FATIGUE BEHAVIOUR OF UNIDIRECTIONALLY CONTINUOUS ALTEX-FIBRE REINFORCED ALUMINIUM-BASED COMPOSITES

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SUMMARY: High quality hpAl/Altex and AlMg1/Altex MMCs were successfully produced by squeeze casting. The fatigue limit at R 0.1 is found to be 380 MPa, regardless of test temperature up to 250°C. Despite characteristic interfacial features and different mechanical properties, at R 0.1 no influence of the matrix chemistry on fatigue performance is noticed. At R -1 AlMg1/Altex shows a particular failure mode which is described as local fibre breakage in tension, followed by fibre crushing/kinking, matrix shear deformation and subsequent macro-buckling in compression; the fatigue limit is reduced by 50% compared to R 0.1. Surface damage from inadequate machining sensibly reduces the fatigue performance and leads to an increased scattering of the results. Monitoring of strain evolution during fatigue life proves to be an effective method to monitor damage development which may not be per-ceptible by the observation of the Young's modulus evolution on apparently intact specimens.

KEYWORDS: MMC, Al/Altex, fatigue, damage development, Squeeze Casting, continuous ceramic fibres, unidirectional reinforcement, machining

INTRODUCTION

Unidirectionally (UD) continuous ceramic fibre reinforced Al based composites are candidate materials to substitute steel and titanium in structural applications where performance is defined in terms of highest specific stiffness and strength. Moreover, in addition to their attractive static properties, good dynamic performance and elevated temperature capabilities are required for many engineering applications, particularly where rapidly oscillating or rotating masses are of major concern.

Provided that the compatibility problems with the matrix alloy composition are understood and the processing is well controlled, the Altex alumina fibre (Sumitomo) has proved to be effective as a reinforcement for Al. In a previous investigation [1] the influence of 1% Mg addition on the static mechanical properties and failure behaviour of a hpAl/Altex composite was investigated. It was shown, that on the one hand the addition of 1 wt-% Mg increases the transverse tensile strength by 100% up to 190 MPa, but that on the other hand the tensile properties in the axial fibre direction are degraded from 910 MPa down to 730 MPa, and even lower if the composite was exposed to temperatures of 550°C prior to testing, due to an interfacial reaction. Nonetheless, AlMg1/Altex features an attractive combination of axial and transverse tensile properties. The aim of this work is to investigate the fatigue properties and fatigue damage mechanisms of AlMg1/Altex in comparison with hpAl/Altex.

EXPERIMENTAL SET-UP

Materials & Fabrication of Samples

Due to its attractive mechanical properties (cf. Table 1), good compatibility with aluminium and affordable price (400 US-$/kg) the Altex fibre from Sumitomo was selected as a reinforcement for Al-based metal matrix composites (MMCs). The fibre features a diameter of 15 μm and consists of 85% γ-Al_2O_3 and 15% SiO_2 (all indications in weight-% unless stated otherwise). Unsized fibres of the type SN-11-1K were chosen for this work. High purity (hp) Al (99.99) and Mg were used for the hpAl and hpAl-1% Mg (AlMg1) metal matrices.
The fibres were processed into unidirectional preforms of the dimensions 90x85x8 mm^3 by filament winding, preheated to 750°C under N_2 atmosphere and infiltrated with the matrix-melt superheated to 800°C by direct squeeze casting under a constant ram speed of 5 mm/s. After infiltration, the control mode was changed to pressure control and a maximum pressure of 130 MPa was maintained for 1 minute.

Test Specimens & Investigation Methods

The test specimens were machined in the axial fibre direction from the obtained MMC plates by cutting and turning, using diamond tools. Special attention was paid to the turning parameters in order to minimise the damage induced on the specimens' surface, as will be discussed later. Cylindrical hour-glass specimens with smooth grip sections, as shown in Fig. 1, were used for the fatigue tests. Specimens with a parallel gauge length of 15 mm, were used for stress/strain measurements as well as for machining tests. The test specimens were gripped along the smooth surface in split collars, as illustrated in Fig. 2. To avoid back sliding at reversed tensile/compression loading, the specimens were backed at both ends in the grips.
The fatigue tests were performed at 30-50 Hz on a horizontal 50 kN MTS servo-hydraulic pulsator under load control. To monitor the damage development during fatigue life by analysis of the evolution of stiffness and absolute strain, specific stress/strain measurements were performed at 5-50 Hz with a clip gage (type DSA from Schenck) fixed on specimens with a 15 mm parallel gauge length, as illustrated in Fig. 2.
Tensile tests were performed in axial and transverse directions on a 20 kN UTS machine.

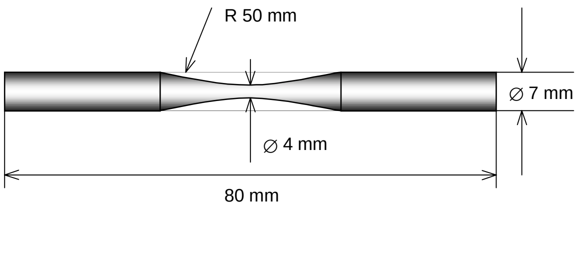

Fig. 1: Schematic of the fatigue test specimen. (cylindrical hour-glass specimen)

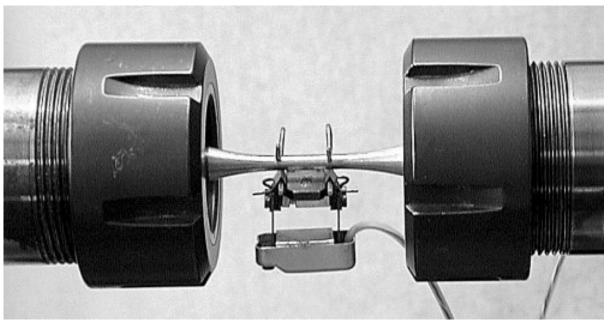

Fig. 2: Test set-up for the stress/strain measurements during cyclic axial loading.

To assess the fatigue performance of the composites under different test conditions according to potential engineering applications, AlMg1/Altex fatigue test specimens were subjected to pure axial tension loading (stress ratio $\sigma_{min}/\sigma_{max}$ R 0.1) and to fully reversed axial tensile/compression loading (stress ratio $\sigma_{min}/\sigma_{max}$ R -1). To evaluate the temperature sensitiveness, AlMg1/Altex was tested under R 0.1 at 25°C and 250°C.
Fatigue damage development was also investigated by optical and scanning electron (SEM) microscopy, as well as by in-situ cyclic loading tests in the SEM.

RESULTS AND DISCUSSION

Microstructure

The fibre distribution is found to be macroscopically quite uniform, as illustrated in Fig. 3. Despite the short melt/fibre contacting times achieved in the direct squeeze casting process (less than 15 s), an interrupted reaction layer of Mg_2Si and MgO is observed at the fibre/matrix interface of the AlMg1/Altex composites (Fig. 4), whereas the hpAl/Altex composites are free of any interfacial reaction products [1]. Due to the high process pressure, the specimens are well infiltrated and free of macroscopic porosity.

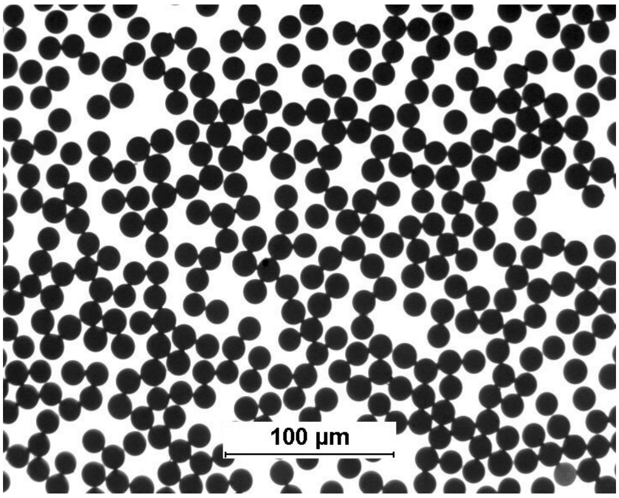

Fig. 3: Typical microstructure of Altex-reinforced Al-based MMCs showing a macroscopically uniform fibre distribution.

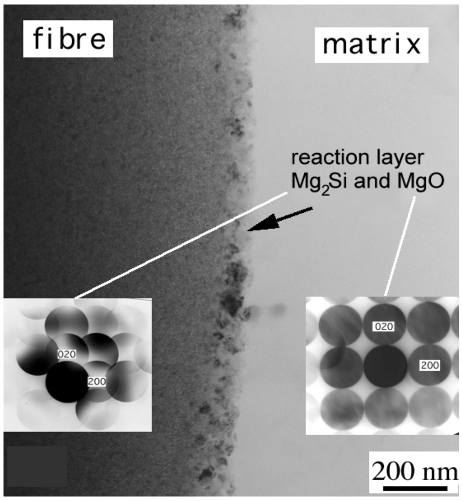

Fig. 4: Interfacial reaction layer in AlMg1/Altex MMCs. (note that hpAl/Altex is free of reaction)

Tensile Properties

The composites' tensile properties are given in Table 1. Note the increase of the transverse strength due to the addition of 1% Mg, indicating a strong interfacial binding strength.

Table1: Tensile properties of AlMg1/Altex and hpAl/Altex composites and of the Altex fibre

Material	v_f, [%]	UTS //, [MPa]	UTS ⊥, [MPa]	E-Modulus, [GPa]	δ, [%]
AlMg1/Altex	50-55	777	189	120	0.75
hpAl/Altex	50-55	891	94	125	0.86
Altex fibre		1800		210	0.85

Fatigue Properties

Fig. 5 shows the fatigue properties of AlMg1/Altex tested at 25°C (R 0.1 & -1) and 250°C (R 0.1) which are compared to those of hpAl/Altex and the PM high temperature AlFe8Ce4 alloy X8019. The results indicate that: i) at R 0.1 and R -1 the fatigue limit is about 380 MPa and 180 MPa, respectively, ii) at R 0.1 and at 25°C the fatigue performance of hpAl/Altex and AlMg1/Altex is comparable, iii) at R 0.1 the fatigue performance of AlMg1/Altex is insensitive to temperatures up to 250°C and iv) at R 0.1 and 250°C the AlMg1/Altex is superior to X8019 by 100% in terms of fatigue stress limit.

The fatigue values of AlMg1/Altex at R -1 (25°C) are confirmed by results reported in [2] where similar materials (AlZnMg/Altex) produced by pressure assisted investment casting were tested under comparable conditions. However, at R 0.1 the performance of the material of the present investigation clearly exceeds the values reported in [2] (+300%). The poor results obtained at R 0.1 in [2] were attributed to material defects, mainly infiltration pores, which are not present in the squeeze cast material; it is suggested in [2] that UD-composites are especially sensitive to such processing defects in tension, particularly taking into account that ceramic fibres have superior compression than tensile properties. On the other hand, at R 0.1 & 25°C, fatigue limits of 600-800 MPa have been reported in [3, 4] for composites based on the systems Al(Cu)/Nextel and Al-1070/Tyranno respectively. While the values published in [3] can be attributed to the stronger and stiffer (and more expensive) Nextel-Al_2O_3 fibres, the higher performance of the Tyranno-fibre (SiC) reinforced lower purity Al-alloy composite with static properties comparable to those of Al(Mg)/Altex may reflect a possibly higher Weibull modulus of the latter fibre or particular processing conditions not mentioned in [4].

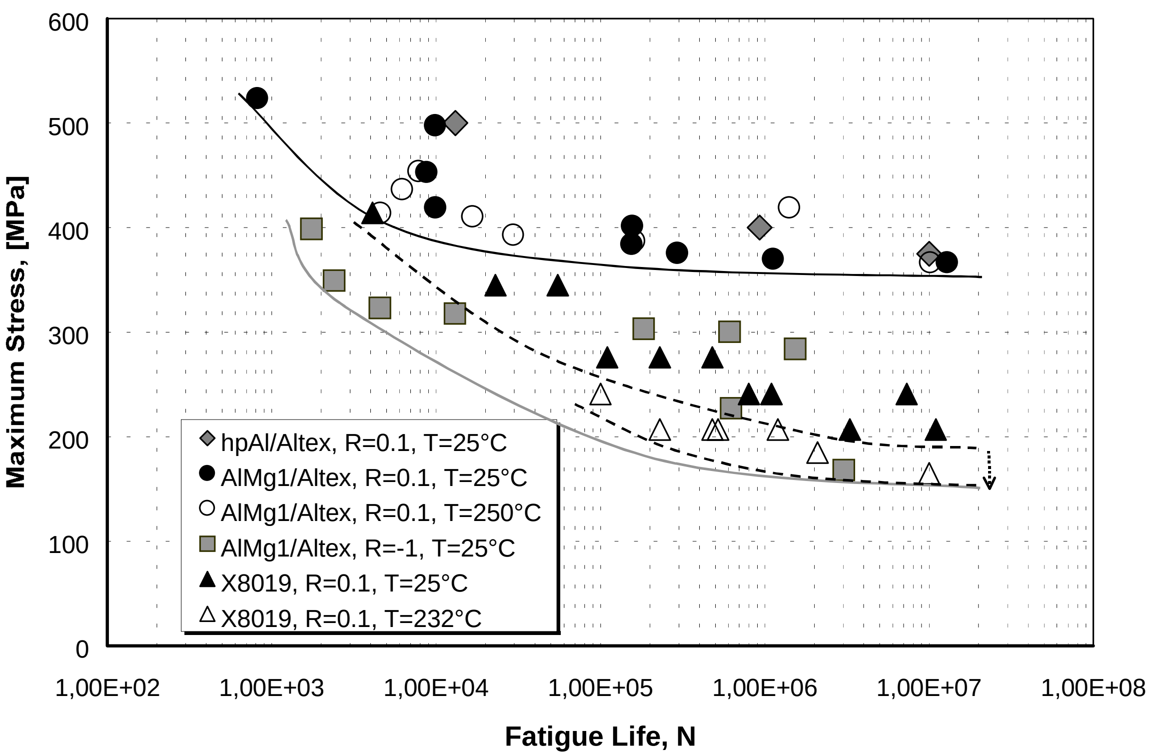

Fig. 5: SN-curves of AlMg1/Altex for various testing conditions compared to hpAl/Altex and an elevated temperature PM AlFe8Ce4 alloy (X8019). Note the insensitiveness of the fatigue performance of AlMg1/Altex to elevated temperatures up to 250°C.

Damage Development

Surface Damage by Machining

Since it is often claimed, that fatigue performance is dramatically affected by the surface quality of the test specimens, particularly for UD continuous fibre MMCs, special focus was put on the machining parameters to reduce surface damage to a minimal extent under practical machining conditions, which precludes finishing steps such as polishing. The aim was to define turning parameters for polycrystalline diamond tools (PCD) leading to as little fibre damage as possible. The cutting speed and particularly the feed were found to be the most important parameters controlling the fibre damage at the surface of the specimen. It has been shown, that some fibre damage will always occur at the surface of the specimen, but that it can be limited at best to the outer two fibre layers. The results of these tests have shown that the fibre damage is less for smaller cutting speeds (28 m/min) and for smaller feed values (0.02 mm/r). It is, therefore, suggested to perform first a roughening stage, followed by a fine turning stage using the values given above. The influence of the turning parameters on the damage depth is illustrated in Fig. 6.

The influence of the turning parameters on the fatigue properties was also investigated. As shown in Fig. 7, a decrease of the fatigue endurance and an increase of the scattering is observed when high feed values are employed, which correlates with the increase in damage depth resulting from these machining parameters, as mentioned above and illustrated in Fig. 6. Nevertheless, the influence of the surface damage is less than expected; this is attributed on the one hand to the strong interfacial binding strength that allows for effective reloading of broken surface fibres of a minimum critical length and on the other hand on a more damage tolerant transition zone in the damaged surface layer.

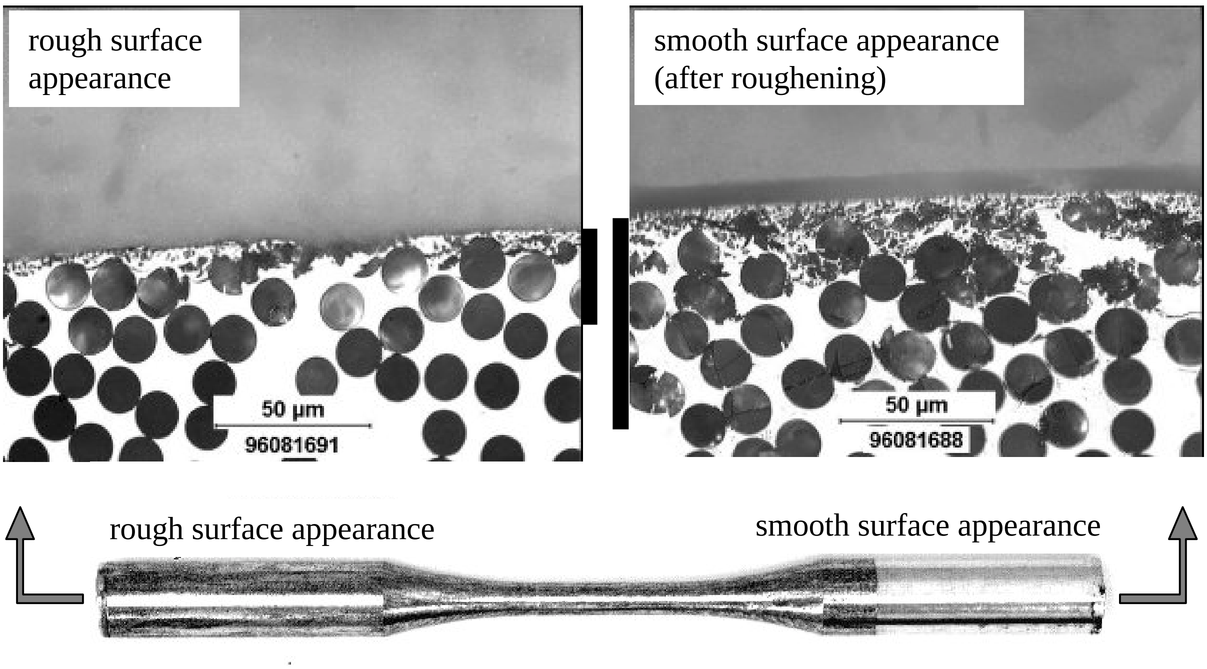

Fig. 6: Influence of machining conditions on the depth of the damage zone in unidirectional continuous fibre reinforced MMCs: more than 5 fibre layers damage depth after roughening (right), 1-2 fibre layers damage depth after turning with optimised parameters (left). (note that bright fibre reflection signalises in-depth fibre breakage)

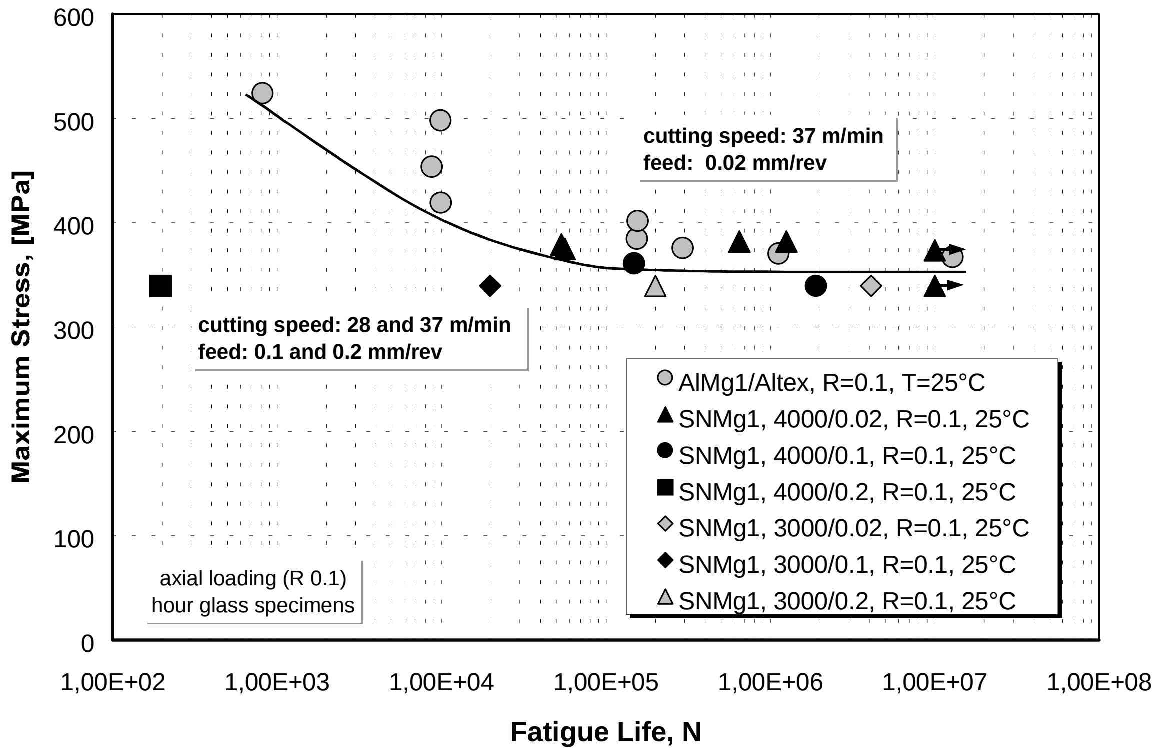

Fig. 7: Influence of the turning parameters on the fatigue endurance of unidirectional continuous Altex fibre reinforced Al-based MMCs. Note the adverse effect of high cutting feed on the composite's fatigue performance. (3000/4000 rpm ⇒ 28/37 m/min)

Damage Accumulation During Fatigue Life

Fig. 8 shows typical stress/strain hysteresis loops as obtained from the measurements with the clipped-on extensometer (Fig. 2) at different fatigue cycles. Two parameters were derived from these measurements to monitor the damage development during fatigue life: i) the Young's modulus determined by a linear regression of the whole hysteresis loop (loading and unloading cycle) and the permanent deformation, i.e. the total strain. The values obtained are plotted as a function of the cycle numbers for selected specimens in Figs. 9-10.

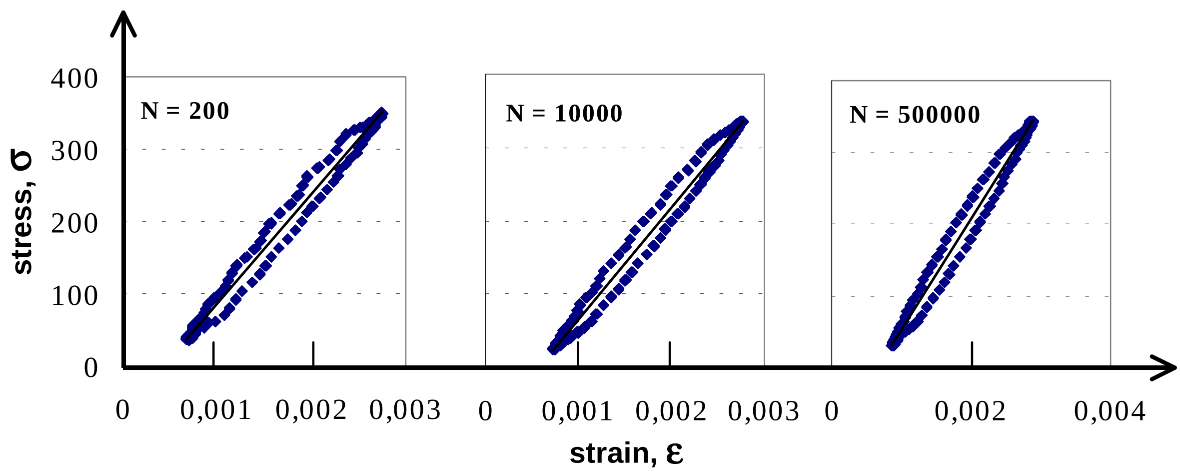

Fig. 8: Typical stress-strain hysteresis loops for AlMg1/Altex at 25°C, R 0.1, σ_{max} 350 MPa / 5Hz at different cycle numbers.

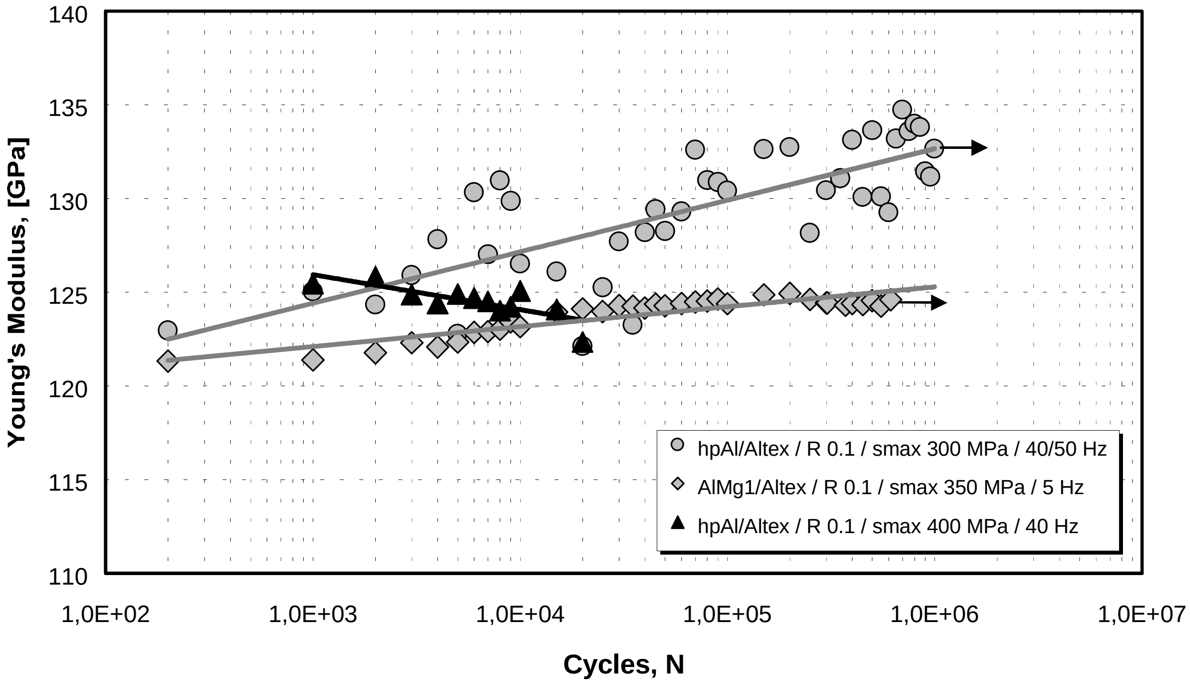

Fig. 9: Variation of the Young's modulus during fatigue life for hpAl/Altex and AlMg1/Altex at 25°C, R 0.1, σ_{max} 400 MPa / 40 Hz, 300 MPa / 40-50 Hz, and 350 MPa / 5 Hz respectively. (Note that the specimens tested at R 0.1, 300 & 350 MPa did not fail)

For the specimens subjected to a sub-critical load condition (i.e. below the fatigue endurance limit of 380 MPa at R 0.1), the width of the hysteresis loops is observed to diminish with increasing cycle numbers (Fig. 8) and the Young's modulus is found to increase (Fig. 9). Both features have also been reported in [4] and [5], respectively, and are attributed to cyclic hardening of the aluminium matrix. On the other hand, if the specimen is tested at R 0.1, 400 MPa, i.e. at a load exceeding the fatigue limit, the Young's modulus is observed to constantly decrease until final failure occurs (Fig. 9). In this latter case, damage development and accumulation is found to prevail over cyclic hardening, which leads to the early formation of fibre cracks and crack coalescence by matrix shear deformation in the inter-fibre regions, as illustrated in Fig. 11 b). The cracks tend to develop and propagate in the inter-fibre matrix area parallel to the fibre direction but not at the fibre/matrix interface; the fact that no interfacial debonding occurs underlines the strong fibre/matrix binding strength (cf. [4]).

The plots of total strain versus cycle number in Fig. 10 confirm the constant development and accumulation of damage for the specimen tested at 400 MPa where the total strain starts to increase after 3'000 cycles until final failure. On the other hand, for the specimen tested at 350 MPa, the strain only starts to increase after 30'000 cycles and obviously keeps going this way up to 613'000 cycles, where the test was stopped. This observation suggests, that damage may start to develop in the specimen after 30'000 cycles and may continuously accumulate during the following fatigue life, although the Young's modulus keeps increasing. Thus, it is assumed that under the described test conditions, the cyclic matrix hardening prevails over the damage accumulation; however it is expected that if the test was prolonged, once a critical damage state is reached, the Young's modulus should start to decrease after having reached a peak value and signalise the forthcoming failure, as reported in [5]. That damage has developed to some extent in the apparently intact specimen indeed, is confirmed by the micrograph of Fig. 11 a), where the start of a crack from the specimen surface is observed in the cross-section (at the middle of the gauge length). Fig. 11 a) also reveals that some fibres have already failed in the vicinity of the crack, as suggested by the reflection of the polarised light under the optical microscope, which makes the broken fibres appear bright. Note that no further signs of damage were observed on the remaining cross-section surface, which confirms the suitability of strain monitoring for damage development prediction rather than the Young's modulus evolution.

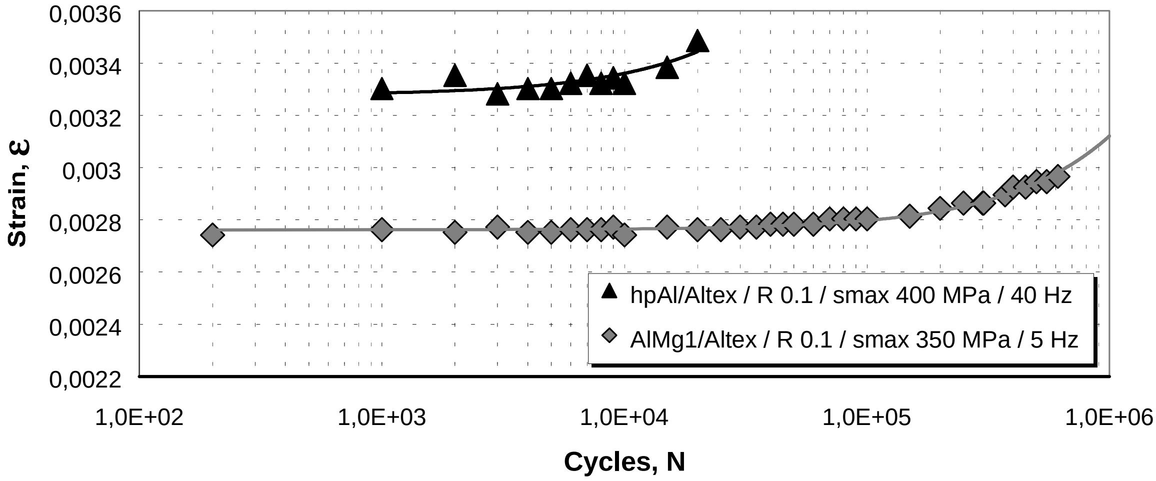

Fig. 10: Variation of the strain during fatigue life for hpAl/Altex and AlMg1/Altex at 25°C, R 0.1, σ_{max} 400 MPa / 40 Hz and 350 MPa / 5 Hz respectively.

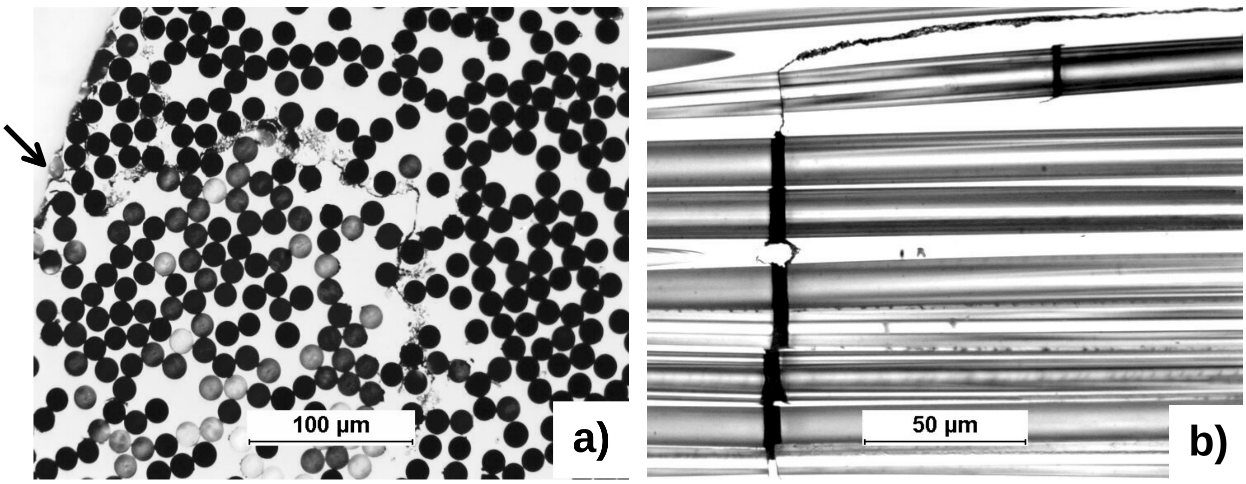

*Fig. 11: Development of cracks in the late stages of the fatigue life in hpAl/Altex at 25°C, R 0.1, σ_{max} 300 MPa / N 10^6 (a) and σ_{max} 400 MPa / N $2{\cdot}10^4$ (b). Note the crack initiation at the surface in (a) and the broken fibres (bright reflection) in the area of the crack initiation (the specimen in (a) did **not** fail at N 10^6; test was stopped).*

The lower fatigue properties of AlMg1/Altex at R -1 are related to the particular failure damage mode of this type of material which is initiated by fibre breakage during cyclic loading and followed by matrix shear deformation in compression and subsequent kinking, as illustrated in Fig. 12. As confirmed by the in-situ cyclic tests in the SEM, weak or damaged fibres will break during the first load cycle; another reason for premature fibre failure may be local stress concentrations induced by isolated material defects such as brittle intermetallic

interfacial reaction products or segregations. For pure tensile cyclic loading (e.g. R 0.1) this isolated fibre cracks are not critically harmful to the composite's performance, since the load is effectively redistributed to the neighbouring fibres in the present strong-interface MMC material. During compression loading, however, this will lead to microscopic fibre crushing and/or buckling as shown in Fig. 12 a) and subsequent shear deformation of the matrix alloy and finally to composite failure by macro-buckling, as illustrated in Fig b-c).
The fractographies (SEM) confirm the damage development observed on the specimens' cross-sections by optical microscopy (Fig. 11) as well as observed during the SEM in-situ tests (Fig. 12) , as illustrated in Fig. 13.

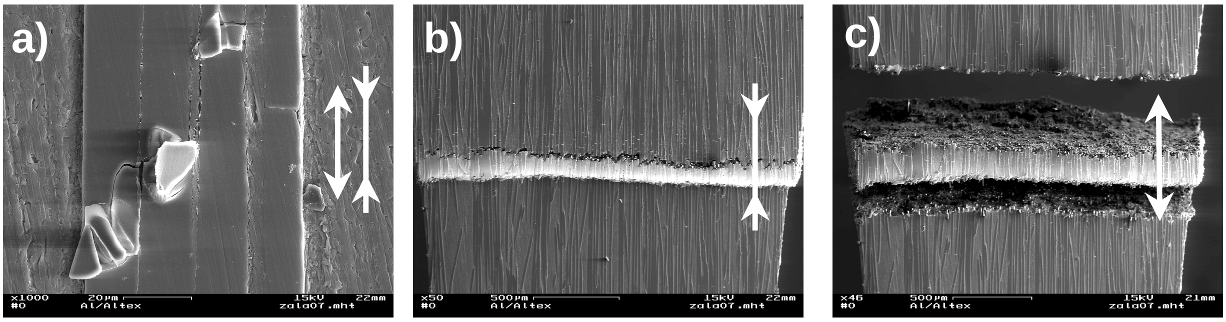

Fig. 12: Failure damage of AlMg1/Altex is initiated by fibre breakage (kinking) (a), followed by matrix shear deformation and subsequent macroscopic kinking (b-c); (R -1, RT).

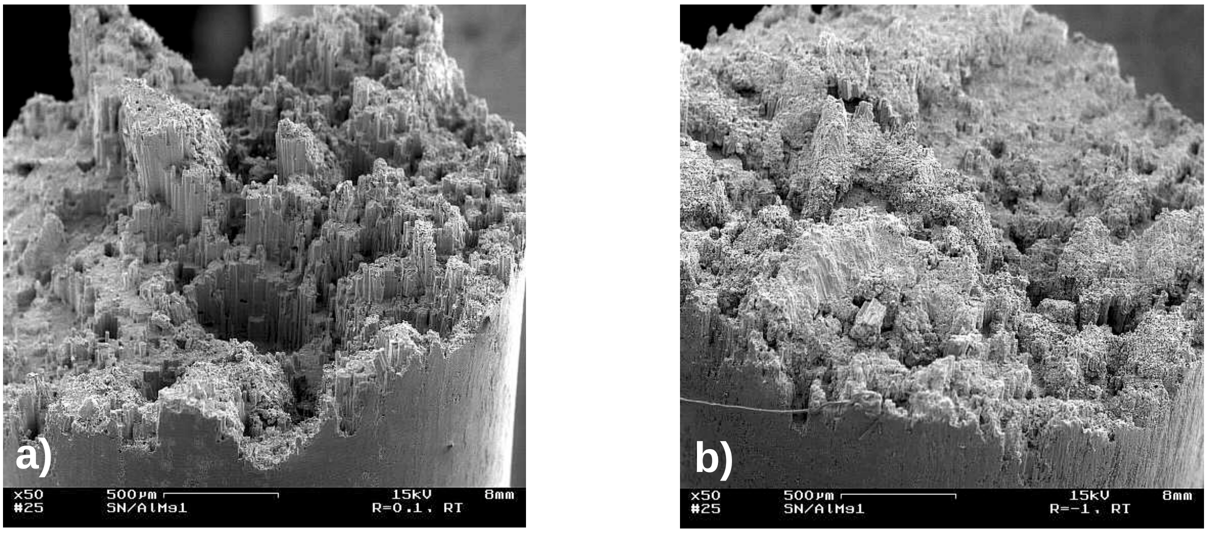

Fig. 13: Fractography of AlMg1Altex at 25°C, R 0.1, σ_{max} 400 MPa (a) and at 25°C, R -1, σ_{max} 300 MPa (b). Note the contrast between the rough, ductile fracture surface with multiple fibre cracks and protruding fibres (covered by a matrix layer) under pure tensile load in (a) and the flat, crushed fracture surface under reversed loading in (b).

Two suggestions are made to improve the performance of unidirectional continuous fibre metal matrix composites: i) avoid premature fibre failure during tensile loading by improving the preforming technique (better fibre alignment, less fibre damage), by reducing interfacial intermetallic phases and/or by selecting a better fibre type less susceptible to premature failure (i.e. with a higher Weibull modulus), and ii) use matrix alloys with higher shear strength values, as suggested in [3].

CONCLUSIONS

High quality unidirectional hpAl/Altex and AlMg1/Altex MMCs can be successfully produced by direct squeeze casting. These composites feature a fatigue behaviour comparable or superior to that of similar composites using the same fibre, as reported in the literature. Surface damage from inadequate machining sensibly reduces the fatigue performance and leads to an increased scattering of the results. Monitoring of strain evolution proves to be effective for the detection of early damage development during fatigue life. The observation of damage development during fatigue life suggests that fatigue failure is induced by premature fibre breakage, which is shown to be particularly harmful during alternate tensile/compression loading. The early fibre failure is attributed to composite imperfections such as fibre misalignment or interfacial intermetallic (reaction) phases on the one hand, and to the comparatively low Weibull modulus of 3.8 of the Altex fibre on the other hand. Thus, to further improve fatigue performance, process defects should be minimised and a better fibre and a fibre- and process- compatible matrix alloy with a higher shear strength should be used.

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