650°C about 200 MPa.

Nearly nothing is known about stresses in surfaces of die casting dies. In this paper an attempt is made to estimate these stresses by means of the Finite-Element-Method (FEM).

TEMPERATURE AND STRESSES IN TEST SPECIMENS

Temperature- and stress-distributions in the cylindrical specimens were tested in the test equipment by alternated dipping in liquid Aluminium and water. The distributions of the temperature in the specimen and the resulting stresses were calculated by the FEM program ADINAT/ADINA (5). The difficulties arising in estimating the conditions of heat transfer were solved by fitting the heat transfer coefficients based on comparison between measured and calculated temperatures in the specimens at different spots. Thermocouples were located at different distances from the end plane (0.1, 0.5, 15 mm). With the heat transfer coefficients determined by the above mentioned concept calculations were performed also to different bath temperatures and dipping intervals.

The temperature distribution depends to a great extend on the site and on the time. After an initial phase of about 20 cycles a periodical distribution of temperature arises. Now according to the temperature distribution the stresses were calculated for linear elastic material behaviour.

The stresses are produced by different thermal expansion of the volume elements. The changing temperature in each volume element at every moment requires an iterative and time-consuming procedure.

Fig. 5 shows the specimen with the points for measurements MP1, MP2. In Fig. 6 the temperature in MP1 is plotted together with the Mises equivalent stresses in relation to the time . MP1 lies in the centre of the end plane where the stress state is two-axial. (The stress state at MP2 is uniaxial). When the components of the stress tensor are negative the equivalent stresses also are plotted negative. The temperature and stress distribution in Fig. 6 describe the second loading cycle of a specimen dipped in an aluminium melt of 750°C for 5 seconds and subsequently for 5 seconds in cold water bath for cooling. (Before the first cycle the specimen was at room temperature.) At this second cycle the "quasistationary" state was not reached. This means that the heat absorption was higher than the heat emission. The maximum temperature in the centre of the end plane has a value of about 570°C in the second cycle and after reaching the quasistationary state the temperature is 635°C. The difference of the temperature between MP1 and MP2 is about 100°C and this difference is mainly responsible for the development of thermal stresses . An estimation by an analytical procedure shows extremely small stresses in a cylindrical specimen by temperature gradients only in axial direction. Only the temperature variation along the radius of the specimen generate successivly an equivalent stress above the hot yield strength of the material. Assuming a parabolic temperature distribution $T = To.(1+ \delta r^2)$ the following approximative value for the radial and circumferential stress can be formulated.

$$\sigma = \frac{E}{1-\nu} \cdot \alpha \cdot T_0 \cdot \gamma R^2 \qquad \text{............(2)}$$

Inserting characteristic parameters of the material in this equation a stress of 38 MPa per °C arises according to a temperature difference of 5 % between the center and the edge of the specimen. This evaluation confirms the necessity of a continuous and possible constant distribution af cooling over the whole surface of the die casting die. The FEM calculations result in circumferential compression stresses of more than 200 MPa in the edge of the specimen during the hot phase and circumferential tension stresses more than 300 MPa during the cooling procedure.

The compression stresses during the cavity fill phase give reason for the creep mechanism in the surface of the die casting dies and consequently a further increase of tension stresses produced by cooling. The process of accumulation of creep strains by successive increase of tension stresses is responsible for failure in die casting dies.

OPTIMIZING OF THE CASTING PROCESS

Because of the dependence of the life time of die casting dies on the creep strength due to equation (1) following consequences arise for the casting process.

To avoid different thermal expansions and - as the consequence - large thermal stress levels the casting temperature should be as low as possible. From this follows a short solidification time te reducing the loading time.

In order to avoid higher heat accumulations it is necessary to avoid an unnecessary accumulation of material, for instance at stiffeners and bearing edges. This would result in a longer solidification time and a higher transition temperature. According to small differences of the temperature in the die casting die it would be appropriate to keep the average temperature resp. the preheat temperature as high as possible.

Exceeding the optimal preheat temperature has certainly a disadvantageous effect. The gradient of temperature in the die casting die will become very small causing a slowly heat flow from the castings to the die casting die and the solidification time will be longer. The result is a longer and higher loading of the surface.

OPTIMIZING OF THE HOT WORK STEEL

The result of this paper is the recommendation of a high 10 hours creep strength of the die casting die materials. Furthermore there is the necessity of other quality properties as for instance homogeneity, isotropy, degree of purity, toughness and fine grained materials. There is no contradiction between a high creep strength and the required fine grain. (Only in the regime of long time creep a coarse grain will be advantageous).

The life time of the die casting die can be doubled in the range between 600°C and 800°C using isothermally transformed bainitic structures instead of quenched and tempered martensite structures (Fig. 7). An other advantage of the isothermal treatment is a uniform development of the structure in larger cross sections. Deep cooling of the hot work steels removes retained Austenite, and temper procedure can be avoided. Therefore the life time can be elongated by that time which would be necessary for the tempering process.

Considering all these proposals prolongation of the life time by 40 to 50 percents can be expected.

RESUMEE

Crack initiations and crack growth in hot work tool steels by thermal cycling are mainly caused by creep. This important result can be applied both to optimize hot work steels and to improve the condition of production.

SYMBOLS USED

E ..... Young-Modulus
ν..... Poisson Ratio
α..... Thermal expansion coefficient
R ..... radius of cylindrical specimen, $0 \leq r \leq R$

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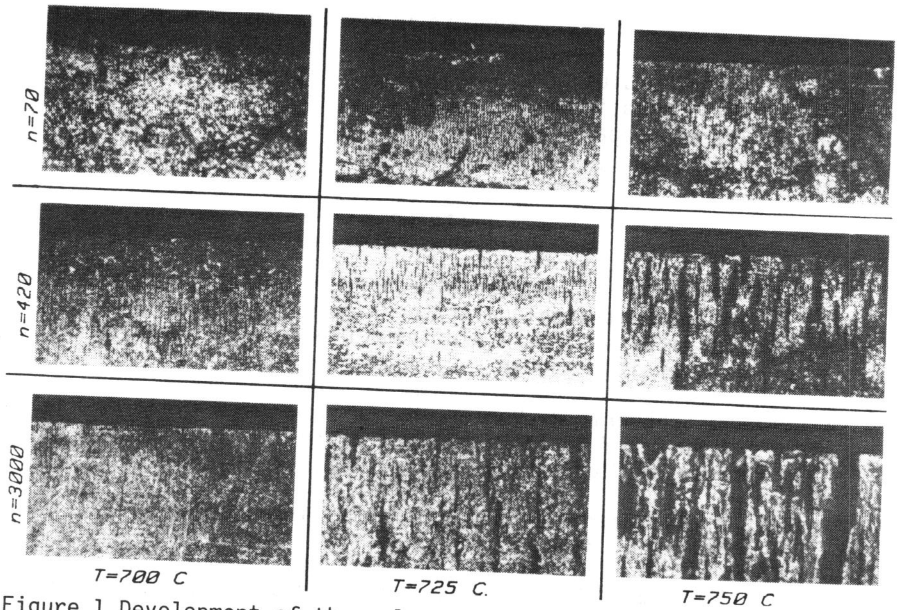

Figure 1 Development of thermal cracks in dependence of temperature T and number of cycles Nf

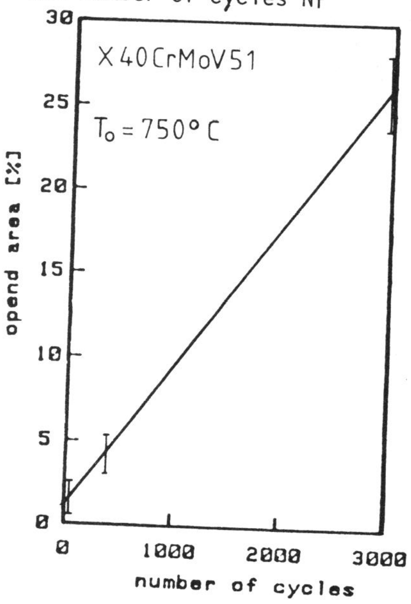

Figure 2 Damage versus number of cycles (750°C)

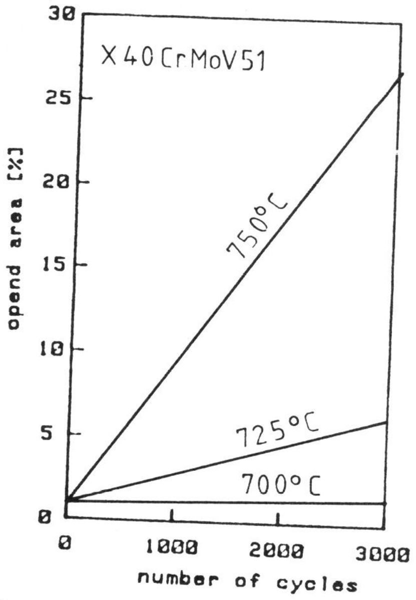

Figure 3 Damage versus number of cycles for different temperatures

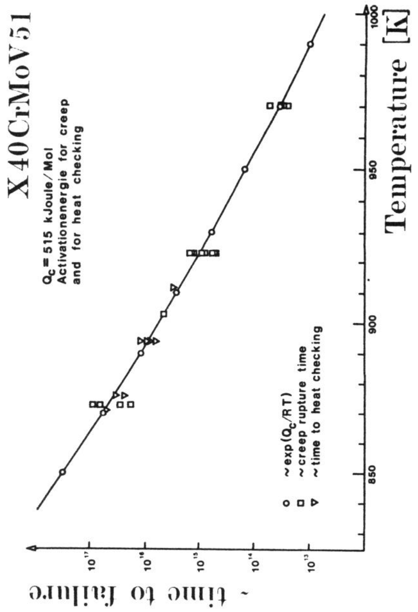

Figure 4 Life time versus temperature

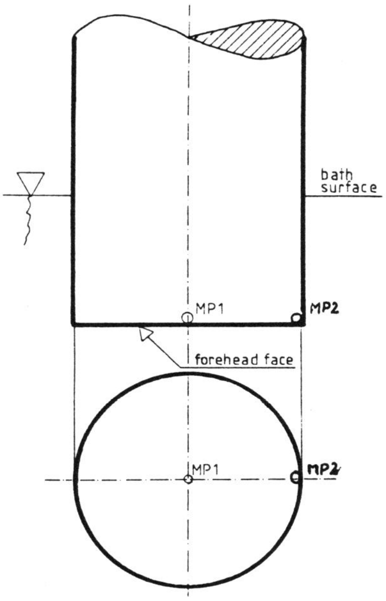

Figure 5 Dipping specimen with location of measuring points

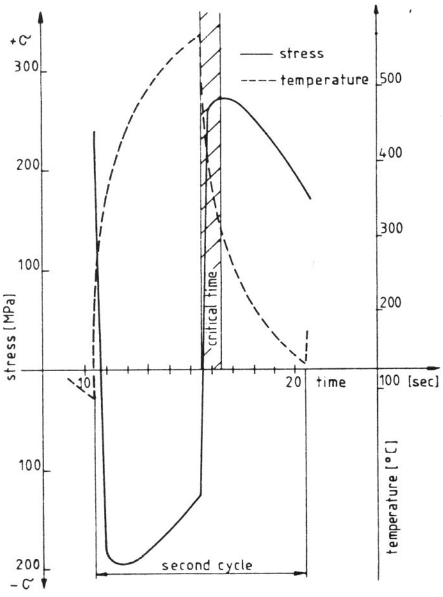

Figure 6 Stress and temperature dependence versus time (2. cycle)

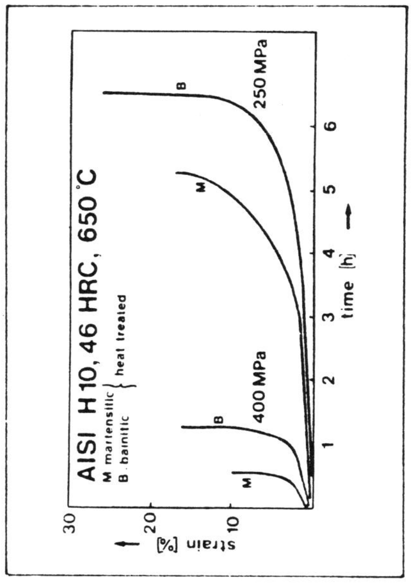

Figure 7 Comparison of creep strain versus time