Thermal Fatigue of Locally Fiber Reinforced Magnesium with Graded Structure

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SUMMARY: Magnesium with local reinforcement of carbon long fibers is extremely attractive for weight saving in structural applications. However, due to the dissimilar material properties between the reinforced and the unreinforced region, temperature changes induce high internal stresses during fabrication and service.

Locally reinforced ring specimens with graded and ungraded composition were produced and subsequently thermally cycled. Besides the measurement of the crack density a shear test was used to document the damage accumulation as a function of the number of temperature cycles. The experiments were supplemented by FE calculations of the thermal stresses.

It is shown that with partially reinforced *ungraded* rings thermal cycling results very early in severe macroscopic damage near the interface between reinforced and unreinforced areas. The cracks are initiated by radial stresses during heating. A *graded* composition offers the capability to improve the thermal fatigue behaviour significantly as the material strength in the critical regions near the interface is improved and the stresses are somewhat lowered.

KEYWORDS: graded structure, local reinforcement, carbon magnesium composite, thermal cycling, shear testing, interfacial cracks, interfacial strength, thermal stresses.

INTRODUCTION

Advanced metal matrix composites (MMCs), like carbon long fiber reinforced magnesium, are presently being considered for a range of weight saving structural applications. The outstanding strength at elevated temperatures as well as after long thermal exposure make C/Mg-composites extremely attractive for internal combustion engine and drive train components [1, 2]. Nevertheless, the widespread industrial use of long fiber reinforced MMCs is still severely restricted by high fiber prices. This problem could be partially solved by applying a load-adapted local reinforcement [3-5]. The dissimilar properties of reinforced and unreinforced material, however, create high internal stresses during processing and service which may lead to premature failure near the interface [6]. A graded fiber content is expected to overcome this difficulty because of an improvement in material properties or a reduction of thermal stresses or stress concentrations [7].

EXPERIMENTAL

Composite Manufacturing

As composite system magnesium alloys unidirectionally reinforced with high strength carbon long fibers (T300J) were used. Earlier investigations showed that the Al content considerably influences the fiber/matrix reaction and thereby the mechanical behaviour of the composite [2, 8]. In order to study the effect of the Al-content on the thermal fatigue behaviour the matrix alloys listed in Table 1 were investigated.

Table 1: Composition of the Mg-alloys investigated [9].

Magnesium alloy	Al content [wt.-%]	Remaining composition
cp-Mg	0	99,9 % Mg
AM20	1,7-2,2	0,1 % Zn, 0,5 % Mn, balance Mg

The fiber preforms were fabricated by filament winding on a cylindrical drum with a diameter of 30 mm. The fibers were oriented in circumferential direction with a misalignment of ≤ 0,9 °. In order to vary the local fiber content and to produce graded structures a special particle impregnation technique has been developed [10]. This process allows to introduce ceramic particles into the fiber bundle thereby acting as spacers. By changing the winding speed the fiber volume fraction can be varied in a range from 25 to 60 Vol.-% (Fig. 1). For comparison of the thermal fatigue behaviour, preforms with graded and ungraded composition but the same overall fiber content were fabricated.

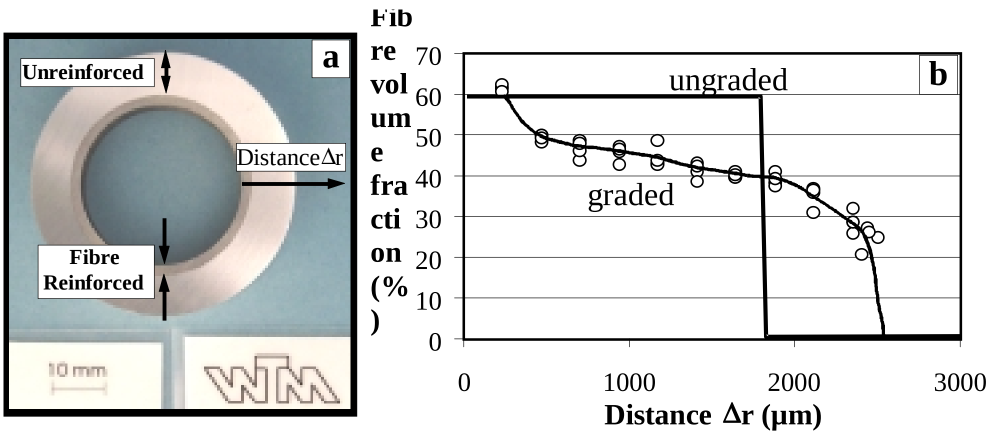


Fig. 1: Ring like specimens were prepared with local reinforcement by infiltration casting (a). Using a special particulate spacer technique, a sharp or smooth transition of fiber content was realised (b).

Locally reinforced composite tubes with a total wall-thickness of 10 mm were manufactured by an infiltration casting technique (720°C, 15 MPa)[11] and subsequently cut into ring shaped specimens with a height of 10 mm.

Characterisation

Thermal cycling

The specimens were thermally cycled several times between 25° and 300° C. The upper temperature, which is obviously too high for magnesium matrix composite applications, was chosen to be able to study the damage caused in a reasonable time period. Forced air heating and cooling was realised using a simple set up built in house. With a pneumatic arm the specimens were transfered into the circulating air oven, withdrawn again and transported to the electric fan cooler after a preset time. In order to guarantee a thoroughly homogenous temperature the holding period for both the heating and cooling was ascertained to be 5 minutes.

Microstructure

In order to study the fiber/matrix interface morphology in dependence on the matrix alloy and the fiber volume content, composite specimens are etched with a 2 % alcoholic HNO_3 and afterwards analysed by SEM micrographs. Moreover, cross sectional micrographs are made to determine the fiber volume fraction via digital image analysis.

Crack density

The observed damage is quantified by measuring the crack density by SEM micrographs. In each case two equivalent circle segments are arbitrarily marked on the polished specimens and the crack length measured inbetween as a function of the number of the cycles. The crack density is defined as total crack length relative to the segment surface area investigated.

Interfacial shear strength

For measuring the interfacial strength in dependence on the thermal cycles the ring specimens are cut into uniform segments with a secante length of 6 mm and a thickness and height of 10 mm, respectively. The interfacial strength test involved shearing the specimens along the reinforced/unreinforced interface in direction of the fibers by applying a compression load to the ends of the beam. The load was applied with an 100 kN Instron 4505 machine and a crosshead speed of 0,5 mm/s. The device was originally developed for measuring the shear strength of curved thermoplastic composite samples [12] and is shown in its modified form in Fig. 2.

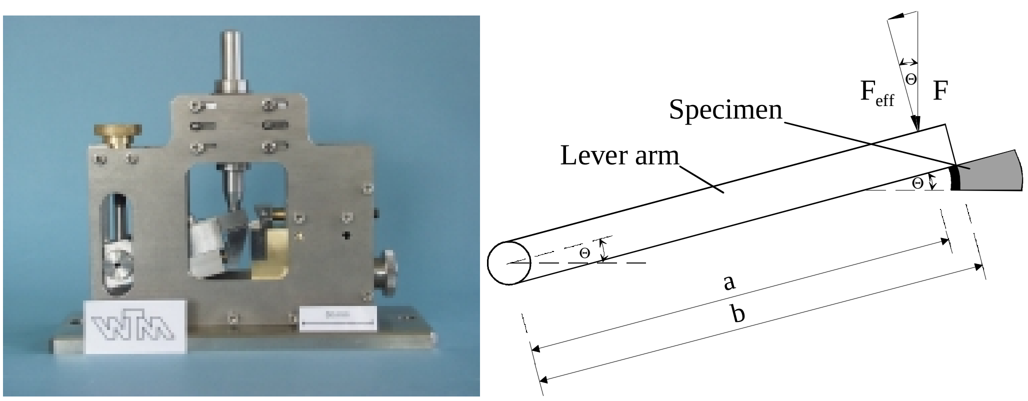


Fig. 2: Interfacial strength testing device with specimen inserted (left) and the geometric dimensions for the calculation of the force acting on the specimens by leverage (right).

As the load is neither applied perpendicularly nor directly from above the specimen the lever transmission has to be taken into account. The effective applied force F_{eff} is calculated as follows:

$$F_{eff} = \frac{a}{b} \cdot F \cdot \cos\Theta \qquad (1)$$

where F is the applied force and a, b and Θ are explained in Fig. 2.

The interfacial shear strength τ is then calculated by referring the actual load at failure F_{eff} to the fracture area A:

$$\tau = \frac{F_{eff}}{A} \tag{2}$$

For each parameter combination at least 15 specimens were tested.

Transverse tensile strength

The transverse tensile strength was measured according to ASTM D3552-77 with flat specimens of the dimensions 57x12,7x2 mm³.

FE calculations

To examine the stress distributions in the specimens in dependence on the fiber composition FE calculations were carried out. The commercial FE software SYSWELD was applied for this analysis.

RESULTS AND DISCUSSION

Influence of a graded structure on the material strength

With cp-Mg composites no reaction products at the fiber surface are recognizable in the SEM analysis. In contrast, the microstructure of the aluminium containing matrix alloy AM20 shows characteristic flat hexagonal plate-like reaction products at the carbon fiber/matrix interface which were identified as mainly Al_2MgC_2 and with high aluminium contents also as Al_4C_3 [8, 13]. The carbides are probably formed from the melt when aluminium in the matrix alloy comes into contact with the fiber surface. The reaction stops when the matrix is sufficiently depleted from aluminium. A *gradation* modifies the carbide formation. Besides the aluminium content of the matrix material the extent of the carbide formation is strongly dependent on the fiber volume fraction. The micrographs of a graded AM20/T300J composite in Fig. 3 demonstrate that a lower fiber content results in a more pronounced growth of reaction products. The reason for the stronger carbide formation is the larger matrix volume per fiber surface area, i.e. there is more aluminium available for each fiber before depletion occurs. The carbide formation leads to an increase of the fiber/matrix adhesion. Consequently, the transverse tensile strength $\sigma_{90°}$ and the shear strength τ is greater in regions of low fiber contents.

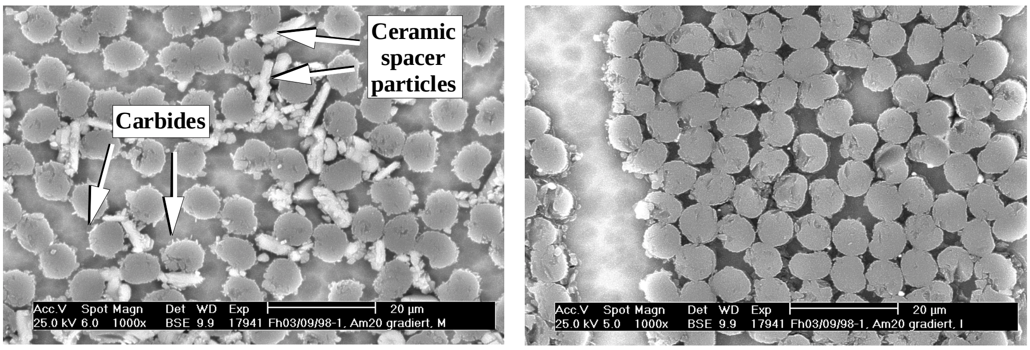


Fig. 3: Influence of the fiber volume fraction on the interface reaction in a graded AM20/T300J-composite. With lower fiber contents of about 40 vol.-% (left) a stronger formation of carbides at the fiber/matrix interface is obtained compared to higher fiber fractions of 60 vol.-% (right).

Besides the carbide formation, low fiber volume fractions contribute to the transverse tensile strength $\sigma_{90°}$ in another way. Considering the fibers as cylindrical holes in a square array, the load-bearing matrix cross sectional area is reduced in dependence on the fiber volume fraction V_f and the matrix strength σ_M (here $\sigma_{M,\,AM20}$=120 MPa), according to Eqn. 3 [14]:

$$\sigma_{90°} = \sigma_M \cdot \left(1 - \sqrt{\frac{4 \cdot V_f}{\pi}}\right) \tag{3}$$

Fig. 4 shows experimental data for the transverse tensile strength $\sigma_{90°}$ as a function of the fiber volume fraction , as well as the strength $\sigma_{90°}$ predicted by Eqn. 3.

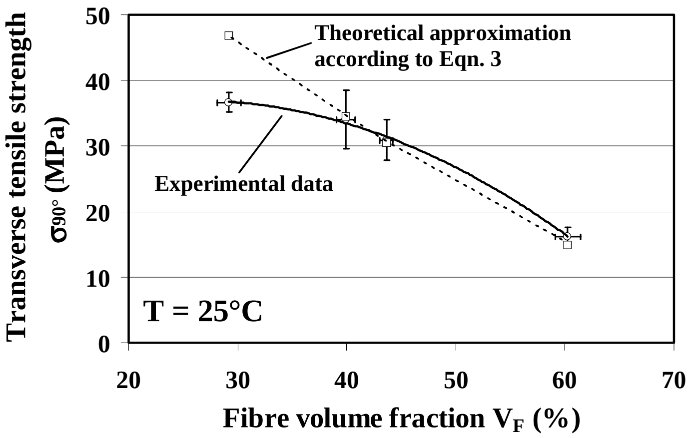


Fig. 4: Influence of the fiber volume fraction on the transverse tensile strength at room temperature of AM20/T300J. The experiments fit approximately the theoretical predictions according to Eqn. 3.

The experiments and the theoretical approximation fit relatively well. With low fiber contents the calculation differs somewhat from the experimental data, probably since the increasing ceramic spacer particles have an effect that is not taken into consideration in Eqn. 3. The increase of strength because of a more pronounced fiber surface reaction is not apparent in Fig. 4 but has been clearly established in other research work [2].

Regarding the carbide formation the location in the fiber preform is of importance as well (see Fig. 5). Fibers which are situated directly at the reinforced/unreinforced interface can be supplied with additional aluminium from the unreinforced part. Therefore the fiber/matrix reaction in the first fiber layers is always more pronounced than further inside the fiber preform whether graded or not, which is illustrated by comparing Fig 3 and Fig 5.

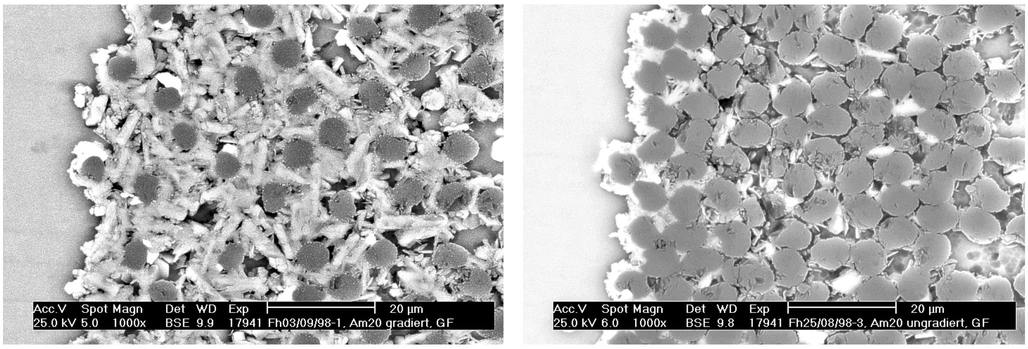
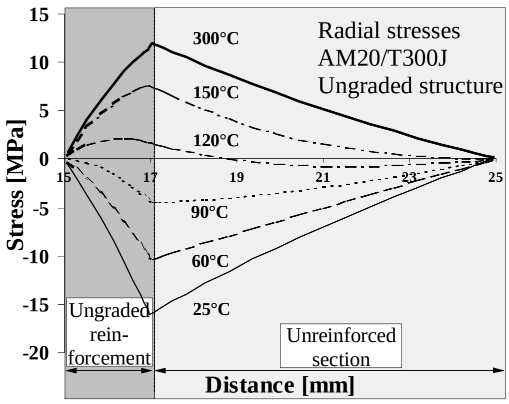


Fig. 5: The interfacial reaction between the fibers and the matrix is dependent on the location in the preform. Either graded (left) or ungraded (right) the interfacial reaction at the reinforcement/unreinforced interface is always more pronounced due to additional aluminum supply from the unreinforced parts of the specimen.

Influence of a graded structure on the thermal stresses

In the following the results of a finite element analysis of the problem will be presented. The emphasis is put on the radial stresses acting normal to the interface between the fiber reinforced inner section and the unreinforced outer section. As will be shown below, these are the most important stresses for crack formation in the present example as cracks form parallel to the interface between reinforced and unreinforced regions.

As a consequence of the dissimilar properties of reinforced and unreinforced material, thermal stresses during thermal cycling are created (see Fig. 6). During the cooling period after the infiltration, the unreinforced material shrinks more than the reinforced section because of the significantly higher thermal expansion coefficient. However, the shrinkage is constrained by the reinforced insert. Therefore, whether graded or not, in the as cast condition at room temperature both the reinforced insert as well as the unreinforced section exhibit a compressive stress state in radial direction.



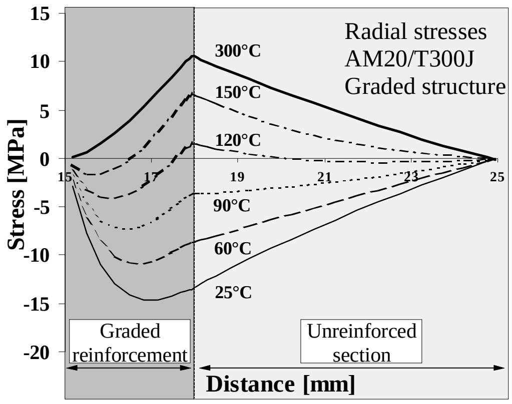


Fig. 6: Change of the radial stresses during thermal cycling obtained by finite element calculation for locally reinforced ungraded (left) and graded (right) AM20/T300J material.

When raising the temperature the unreinforced section tries to expand more than the reinforced insert. Consequently, there is a change of the radial stresses from the compressive stress state in the as cast condition to tensile stresses. The maximum radial tensile stresses are reached at the interface between the reinforced insert and the surrounding unreinforced section. It can be seen from Fig. 6 that the graded fiber content has only a minor effect on the radial stresses near the interface.

Both the tangential and the longitudinal stresses, which are not shown here, have a discontinuous step directly at the interface from the unreinforced part to the composite insert. A gradation is able to modify the stresses in the reinforced region as the discontinuous step at the interface is somewhat reduced. Certainly these stresses contribute to the crack propagation normal to the radial forces as the induced shear stresses at the crack tips are approximately proportional to the stress step. In spite of this we consider the radial stresses are most important in the present case for crack initiation and here is only little effect of gradation.

Influence of a graded structure on the thermal fatigue behaviour

Ungraded fiber distribution

The rings show tangential crack nucleation and growth along the reinforced/unreinforced interface in accordance with the radial forces described above (Fig. 7). With the ungraded fiber distribution cracking occurs already during the first few temperature cycles. A difference can be noted in the cracking behaviour of aluminium and non alumninium containing matrix alloys (Fig. 7). With the Al containing alloys the cracks start not directly at the interface but they are slightly displaced towards the interior of the reinforced region. This reflects the increased transverse strength $\sigma_{90°}$ due to particularly high aluminium concentrations close to the reinforced/unreinforced interface (Fig. 5 above).

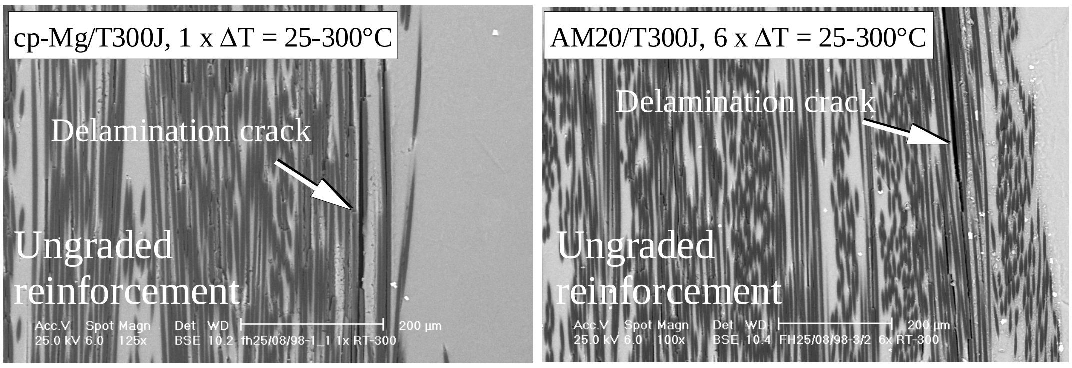


Fig. 7: Thermal fatigue crack growth in locally reinforced ungraded AM20/T300J composite (left) and cp-Mg/T300J composite (right) respectively.

Continued thermal cycling results in a gradual increase of the crack density, see Fig. 8. Once cracks are generated, they quickly propagate along the interface because of the radial tensile stresses during heating. In consequence, the interfacial strength of the ungraded cp-Mg composite approaches zero after 25 cycles and that of the ungraded AM20 composite after 150, respectively (see Fig. 9). The damage accumulation per cycle decreases as cycling continues. This is because the higher crack density leads to a lower stiffness of the sample and therefore lower stresses.

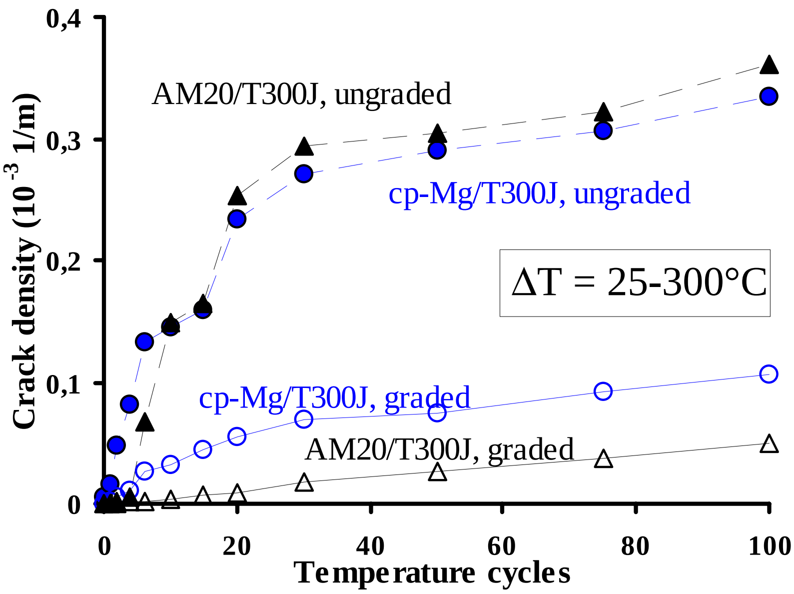


Fig 8: Interfacial crack density (crack length per surface area) as a function of the number of temperature cycles for locally reinforced ungraded and graded cp-Mg/T300J and AM20/T300J composites. The graded composite structure inhibits the crack growth successfully.

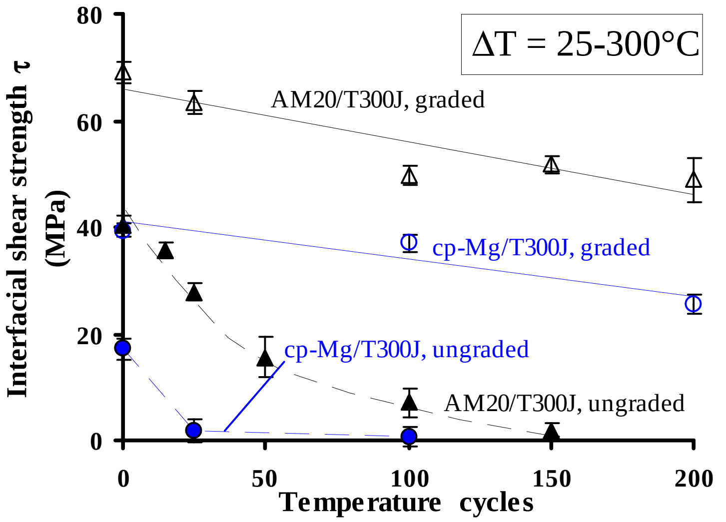


Fig 9: Shear strength of the interface reinforced/unreinforced area as a function of the number of temperature cycles for locally reinforced ungraded and graded cp-Mg/T300J and AM20/T300J composites. With graded composites damage accumulation occurs more slowly.

Graded fiber distribution

With a graded fiber reinforcement, cracking occurs in principal in the same way as without grading, i.e. by delamination along the reinforced/unreinforced interface caused by radial stresses (Fig. 10). In contrast to the ungraded material, however, cracks are always formed exactly at the interface, irrespective of the aluminium content of the matrix. The slight displacement shown in Fig. 7 is not observed. This can be explained by the higher transverse strength of the graded material, which can be expected based on the reduced fiber content (see Fig. 4).

Fig. 10: Thermal fatigue crack growth in locally reinforced graded cp-Mg/T300J composite (left) and AM20/T300J composite (right) respectively after 100 cycles.

Grading of the fiber distribution leads to an increase of the interfacial shear strength (Fig. 9). This is another reflection of the beneficial effect of a reduced fiber volume fraction (Fig. 4).

Most importantly, grading of the fiber distribution retards significantly the damage accumulation in the sample during thermal cycling, see Fig. 8 and Fig. 9. This is attributed to the improvement of strength and the decrease of crack propagating stresses by grading. Fig. 11 tries to rationalize the beneficial effect of grading. Unfortunately we do not know the relevant fatigue strength at temperature for our material. Based on the static room temperature strength, however, we can assume the graded material to exhibit considerably higher strength. In addition the FE calculation indicates somewhat lower stresses for the graded material, although the stress effect for the radial direction seems to be relatively small.

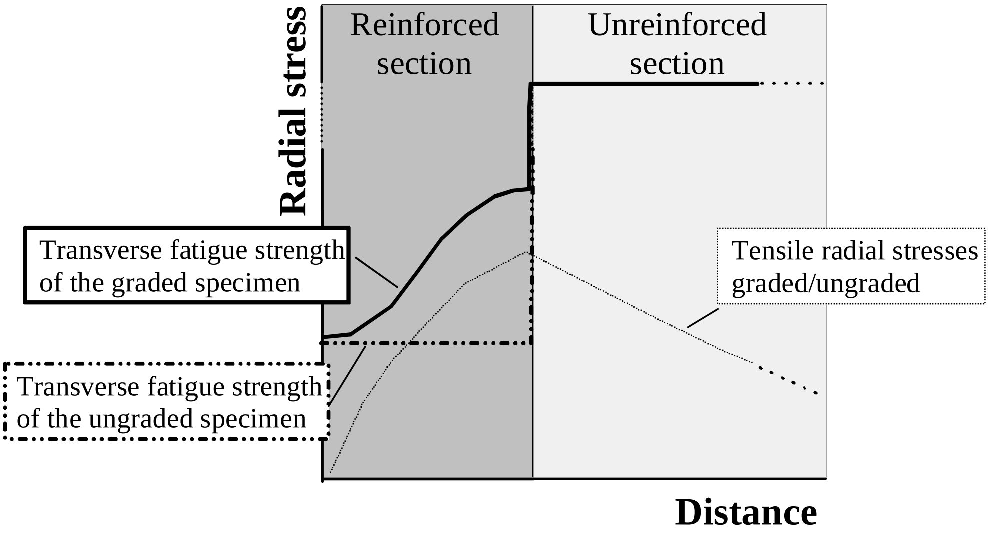


Fig. 11: The schematic diagram illustrates the cracking process in the ring specimens. The tensile forces created during thermal cycling are high enough to fracture the ungraded but not the graded specimen due to their improved strength. The radial stresses are almost the same in the graded and ungraded samples.

Fig. 9 points towards a much slower damage accumulation in the graded cp-Mg/T300J than in the ungraded AM20/T300J, although both materials seem to have the same interfacial strength. This can be explained in two ways. Either the effect of grading on stress is really more important than the one on strength or the ratio of static and dynamic strength is different in the two materials, i.e. the graded material has the higher dynamic strength even if the static strength is the same.

CONCLUSIONS

- With locally reinforced ungraded ring specimens (cp-Mg/T300J and AM20/T300J) thermal cycling results very early in severe macroscopic damage near the interface between the reinforced and unreinforced area. The interfacial strength of the composites is considerably decreased with the number of thermal loadings reflecting the gradual accumulation of damage in the sample.

- A grading of the fiber volume fraction offers the capability to improve the thermal fatigue behaviour significantly. Mainly due to increased strength but also to lower stresses, the graded composition shows a much improved life.

- The beneficial effect of grading on the interfacial bond strength is mainly due to the larger matrix material cross section.

- The cracks are initiated by radial tensile stresses during heating. With the maximum cycle temperature of 300°C chosen in this investigation the radial stresses are lowered but not very significantly.

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