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FATIGUE CRACK GROWTH AND DELAMINATION IN FIBER METAL LAMINATE (GLARE) DURING LOADING WITH POSITIVE MEAN STRESS

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Abstract: *The aim of the paper is to present the results of a study on the damage of fiber metal laminate (GLARE) subjected to the low cycle fatigue loading with positive mean stress. The fatigue crack initiation and growth was observed on the surface of notched specimens and then the individual layers of fatigued specimens were removed by chemical etching and polishing to obtain data about cracks length and delamination shape and area. Mechanism of initiation and crack growth in this type of materials differs from homogeneous monolithic materials. The fatigue life in term of number of cycles to crack initiation depending on amplitude of local plastic deformation and local stress in the notch root was evaluated.*

Keywords: ***Fatigue, laminate, crack initiation, crack growth, delamination***

1. Introduction

Fibre metal laminates (FMLs) were developed at Delft University of Technology in Netherlands (Roebroeks 1991). These hybrid laminates consist of fibre reinforced plastic layers, so-called prepregs alternating with metal sheets of aluminium alloy. This combination connects outstanding fatigue resistance and high strength properties of glass fibre composite and ductility of metal layers.

FMLs can be strengthened by different kinds of fibres (Chlupova 2002). Material in this study with commercial name GLARE contains as reinforcing fibres the high strength S-glass fibres. For the metal sheets, the aluminium alloy 2024-T3 of thickness 0.4 mm is used (Prasilova 1998).

The concept of hybrid materials was developed primary for aviation applications (Vasek 1999) and presently is used as a fuselage of Airbus A380 (Hinrichsen 2002); nevertheless it can have very wide range of employment as a material for automotive and ship industry, wind power plants, sports, up to unusual applications such as manufacturing of music instruments or prosthesis in medicine.

FMLs possess different kinds of properties and their anisotropy allows tailoring material exactly according to the stress-strain fields acting in particular structural part (Chlupova et al. 2001). Basic mechanical properties such as strength and stiffness are comparable to conventional materials. The other properties like impact and fire resistance, formability, manufacturability, reparability, weight savings, low costs of production etc. offer in many cases significant advantages and are in the centre of attention (Yaghoubi 2012, Moussavi-Torshizi 2010, Park 2010). The drawback of this material can be seen in the lack of knowledge, i.e. due to insufficient data and information about material characteristics the designers aren't able to make the right decisions at design of structural parts and hesitate to apply FMLs for broader industrial applications.

The aim of this work is to present results obtained at study of fatigue properties of one kind of FML. Contrary to the monolithic metal materials the GLARE exhibits among others longer fatigue life and extremely elongated stadium of fatigue crack propagation which makes this material safer and damage tolerant. Zehnder in his work compared two types of materials: 1) homogeneous material and 2) layered material made of metal and plastics laminas without fibres, show that plastic layers operate as a barrier and a kind of bridging element (Zehnder1997). The glass fibre layers in GLARE can

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therefore even more improve the mentioned barrier and bridging effect. Glass fibre layers have very positive effect on postponing of initiation and on retardation of propagation of already initiated fatigue cracks. This fact elongates efficiently fatigue life and increases safety of structural parts made of this kind of material (Prasilova 1998).

2. Experiment

Material used for investigation: GLARE 2 have unidirectional fibre orientation. Flat specimens having dimensions 200x50mm and thickness: t = 1.4, 3.1 and 6.5 mm (i.e. with number of layers 3/2, 6/5 and 12/11) were provided with different kind of notches: specimens with central semicircular or circular notch or two side shallow notches with stress concentration factor K_t = 1.2, 2.4 and 3.2.

The cyclic loading was performed in force control regime, i.e. different levels of stress amplitudes were chosen with parameter of asymmetry of R = 0.04. Specimens were loaded by computer controlled servohydraulic testing machine MTS 880 at room temperature. Maximum applied stress in cycle σ_{max} varied from 90 to 450 MPa in individual test.

Fatigue crack initiation and growth was observed in-situ on the surface of notched specimens. The surface metal layer at the notch root area was mechanically grinded and polished before the loading to facilitate observation of crack initiation and growth. Observation and measurement of crack length during loading was performed using microscope QUESTAR QM-100 and CCD camera. The data acquisition during loading was performed. Loading was terminated at length of surface layers about 10 mm or at number of cycles 10^6. After test termination the destructive analysis was performed. Individual layers of laminate were removed by means of chemical etching and mechanical grinding and polishing. A level of material degradation inside of laminate was evaluated (i.e. for cracks the number, length, place and direction of growth were investigated; for delamination the size and shape were assessed).

3. Results

FMLs are very complex material which means that damage in this type of material is even more complex problem. The damage can occur at different levels as is seen in *Fig. 1*.

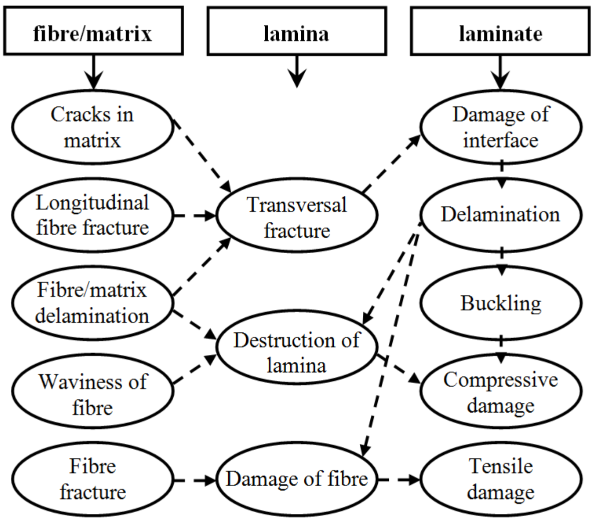

Fig. 1: Different types and levels of damage in hybrid laminates.

Mechanism of initiation and crack propagation differs from the mechanism of initiation in homogeneous monolithic materials. Fatigue cracks initiate first in metal layers in inner layers of laminate. The cracks initiated always at metal prepreg interface even in case of surface metal layer. The latest is the initiation in surface layers nevertheless the crack growth on surface of specimen was the fastest. The crack front in FMLs is not continuous, it is created by crack fronts in individual layers laying usually not in one plane and with the maximum length on the surface of specimen. It is different from the crack front in monolithic metal materials where it is continuous, in one plane and curved with maximum length inside of material.

The initiation place is usually under some angle from the notch root (*Fig. 2a*). The deflection depends on the type of notch and applied stress (in case of central circular hole it was about 7 to 12 degree at lower applied stresses and 5 to 20 degree for higher applied stresses). The wide range of deflection angles of crack initiation place is connected mainly to: 1) fibre structure with intact fibres directly in the notch root which prevent crack initiation and 2) cut fibres acting as defects are situated at certain angle. Between areas of continuous and cut fibres i.e. outside the notch root there is a high level of shear stress on fibre-matrix interface and high level of interlaminar elastic and plastic deformations. The initiation in the notch root is therefore less probable (see *Fig. 2b*).

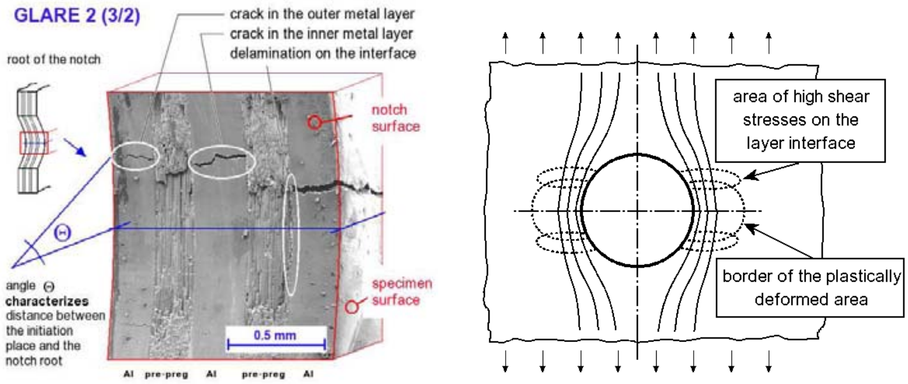

Fig. 2: a) Deflection of crack initiation angle and b) shear stress in the fibre reinforced lamina with circular notch.

Shortly after initiation the cracks are radial i.e. they grow perpendicularly to the edge of the notch. After some propagation period (approximately when cracks reach length corresponding to the notch radius) the cracks deflect to the direction perpendicular to applied loading. From comparison of situation inside and on surface of laminate it is obvious that number of cracks in metal layers inside of laminate is bigger and crack length is smaller.

Number of cycles to crack initiation N_{in} and to elongation to defined length N_f were evaluated in dependence on applied stress level. Obtained results for different notch and different thickness of specimens from unidirectional material GLARE 2 are shown in *Fig. 3*.

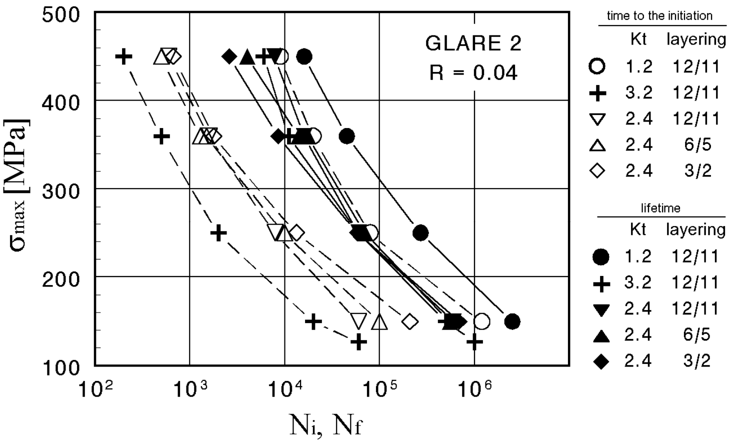

Fig. 3: Number of cycles to crack initiation and up to end of testing for specimens with different lay-up and different notches.

Measured data were then used for finite element method calculation of local plastic deformation in the notch root ε_{pl}. At calculations in 2D analysis by means of ABACUS software the elasto-plastic behaviour of metal layers and internal stresses in unidirectional laminate GLARE 2 were taken into account (Chlupová, 2001). A plastic deformation in metal layers was calculated according to experimentally measured monotonic hardening curve of aluminium alloy 2024-T2, the residual stresses caused by laminate preparation method were taken into account. Results of FEM calculations of plastic deformation for specimen with central circular notch are graphically represented in *Fig. 4*.

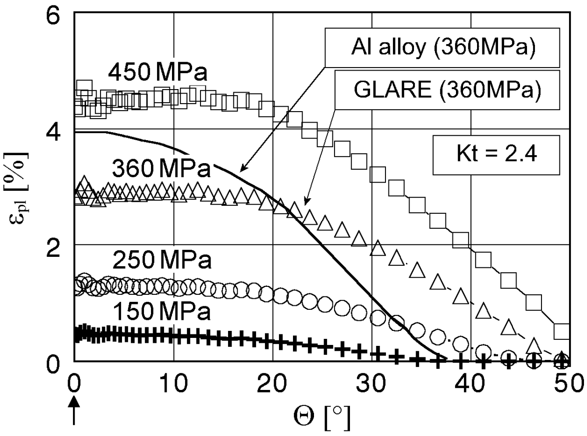

Fig. 4: Results of FEM calculations for specimen with central circular notch.

Calculated amplitude of local plastic deformation in aluminium layers in the notch root was then displayed in dependence of number of cycles to initiation (see *Fig. 5a*). As it is seen from the plot, all data points obtained for different stress concentration factors K_t lie on one curve.

$$\varepsilon_{a,pl,l} = 0{,}036 \cdot N_{in}^{-0{,}214} \tag{1}$$

Amplitude of local plastic deformation in notch root can be therefore considered to be the parameter determining number of cycles to fatigue crack initiation in notched specimens from the material GLARE, similarly like in the case of homogeneous materials (Polák 1991).

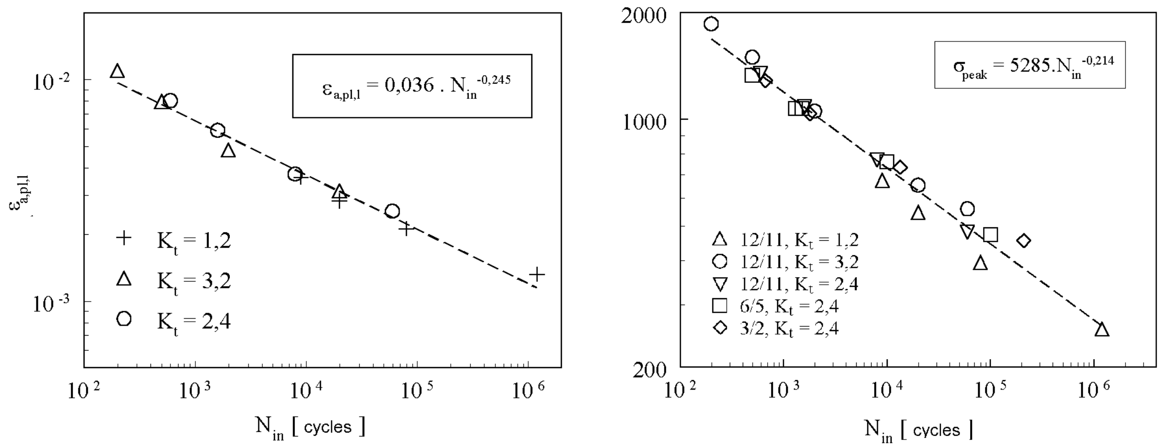

Fig. 5: Dependence of number of cycles to crack initiation (N_{in}) on a) amplitude of local plastic deformation in the notch root and b) local peak stress in aluminium layers the notch root of specimen.

Local plastic deformation in the notch root is induced by local stress σ_{peak}, which is given by maximum applied stress σ_{max}. The value of local stress can be calculated using stress concentration factor in metal layers $K_{t,Al}$ and internal residual stress in metal layers $\sigma_{r,Al}$ as follows:

$$\sigma_{peak} = \sigma_{max} K_{t,Al} + \sigma_{r,Al} \tag{2}$$

In the Fig. 5b there is the dependence of number of cycles to initiation on calculated local peak stress according to equation (2) for different thicknesses and different notch factors together with approximation of data by power function:

$$\sigma_{peak} = 5285 \cdot N_{in}^{-0{,}214} \tag{3}$$

Relationship between N_{in}, $K_{t,Al}$, $\sigma_{r,Al}$ and σ_{max} given by eq. (2) and (3) explains experimentally observed lower number of cycles to crack initiation in thicker laminates. In laminates with higher number of layers (12/11) due to curing cycle in autoclave the higher tensile residual stress in metal layers are present, i.e it results in higher level of local stress in the notch root σ_{peak} and consequently the lower number of cycles to crack initiation. This trend is more pronounced for lower levels of applied stress σ_{max}.

Delamination is one kind of damage in laminates which is related to crack initiation and growth (see *Fig. 6a*). Delamination for this type of material has nearly elliptical shape. The delamination size can be thus characterised by ratio b/l, where l is crack length and b is the height of delamination in the notch root. These two parameters are also axis of "half-ellipse" which can be used as a good approximation of delamination shape. The appearance of delaminated areas on the resin rich surface of prepreg after removing of metal layer with four cracks in specimen loaded at maximum applied stress 450 MPa are exhibited in *Fig. 6b*.

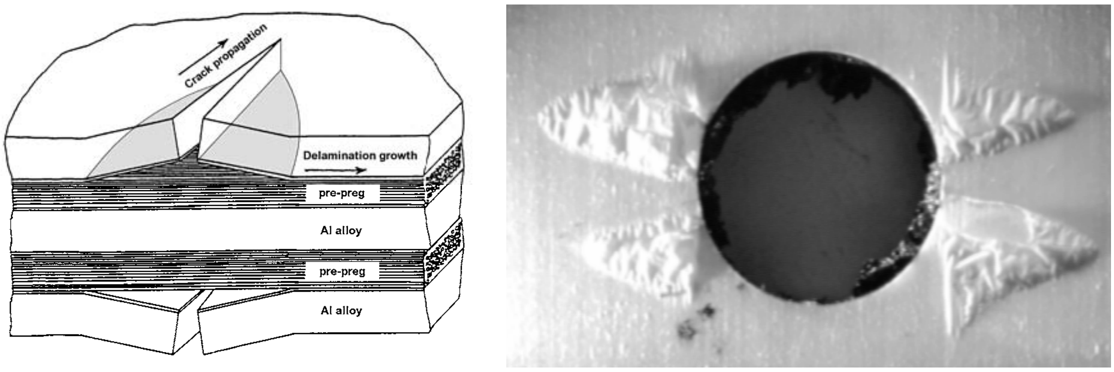

Fig. 6: a) Scheme of relationship between crack growth, delamination and fibres bridging the opening crack; b) real shape and range of delamination.

As soon as the crack in metal layer is initiated simultaneously the delamination appears as a result of shear stresses on layers interface. The size of delamination depends on many factors such as crack length, crack growth rate, fibres properties and fibres volume fraction but predominantly on quality of adhesion on interface. The presence of delamination of certain size is essential to create optimal conditions for outstanding fatigue resistance; nevertheless a judging of effect of adhesion quality is difficult due to its antagonistic influence on delamination. Strong adhesion results in small delamination. In the extreme: in the case of no delamination, the length of fibres actively acting on crack closure would be so small that crack wouldn't open and crack would stop. On the other hand at these conditions the loading of short part of fibres would be so enormous that it would cause the failure of fibres. The right function of fibres and their bridging effect wouldn't be thus possible. Weak adhesion results in big delamination and significant decrease of bearing capacity. In the extreme: it would cause debonding of laminate along the fibre-matrix interface. In that case the transfer of loading through shear stresses from metal to prepreg layers and vice versa wouldn't be possible.

4. Conclusions

Fatigue behaviour of fibre metal laminates containing as a reinforcing material glass fibres was studied. It was found that FMLs exhibit different mechanism of initiation and growth of fatigue cracks than homogeneous monolithic metallic materials. Cracks initiate first inside of laminate, exhibits shorter period of crack initiation and strongly elongated period of crack growth. Number of cracks initiated from the notch is higher and the place is transferred out of the root of notch.

The situation in inner and outer layers of laminate differs slightly – the initiation in inside layers is earlier, nevertheless the growth is slower than on surface. Prepreg acts as an effective barrier against crack growth from one layer to another. Cracks thus grow separately and independently. Crack growth was monitored in relation to growth direction and growth rate.

Relations for prediction of number of cycles to crack initiation and fatigue life of notched specimens from laminate were specified. The dependence of initiation on local plastic deformation and/or local stress in the notch root of metal layers was evaluated.

The delamination for both types of material (GLARE2 and GLARE 3) was found to be dependent on type of material, crack length and location in the metal-prepreg interface closer or farther from the specimen surface.

Delamination area is proportional to crack length, which induced it. Range of delamination is affected by level of shear stresses at metal-prepreg interface. It was found that the shape of delamination in material GLARE can be approximated by an ellipse. The higher is the level of maximum applied stress the higher range of delamination it evokes. The proper function of laminate, i.e. bridging effect of reinforcing fibres on growing crack, can be assured only by optimum strength of adhesion which causes suitable delamination area.

Acknowledgement

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