RESIDUAL LIFE-TIME PREDICTION IN ALUMINIUM ALLOYS

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Microcracks initiation and small cracks growth are most important for fatigue life. Microcracks are formed in the first 20% of life on cracked or debonded particles, the probability of crack initiation being increased with particles diameter. The rate of growth of small cracks is influenced by microstructure and thickness of surface layer. It is possible to express stress intensity factors for all cracks with various lenghts and the rate of growth by the same law but with various exponents.

INTRODUCTION

Experiences gained from the service of transport machines, particularly aircrafts, have shown that the life of the machine is determined by the number of cycles to the initiation of fatigue microcracks from structural and technological notches, and by propagation of small cracks of the size ranging from 10^{-4} to 10^{-1} cm, as shown by the diagram on Fig.1. As a rule, these stages of fatigue damage form almost 90% of the total life of machines and structures. It is therefore necessary to study first of all the initial stages of damaging and to find procedures which would create the necessary barriers against initiation and growth of small cracks. This is concerned with changing the philosophy from the concept of initial strength criterion to that of the required

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life criterion on one hand and from the concept of macrocrack propagation criterion to that concerned with controlling the first stages of the initiation of microcracks and growth of small cracks on the other (1).

INITIATION AND GROWTH OF MICROCRACKS

Due to the cyclic plastic flow in the locations of shear fatigue stress damage of material in the extent of the size of small cracks takes place which can not be described by means of linear fracture mechanics. The processes are of a local character, the microstructure of the material and the properties of the surface layer being the decisive factors. This is why the technology has such a great influence on these processes and why attempts of their study by the models of elasto-plastic continuum fail.

The initial fatigue cracks are formed, as a rule,at surface and subsurface defects and inclusions.It should be realized that the surface layer is a weak place of a body; the yield point is lowered here, the dislocations are most mobile,the intergrain bonds are weakened, and structural and technological residual stresses reach their highest values; on the other hand, the surface layer is subjected to the highest service loads. It should also be noted that for the natural surface of a component the chemical composition of the surface layer is poorer than that of the inside and in many cases it is exposed to the action of aggressive media and thermal effects. It is for these reasons that fatigue cracks are born in the surface layer. They arise at places where relaxation and dilatation centres act and where the plastic matrix is in a contact with a brittle particle. Their deformation characteristics are guite different so that when a body is strain cycled a rigid deformation cycle results, leading to the crack initiation.

As these small cracks leave the boundary between the inclusion and the matrix the crack tip strain conditions are changed; the cracks leave the weak place and enter the material which is cyclically stronger and capable of cyclic hardening. Despite the growth of both the crack and the cyclic plastic strain the mean strain is shifted and the strain range is relatively reduced. This is caused by that the crack is closed during compression, mediating thus the stress flow, while in tension the stress flow must by-pass not only the initial inclusion but also the crack formed. The change in the hysteresis loop is demonstrated on Fig.2.Compared to the growth of a small crack two barriers are formed here(2).

A more effective cyclic hardening in the metal matrix takes place and a more favourable crack tip strain cycle is formed. This leads to retardation and even the arrest of some cracks.

Very essential is the next barrier concerned with the crack passing through the weakened surface layer into the body. The material exhibits here a higher yield point, so that a change of the plastic flow in the front of the crack results; the response of the body and redistribution of the stress flow in the affected zone are also changed. This leads to reduction of the hysteresis loop and to lowering the energy stored in the damaged zone by each cycle. The production technology, e.g. that of the hardened zone in the region of geometric changes of the body plays a significant role here. This leads to a change in the propagation of the magistral crack and to its deceleration. As soon as the crack has grown to the macroscopic size of the order of centimetres neither the barriers nor the initial notch effects play a role any longer.

The problems of the microstructure and purity of material should therefore be taken into account by the fracture mechanics (3). This is supported by the analysis of the initiation and growth of small fatigue cracks in aluminium alloys used in aircraft practice.

EXPERIMENTAL RESULTS

Test bars, made from extruded Al alloys of the type 2024 in the naturally aged state, were investigated by Ruščak and Sedláček (4). The occurrence and distribution of intermetallic phases in the longitudinal and transverse sections were established. The density of particles was 2 300 - 4 300 mm^{-2} , representing 0.9 - - 2.5% of the surface. The mean size of the particles on the transverse section was 2.7 μm. The test bars were subjected to stress cycling with the amplitude 100 - 200 MPa and the stress ratio R = 0.1. During cycling changes in the surface layer and formation of microcracks were established by means of the differential interference contrast technique with the magnification 1:250. Attention was paid to the direction of growth of microcracks and their relation to the microstructure.

Most of the cracks were formed at the interface of matrix and intermetallic phases at both situations:after cracking the particles and after their decohesion from the matrix. The dependence of the density of microcracks on the stress amplitude in various stages of cycling is on Fig.3. At low stress ranges a big increase in the density of microcracks is observed in the beginning of cycling up to about 20% of the total life; later the density of microcracks stabilizes and further cracks are formed towards the end of life and are limited to the vicinity of the magistral crack. The probability of initiation of microcracks on a particle is given by the ratio of the number of microcracks initiated at particles of the same size to their total number - Fig.4. Particularly dangerous are clusters of particles of intermetallic phases at which microcracks are initiated.

The minimum lengts of microcracks found was 0.5 μm, most of them were, however, twice as long. From there a theoretically predicted fact follows: microcracks are not formed untill the volume of material, damaged by fatigue,reaches a certain critical size for which the opening of a crack and formation of a relaxation centre requires less energy than the further increase of the size of the cyclically deformed region.A number of cracks were found to be stopped during cycling. The rate of growth of microcracks was always observed to decrease in the predicted way. After reaching the size of about 0,3 - 1 mm and having passed the surface layer of material the cracks start to accelerate again. This point defines the extent of so called small cracks.

SMALL CRACKS

The formation of small cracks from the system of microcracks at the surface of bodies is complex and it depends on the type of material and its structure.Their development through the surface layer is enabled, first of all, by connecting two adjacent microcracks through breaking the ligament. In this case, however, the front of the new crack has tendency to minimize its length and reduce thus the tension along it according to Fig.5. In this way a crack capable of growing is gradually formed; after the crack has grown through the surface layer it enters the inside material which is of a better quality. In this stage the crack growth rate reaches its minimum and the crack itself can be arrested most easily.

As it was mentioned earlier some experimental studies show that the rate of growth of small cracks depends on the stress range while the growth rate of long cracks depends on the stress intensity factor range. In fact, the crack growth rate is always dependent on the complex factor composed of quantities which express the level of stress range and the characteristic size of the damaged region of a material:

$$K^{*}_{ef} \sim \sigma_a \sqrt{q} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where q is the size quantity. This quantity is equal to (i) the magnitude of microstructure parameters like diameter and distance of particles, dislocation density, slip band distance and others (q=d) for microcracks of the order 10^{-4} - 10^{-3} cm, (ii) the thickness of the surface layer of the body (q=s), given by the type of material and technology, for small cracks of the order 10^{-2} - 10^{-1} cm, and (iii) crack length ($q=\ell$) for macrocracks. Because the region affected by cyclic plastic strains is considerably greater than the length of small cracks, the crack length can not be considered as having sufficiently contributed to the size quantity so that the crack growth rate appears to be stress range dependent.

In individual stages of fatigue crack propagation various barriers against crack development come into effect. The threshold value of the stress intensity factor is therefore different. For small cracks it is determined by the value $K^{*}_{th} = K_s$, while for long cracks it is given by the threshold value $K^{*}_{th} = K_o$ which expresses the effect of residual compressive stresses induced in front of the crack. Proceeding from these considerations it can generally be written:

$$v = \frac{d\ell}{dN} = C\,(K^{*\lambda}_{ef} - K^{*\lambda}_{th}) \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

The process is schematically shown on Fig.6. The dependence of both the crack growth rate and their nascent state on the crack length is shown on Fig.1 for various shapes of bodies (initial stress concentrations). On the basis of the curves on this figure the life of bodies can be determined by integration. It should be realized there are big differences between real bodies and test bars.

If a number of cycles to fracture is investigated on smooth specimens then the stage of crack initiation is decisive and the effect of constructional or structural notches can be expressed by the ratio of the life N_c of a small unnotched specimen to that of a structure:

$$\beta_N = \frac{N_{c \text{ unnotched spec.}}}{N_c \text{ body}} \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

This is a new way of expressing changes of the life of a structure in comparison with that of a model; the initial phenomenological and impirical relationships regarding the effect of a notch are substituted here by the physical idea of the formation and propagation of cracks. This removes a number of obscurities which were called forth by an effort to express the notch effect by the ratio of the fatigue limit of an unnotched bar to that of a notched bar. In fact, a notched bar has never been an objective model of a structure because the actual course of damaging and the actual process of damage accumulation in a geometrically complicated structure with a real manufacturing technology were neglected.

CONCLUSION

The basic model of the process of decohesion of metallic materials is based on the idea that the process depends not only on the strain or stress level but also on the volume being damaged. The quantity of the damaged volume depends on the type of the process and it varies (increases) as the decohesion develops. The microvolume, mesovolume, and macrovolume should be distinquished here. In any case the product of stress and size factor is decisive. This complex parameter is significant for keeping the crack development in a given stage of crack propagation. In the substructure scale the parameter is determined by the size and distance of inclusions, e.g. intermetallic phases, as well as by the density of dislocations piled-up at the inclusions. In the scale of mesovolume the parameter is determined by the thickness of the surface layer of material. The length of crack is decisive in the macrovolume as it determines the plastic zone in which damaging of material takes place. As far as the rate of the process of damage accumulation is to be evaluated it should be realized that both the exponent of the power dependence on this parameter and the threshold value of the parameter change.

SYMBOLS USED

K_{ef}	stress intensity factor ($MPa.m^{1/2}$)

K_{th}	threshold value of K (MPa.m$^{1/2}$)
l	crack length (m)
N_c	number of cycles to failure
s	thickness of surface layer (m)
v	crack growth rate (m/cycle)
λ	exponent
σ_a	stress amplitude (MPa)

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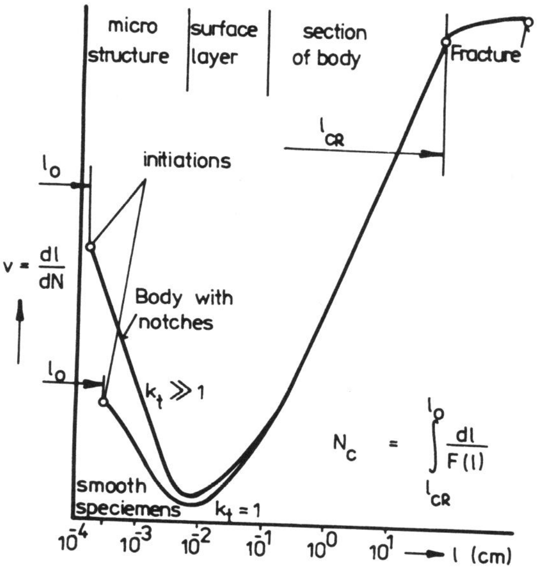

Fig.1 Dependence of the crack growth rate on the crack length

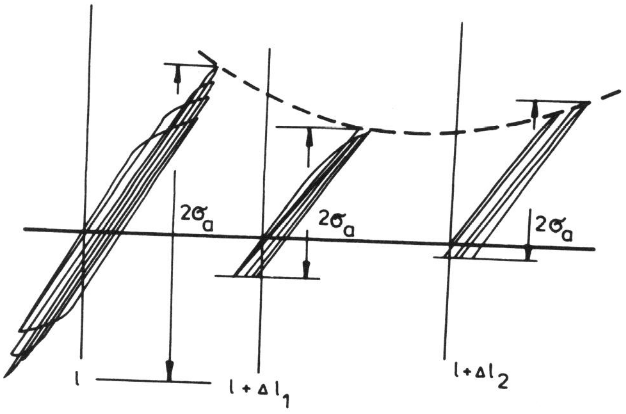

Fig.2 Changes in the hysteresis loop

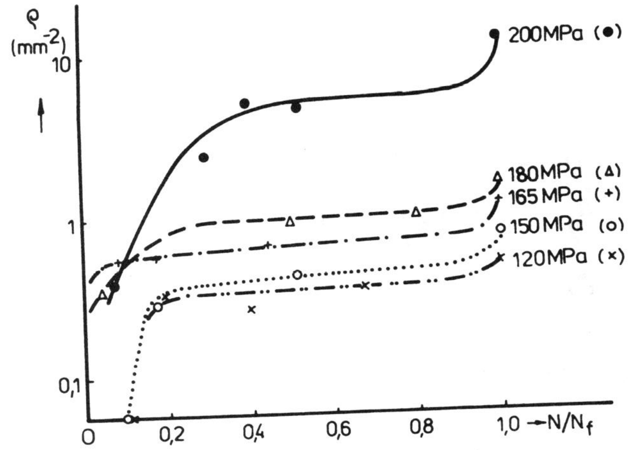

Fig.3 Change in microcrack densities

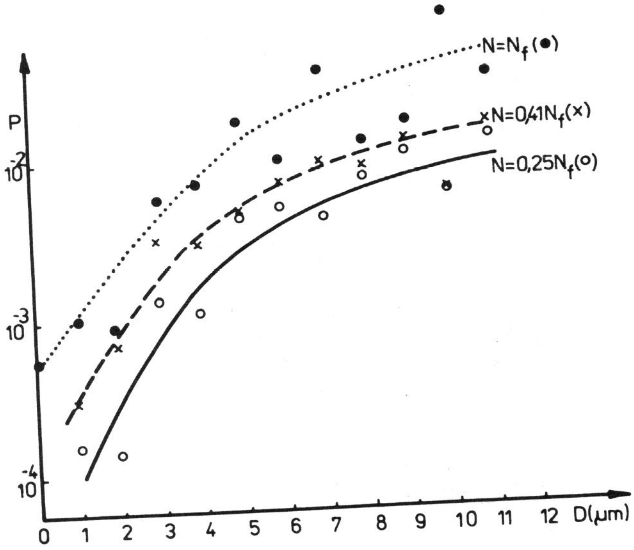

Fig.4 Probability of crack initiation

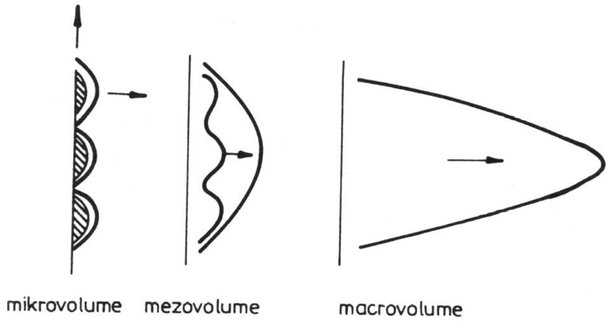

Fig.5 Growth of cracks in growth volumes

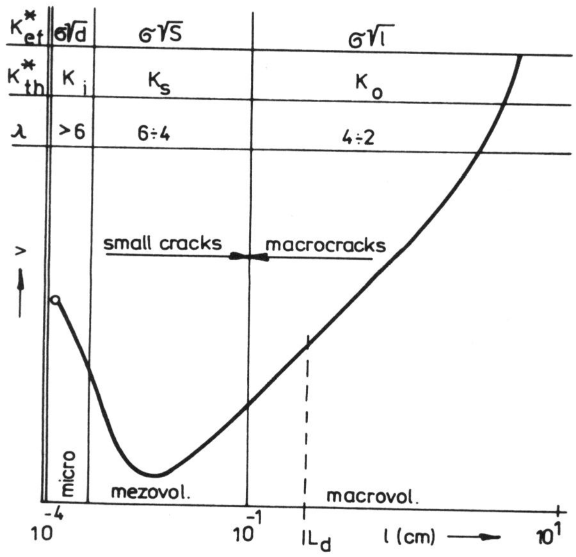

Fig.6 Parameters of the crack growth rate