FATIGUE CRACK INITIATION AND EARLY GROWTH IN THE MULTI-LAYERED FIBRE-METAL LAMINATE GLARE 2

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Results of a recent investigation of fatigue crack initiation and early growth in notched panels of various thickness made of fibre-metal laminate GLARE 2 are presented. Crack initiation life and total life up to the 10 mm crack length are shown. Early microcrack nucleation in inner metal layers and deviation of surface major crack initiation sites from the notch tip are explained in terms of local stress and strain fields in the laminate layers including the residual stress distribution. The decrease of crack growth rate with increasing crack length corresponds to a drop of stress intensity. Effect of the notch factor and the number of lay-ups in the laminate are discussed.

INTRODUCTION

Fibre-metal laminates represent a new type of structural material used for light-weight structures (1). Application of the fibre-metal laminates is motivated by their excellent mechanical properties and weight savings with respect to the traditional aluminium alloys and under certain conditions also with respect to carbon composites. Fibre-metal laminate GLARE 2 consists of alternating layers of 0.3 mm thick high strength aluminium alloy (2024-T3) sheets and layers of unidirectional glass fibre reinforced adhesive (0.25 mm). The excellent fatigue resistance of GLARE 2 makes this material attractive for damage-tolerant structural applications, especially in aerospace industry, like parts of the fuselage or lower wing skin and stabilisers (2). In structural parts where the final failure may occur in the presence of a relatively short crack (e.g. attachment lugs or riveted lap joints), the period of crack initiation and early growth determine the fatigue life.

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The objective of this work was to investigate the initiation and growth of fatigue cracks in the notched multi-layered fibre-metal laminate GLARE 2 with the aim to find a mechanism of initiation and early growth of fatigue cracks in this type of material and to discuss the effect of notch stress concentration and laminate thickness..

EXPERIMENTAL

Flat notched specimens having the dimensions of 50 x 200 mm and thickness ranging from 1.4 to 6.5 mm were prepared. The thickest specimen consists of 12 aluminium and 11 prepreg layers (i.e. 12/11 lay-ups). The 6.5 mm thick specimens were provided with three types of notches: (a) two side shallow notches (7.5 mm depth and 70 mm radius), (b) one central circular hole (15 mm in diameter) and (c) one central slot hole (15 mm width and 3 mm radius). The notch factors K_t were 1.2, 2.4 and 3.2, respectively. Specimens were fatigued in a servo-hydraulic testing machine with R ~ 0.04 and under constant load amplitude control. The maximum net-section stress σ_{max} was in the interval 127 MPa to 450 MPa. The tests were terminated when the dominant surface crack became longer than 10 mm. Loading direction was always parallel to the specimen length (parallel to aluminium rolling direction and unidirectional fibre orientation).

The specimen surface in the vicinity of the notch root was observed by means of the optical microscope. Four areas on the outer aluminium layers close to both notch roots on both sides of the laminate specimen were observed in order to detect the crack initiation and to measure the early growth of fatigue cracks. Lateral notch sides were checked as well. Before loading, the surface of the specimen was mechanically polished.

RESULTS

Crack Initiation

First fatigue cracks were observed in inner aluminium layers on the lateral side of the notch. The microcracks nucleated simultaneously at many sites dispersed symmetrically to the direction perpendicular to the loading axis in the interval of angles $\theta = \pm 20$ degrees. The lateral side of the notch and the definition of the angle θ are schematically shown in Figure 1. When a fatigue microcrack appears in the outer laminate layer, i.e. on the aluminium surface layer, the surface crack is initiated.

Number of cycles necessary for surface crack initiation N_i versus maximum stress level of loading cycle σ_{max} is shown in Figure 2. Crack initiation life is significantly affected by the notch factor K_t, with earlier initiation in the sharper notches. The effect of thickness is much less pronounced and was observed under low amplitudes where earlier crack initiation occurs in the thicker laminates.

Crack Growth

Linkage of microcracks from neighbouring aluminium layers and crack growth through the laminate thickness is restricted by fibres in prepreg layers separating the neighbouring aluminium layers. Correspondingly, crack growth in this direction was not found (see Figure 3). Growth of these microcracks in the inner metal layer is possible after some delamination between prepreg and metal layers. Investigation of the inner cracks has not been carried out and further crack growth was followed exclusively on the laminate surface.

During loading some surface microcracks on the notch edge began to grow faster than the others and later the major cracks were identified. Other microcracks stop growing. Location of initiation sites of the major cracks were measured as an angle θ between the direction perpendicular to the loading axis and the early crack growth path (see Figure 1). Angle θ depends on the stress amplitude and the notch factor; small effect of the laminate thickness was observed at low amplitudes. Values of angle θ varied from $\theta = \pm 5$ degrees in shallow notches at low amplitudes up to $\theta = \pm 20$ degrees in the sharper notch at the highest loading amplitude.

The major cracks grew from the notch edge radially and in some distance from the notch corresponding to the notch radius the cracks turn their growth to the direction perpendicular to the loading axis. Figure 4 shows major cracks in the centrally notched specimens. Major cracks in the shallow notches grew radially during the whole test. The crack growth rate is maximum at the crack initiation and decreases with increasing crack length. At the crack length longer than the notch radius, the crack growth rate become approximately constant, independent on the crack length.

DISCUSSION

Stress peak which develops local plastic strain at the notch root is a controlling parameter for fatigue crack initiation in a notched body. The local stress peak in fibre-metal laminates depends on the notch factor K_t and the internal residual stress by the expression: $\sigma_{peak} = \sigma_{max} \cdot K_t + \sigma_{res,Al}$, where σ_{max} is the maximum net-section stress level of the loading cycle and the residual stress $\sigma_{res,Al}$ is calculated for aluminium layers, where fatigue crack initiation occurs. Tension residual stress in metal layers in an as-cured laminate contributes to the stress level and can reduce crack initiation life with respect to the monolithic aluminium alloy. However, plastic strain at higher applied load can reduce or reverse the residual stress in metal layers and thus extend crack initiation life. Shorter crack initiation life observed under low amplitudes in thicker laminates is due to the higher residual stress in thicker laminates with respect to thinner ones. Residual stresses in the specimens tested are given elsewhere (3).

To explain earlier initiation of fatigue microcracks in the inner aluminium layers of the laminate a through-thickness distribution of the residual stress must be taken into account. The residual stress in inner aluminium layers is higher than in outer aluminium layers due to a free surface of the outer layer. It implies higher peak stress in the inner aluminium layers with respect to the outer layers and later initiation of fatigue microcracks on the laminate surface.

Deviation of initiation sites of the major cracks from the position $\theta = 0$ degrees has been already observed by Newaz and Majumdar (4) in the Ti-3/SCS-6 metal matrix composite. Location of crack initiation sites in MMC was explained by Shen et al. (5) in terms of the multiaxial parameter combining shear and normal strains on the critical plane. In fibre-metal laminates the interaction of stress and strain fields in prepreg and metal layers must be considered. Stress peak in a separate aluminium sheet occurs at the notch root ($\theta = 0$ degrees) as in an isotropic material. Stress field in a separate prepreg layer is affected by a seriously disturbed fibre structure around the notch. Transmission of the load from the cut fibres above the notch to the continuous fibres behind the notch is restricted by a low shear modulus of the epoxy matrix in the prepreg what leads to high shear strain between the regions of continuous and cut fibres. Hence the stress and strain fields in prepreg layers and in aluminium layers are significantly different. In a bonded fibre-metal laminate it results in high inter-laminar plastic shear strain with peaks out of the notch root. As a consequence, crack initiation occurs at sites which deviate from the „isotropic position“.

Crack growth rate in notched GLARE 2 specimens decreases during the test. Crack growth rate is determined by the effective stress intensity factor which is in libre-metal laminates a function of local stress level, crack length and crack bridging (6). The local stress decreases with increasing distance from the notch. The effect of increasing crack length in fibre-metal laminates is minor due to the crack bridging fibres that reduce the effective stress intensity factor. Hence the early growth of fatigue cracks in notched fibre-metal laminates is dominantly affected by the notch stress gradient. When the crack length becomes longer than the notch radius, the effect of the notch can be neglected and the crack growth rate is controlled predominantly by the stress intensity factor. Laminate thickness affects crack growth rate through the fibre volume fraction in the laminate that influences crack bridging forces. Fatigue cracks thus grow faster in thinner laminates with lower fibre volume fraction.

CONCLUSIONS

Investigation of fatigue crack initiation and early growth in flat notched specimens made of as-cured fibre-metal laminate GLARE 2 of different thickness led to following conclusions:

- First fatigue microcracks nucleate simultaneously in inner aluminium layers on the lateral side of the notch. Major surface cracks initiate from the microcracks at the notch edge at sites which deviate from the direction perpendicular to the loading axis by an angle from ±5 degrees to ±20 degrees.
- Crack growth rate is maximum when crack initiation and decreases with increasing crack length. When the crack length is longer than the notch radius, the crack growth rate becomes approximately constant.
- Effect of sharper notch on crack initiation is generally negative. Crack growth is affected by the notch up to a distance corresponding to the notch radius.
- Effect of higher laminate thickness is important in loading below 200 MPa when higher number of lay-ups causes reduction of crack initiation life and results higher crack growth rate. Crack growth beyond the influence of a notch is faster in thinner laminates.

ACKNOWLEDGEMENTS

This work was financially supported by the Grant Agency of the Czech Republic (No. 101/94/0991) and by the NATO Scientific Affairs Division (No. HITECH.LG.941331).

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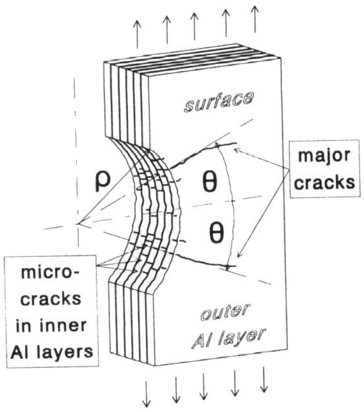


Figure 1 Fatigue cracks in the notched GLARE 2 specimens.

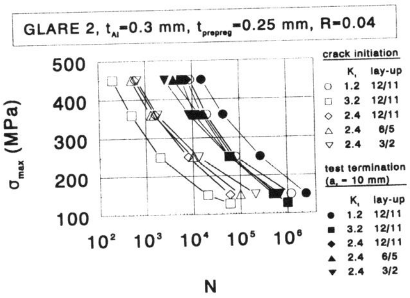
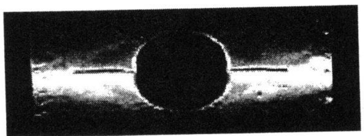
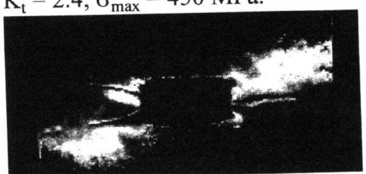


Figure 2 Crack initiation life and fatigue life of the notched GLARE 2.



$K_t = 2.4$, $\sigma_{max} = 150$ MPa.

$K_t = 2.4$, $\sigma_{max} = 450$ MPa.



$K_t = 3.2$, $\sigma_{max} = 360$ MPa.

Figure 3 Major surface cracks in the notched GLARE 2 (12/11) specimens.

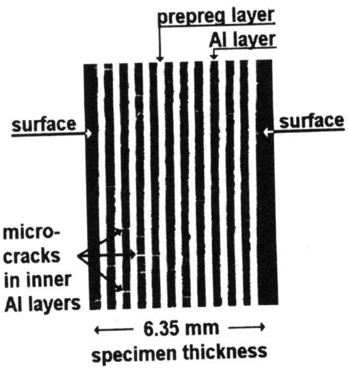


Figure 4 Microcracks in the inner Al layers. $K_t = 1.2$, $\sigma_{max} = 250$ MPa.