FATIGUE CRACK GROWTH IN GLARE, ROLE OF GLASS FIBERS

M. Papakyriacou *, S.E. Stanzl-Tschegg+, H. R. Mayer+ and J. Schijve++

Constant amplitude fatigue crack growth tests have been performed on two types of glass fiber reinforced Aluminium laminate material, GLARE 1 and GLARE 2. They were found to be superior not only to monolithic aluminum alloys, but also to ARALL (aramid fiber reinforced alloy). Fatigue crack propagation is smaller at identical stress amplitudes and decreases with increasing crack length. This is caused by more effective fiber crack bridging. The superiority of GLARE in comparison to ARALL is associated with significantly less fiber fracture, owing to the better mechanical properties of the glass fibers and the better bonding strength between glass fibers and resin. The crack growth rates in post-stretched GLARE 1 are lower than in GLARE 2. Post-stretching reduces the tensile part of loading in the metal layers during cyclic loading and thus the crack growth rates.

INTRODUCTION

Light and high strength fiber-metal laminates, which are in addition not fatigue sensitive to notches, have been developed for fatigue critical aerospace applications. ARALL (Aramid Fibers Reinforced Aluminium Laminates), for example shows 10 to 1000 times longer fatigue lives than the unreinforced aluminium alloy. It has been shown to be a promising material for crack stoppers (1, 2). However, under certain loading condition fiber failure in the wake of the crack does occur, especially if σ_{min} is low or compressive (3). Therefore it has been tried to develop a material with better fatigue properties in Delft by replacing Aramid fibers by glass fibers (3). The new material is called GLARE. The few investigations on GLARE show that it can give fatigue lives up to 5 times longer than ARALL and that fiber failure does not occur (3).

In the present paper the fatigue crack growth properties of two types of GLARE were tested and compared with results on ARALL (1). Especially the role of glass fibers for the fatigue crack growth properties was investigated and compared with the role of Aramid fibers.

* Institute for Solid State Physics, University of Vienna, Austria
+ Institute for Met. and Physics, University of Agriculture, Vienna, Austria
++ Faculty of Engineering, Delft University of Technology, Netherlands

MATERIAL

Fiber-metal laminates consist of thin high strength aluminium alloy sheets and resin layers containing high strength and unidirectional stiff fibers. GLARE is a modification of ARALL where the Aramid fibers are replaced by glass fibers.

TABLE 1 - Mechanical properties (L- direction) of fiber-metal laminates with glass-and aramid-fibers (3)

	GLARE 1	GLARE 2	ARALL 1	ARALL 2
Alloy	7075	2024	7075	2024
Fibers	glass	glass	Aramid	Aramid
Condition	stretched 0.5%	as cured	stretched 0.4%	as cured
R_m, MPa	1300	1230	800	717
$R_{p0.2}$, MPa	550	400	641	359
A_5, %	4.6	5.1	1.9	2.5
$E_{tensile}$, GPa	64.7	65.6	67.6	64.1

EXPERIMENTAL PROCEDURE

The materials tested in this paper are GLARE 1 and GLARE 2 in the 3/2 lay up, i.e. three Al-alloy sheets (thickness 0.3mm) and two intermediate fiber layers (thickness 0.2mm). The nominal thickness of the fiber-metal laminates was 1.3 mm. Specimens (width 12mm, length 118mm) were tested with an ultrasound resonance device, working at a frequency of 21 kHz. The specimens are stressed longitudinally (in the fiber direction) with a zero mean stress (R = -1). The specimens were provided with an edge notch (depth 2mm) to initiate fatigue cracks.

The experiments were performed at constant stress amplitudes (CA). Crack propagation was recorded by an optical microscope (magnification 140x) on the outer alloy layer up to a crack length of 5mm (without notch depth). Crack growth rates were measured down to $2x10^{-13}$ m/cycle. For details of the testing procedures see (1). Additional studies on damage of the resin- and fiber layers were performed with light and scanning electron microscopy (SEM).

RESULTS AND DISCUSSION

GLARE 1 and GLARE 2:

Figs. 1 and 2 show that the crack growth rates in GLARE 1 and GLARE 2 decrease with growing crack length for CA loading contrary to LEFM´s laws. For low amplitudes, crack growth even stops at a defined crack length. Unbroken stiff fibers bridge the crack in the metal sheet and reduce the effective stress intensity factor. The bridging capability increases with decreasing stress amplitude and with growing crack length (number of unbroken fibers increases with growing crack length in metal layer) (1).

The crack growth rates in GLARE 1 are lower than in GLARE 2 for similar stress amplitudes and crack lengths and are reduced more in GLARE 1. Crack growth retardation in GLARE 2 occurs at stress amplitudes up to 90 MPa, but crack growth arrest requires an amplitude of 30 MPa or lower for the tested crack length regime. For GLARE 1 the retardation was observed at all amplitudes up to 130 MPa while crack growth arrest did still occur at 80 MPa.

Figs. 3 and 4 show the zone of delaminated fibers in the cracked resin layer of GLARE 1 and GLARE 2 after fatigue loading at a stress amplitude of 90 MPa. One metal layer was removed for these visual observations. The crack length (without notch depth) is 5 mm in the metal layers of both materials. Delamination is visible along the whole crack length. The damaged zone is larger in GLARE 2.

Careful evaluation in SEM shows that fiber fracture is negligible (0.3mm) in both GLARE 1 and GLARE 2 specimens, which were tested at a stress amplitude of 90 MPa. The bridging zone (unbroken fibers in the wake of crack in metal layers) is 4.7 mm in both specimens. Therefore fiber fracture cannot be held responsible for the superiority of GLARE 1.

The superior crack growth results of GLARE 1 should primarily be associated with the 0.5% post-stretching operation after the curing cycle. As a result, a residual stress system is introduced with the fibers in tension and the Al - alloy sheets in compression (3,4). It then requires a higher tensile load on the specimen to open the crack, the effective stress intensity factor will be smaller, and the crack growth rate will be reduced. Secondly, due to the reduced crack tip opening, the cyclic stress on the crack bridging fibers will be smaller, the cyclic delamination will also be smaller, as shown in Figs. 3 and 4, and as a result, the bridging capability of the fibers will be higher.

GLARE and ARALL:

In Fig. 5, the crack growth rates of CA tests are compared for GLARE and ARALL (1). The crack growth properties of GLARE 1 are obviously better than those of ARALL 1 and GLARE 2 is better than ARALL 2. The initial crack growth behaviour up to about 1.5 mm crack length appears to be similar for GLARE 1 and ARALL 1, as well as for GLARE 2 and ARALL 2. With growing crack length however, the superiority of GLARE becomes obvious.

Comparison of the delamination zone in GLARE 1 (Fig. 3) and in ARALL 1 (1) shows that delamination is more pronounced in ARALL 1 although the stress amplitude was identical. This result indicates that the delamination resistance in GLARE was larger than in ARALL. The slightly higher degree of post-stretching in GLARE (0.5%) in comparison with ARALL (0.4%) might also have contributed to less delamination.

Contrary to ARALL, fiber cracking is less pronounced in GLARE (1); i. e. the bridging zone with unbroken fibers behind the crack tip in the metal layer is larger in GLARE than in ARALL, even at low stress amplitudes. The glass fibers have a better fatigue resistance, especially under cyclic buckling in compression, which can happen if fiber pull out occurs in the cracked resin matrix. Cyclic buckling will damage aramid fibers, which will reduce the tensile strength and induce fiber failure in ARALL (3). In addition, less fiber pullout due to the superior bonding properties of the glass fibers and the resin intensifies the reduction of fiber buckling.

CONCLUSIONS

1. The fatigue crack growth properties of GLARE 1 at constant stress amplitudes are better than those of GLARE 2. This superiority is mainly achieved by post-stretching during the production procedure of GLARE 1, which results in residual compressive stress in the Al-alloy sheets and in smaller crack opening displacements during fatigue loading. It also leads to smaller cyclic shear stresses in the fiber-resin layer and thus to less delamination.

2. Delamination in GLARE is smaller than in ARALL which indicates superior bonding properties between glass fibers and resin than between aramid fibers and resin.

3. In GLARE fiber fracture occurs on a more limited scale, which is not true for ARALL. Higher fatigue resistance of the glass fibers under compression and less fiber pullout due to the stronger bonding between glass fibers and resin limit fiber-buckling and fiber-fracture.

4. GLARE shows better fatigue crack growth properties in constant amplitude tests than ARALL. This probably results from the higher bridging capability of the fibers due to less fiber fracture. Both fiber-metal laminates are highly superior to the traditional aircraft aluminium alloys.

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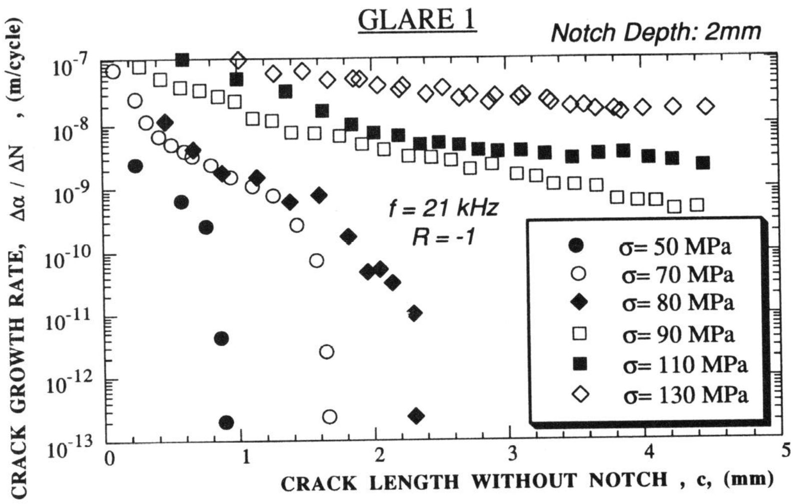

Figure 1 CA Tests: Fatigue crack growth rates as a function of crack length in GLARE 1 at constant stress amplitudes.

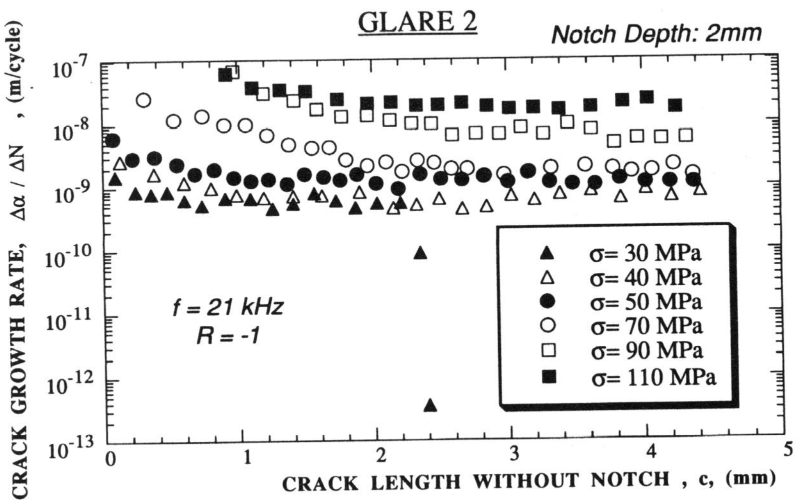

Figure 2 CA Tests: Fatigue crack growth rates as a function of crack length in GLARE 2 at constant stress amplitudes.

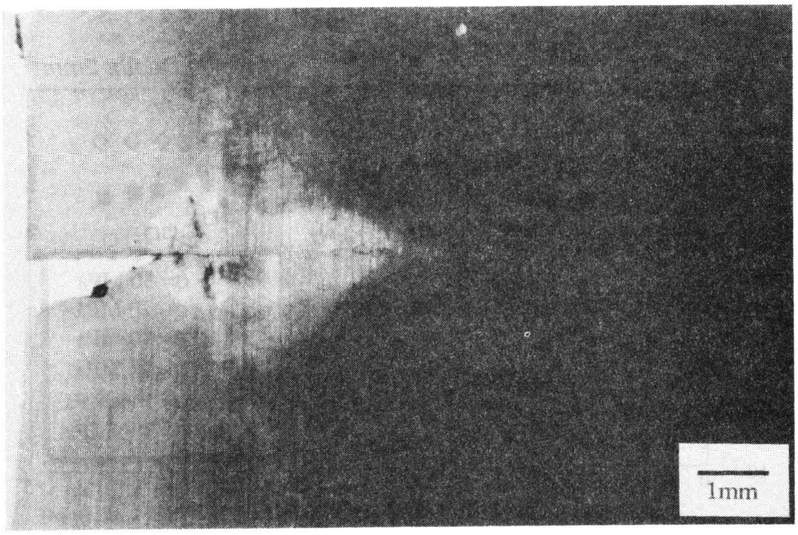

Figure 3 Delamination of the fibers in the cracked resin of a GLARE 1. Specimen loaded at 90 MPa.

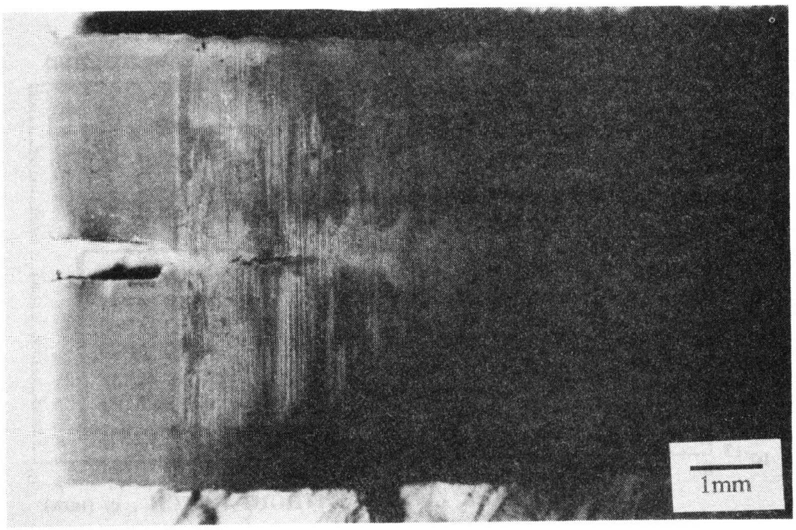

Figure 4 Delamination of the fibers in the cracked resin of a GLARE 2. Specimen loaded at 90 MPa.

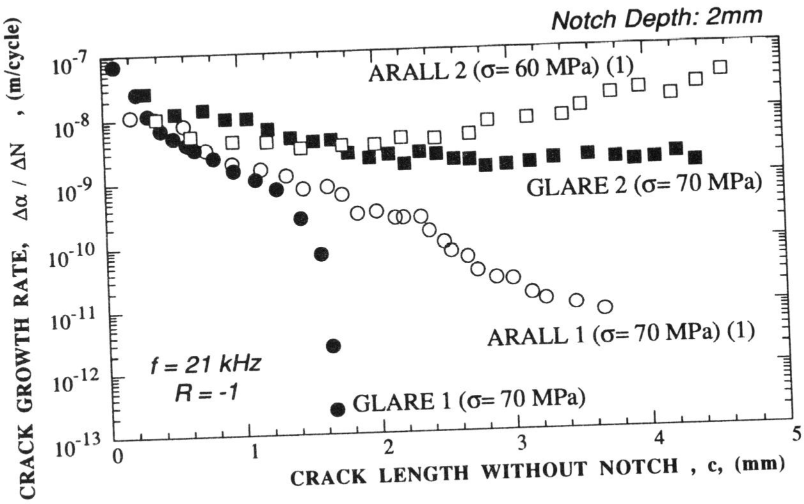

Figure 5 CA Tests: Fatigue crack growth rates as a function of crack length in GLARE 1, GLARE 2, ARALL 1 (1) and ARALL 2 (1).