THERMAL CYCLING CREEP OF PARTICLE REINFORCED ALUMINIUM

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SUMMARY: The thermal cycling creep behavior of the aluminium alloy 6061 reinforced by 10 vol.-% Al_2O_3-particles and its dependence on the applied mechanical creep load was analyzed with respect to different heat treatment conditions. The specimens were thermally cycled between room temperature and 300°C. It was found that a stabilizing aging of the composite at 300°C increases the lifetime significantly at an initial stress of 40 MPa but reduces the cycles to failure tremendously at 80 MPa. Void formation at particles, promoted by internal and external stresses, and their transverse linkage was the main failure mechanism

KEYWORDS: particle reinforced aluminium, thermal cycling creep, lifetime, void formation, aging condition

INTRODUCTION

Combining a high strength ceramic phase with an aluminium matrix to form a metal matrix composite (MMC) offers attractive choices for the use as structural components in combustion engines or brake components because of improved stiffness, dimensional stability, fatigue and wear resistance compared with unreinforced alloys. Compared with other MMC the key advantage of stir-cast particle reinforced metals (PRM) is, that conventional processing routes such as casting, forging or extrusion can be applied for industrial production [1, 2].

Like other types of MMC the elevated temperature behaviour of PRM is governed by internal stresses developed due to the mismatch in the coefficient of thermal expansion between matrix and reinforcement. In particular, cyclic thermal loading in combination with relatively small applied stresses can result in strongly increased creep rates and even superplastic deformations compared to static temperature conditions [3, 4, 5]. The understanding of the factors influencing this so called thermal cycling creep behaviour (TCC) is of significant importance for the selection of particle reinforced aluminium as candidate material for elevated temperature structural applications.

In this work investigations on the thermal cycling creep behaviour of various particle reinforced aluminium alloys were performed with respect to the influence of the initial heat treatment condition.

EXPERIMENTAL CONDITIONS

The investigated metal matrix composite was the aluminium alloy AA6061 reinforced by 10 vol.-% Al_2O_3 particles (made by DURALCAN by stir-casting). Its important to mention that during the high temperature exposure in the course of production and during solution treatment the particles react with the magnesium of the alloy forming a thin layer of spinel crystals ($MgAl_2O_4$) which plays an important role on the mechanical properties [6, 7]. The thermal cycling creep behavior was analyzed on specimens prepared from 11 mm diameter rods extruded by Leichtmetall-Kompetenzzentrum Ranshofen/Austria. After quenching from solution treatment the following aging conditions were investigated: room temperature aged T4, peak-hardened T6 and both in a combination with an additional short term exposure to 300°C (according to the maximum test temperature in the thermal cycling creep experiments) for 30 minutes. The aim of this stabilization was to produced a precipitation condition which will be approached by about 600 thermal cycles. Table 1 gives an overview on the matrix composition and particle content of the investigated composite, table 2 describes the applied heat treatments.

Table 1: Composition of investigated Duralcan aluminium matrix composite

matrix	designation	particle [vol.-%]		Fe	Si	Cu	Mn	Mg	Ti
AA6061 - AlMg1SiCu	W6A10A	10	Al_2O_3	0,20	0,69	0,28	0,009	0,93	0,10

Table 2: Heat treatment conditions of investigated material

material condition	560°C/30 min, water quenched	heat-treatment description
T4	+ RT/ > 30 days	Solution treatment and room temperature ageing
T4-S	+ 300°C/30 min	T4 + stabilisation
T6	+ 160°C/8h	Solution treatment + artificial peak ageing
T6-S	+ 160°C/8h+300°C/30 min	T6 + stabilisation

Thermal-cycling creep experiments were executed by the use of a Gleeble 1500 apparatus which combines full resistance heating thermal capabilities and hydraulic servo-mechanical testing performance in a single system [8]. Specimens were subjected to thermal cycles between 50°C and 300°C (heating/cooling rate=12.5 K/s) and a holding time of 3 seconds. The constant mechanical load was 2.02 and 4.04 kN, corresponding to initial stresses of σ_0= 40 and 80 MPa, respectively. Fig. 1 gives an overview on the described thermal cycling creep experiments with thermal cycling and constant mechanical loading and the corresponding variation of total strain. During each thermal cycle an incremental amount of plastic strain is developed (superimposed by the thermal elongation and contraction) which results in a significant plastic elongation (ε_{pl}) in the composite after several thermal cycles.

In order to identify the damage mechanisms governing the life-time specimens were investigated by scanning electron microscopy (Philips XL30) after failure. Representative material conditions were prepared for transmission electron microscopy (TEM) by the use of diamond saw, subsequent mechanical polishing and ion-milling.

Specimens for metallographic investigations were prepared by subsequent mechanical grinding and polishing with diamond paste up to 1 µm. Dissolving the aluminium matrix by additional electrolytic polishing provided an exact analysis of possible existing voids.

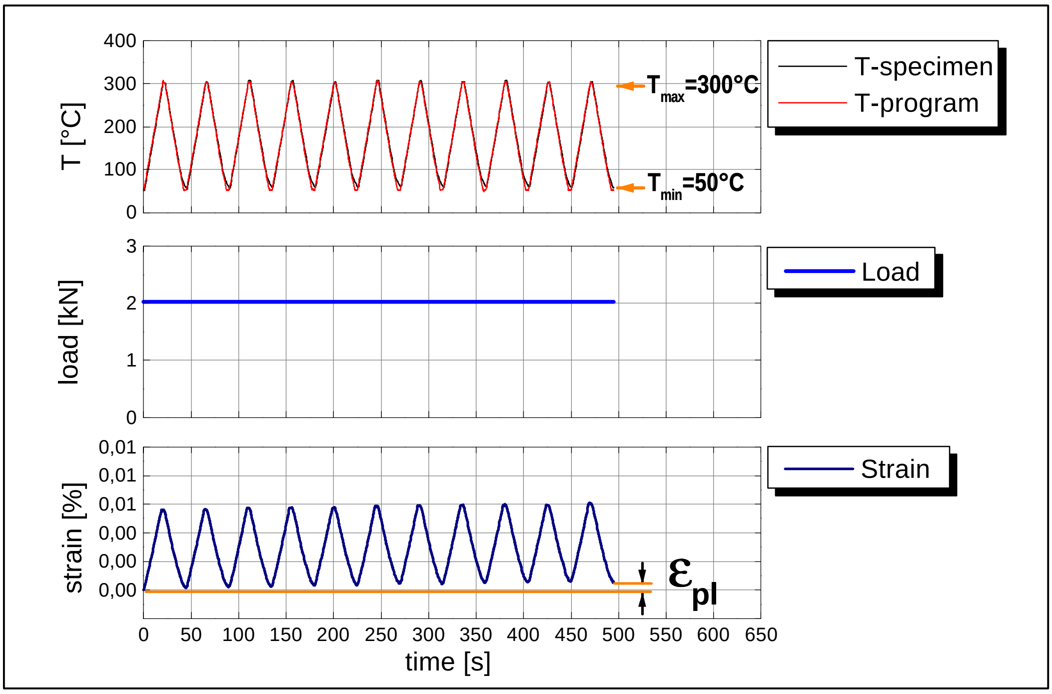
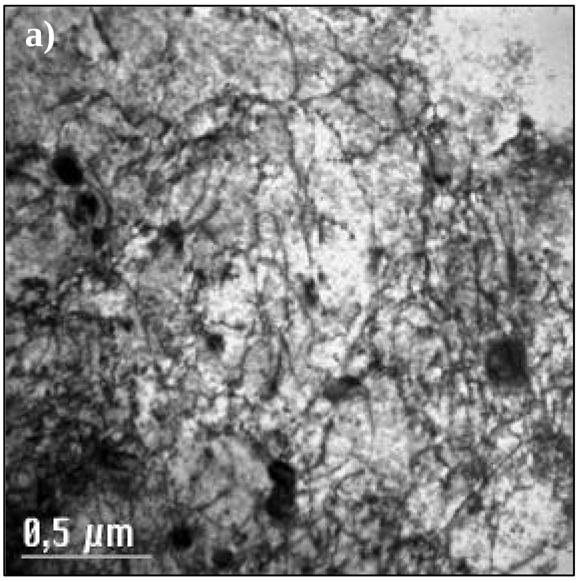


Fig. 1: Thermal cycling creep experiments

RESULTS AND DISCUSSION

Results of TEM investigations on the initial heat treatment conditions are presented in Fig. 2, a) and b). Compared with the conventional T6 substructure with its fine dispersed precipitates (a) the additional short term exposure to 300°C for 30 minutes produces an over-aged matrix with very coarse precipitates (b).



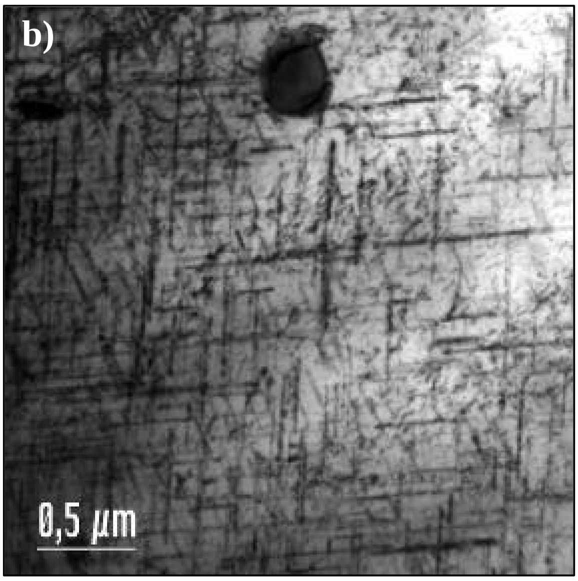


Fig. 2: a) Microstructure of W6A10A in T6 condition: fine precipitates and dislocations
b) Microstructure of W6A10A in T6-S condition: coarse precipitates

Strain-time diagrams under thermal cycling conditions

Fig. 3 shows the strain-time curves resulting from thermal cycling creep tests at an initial stress of 40 MPa for the W6A10A composite material in the different heat treatment conditions.
Similar to more conventional materials and creep, with its primary, secondary and tertiary creep regions, 3 regions can be observed: (1) decreasing strain-rain rate per cycle during the first cycles, (2) a long period with a nearly constant strain-rate and (3) a regime characterized by accelerated creep and final fracture. In spite of the different initial material conditions the general appearance of the strain-time diagrams is very similar: in (1) all exhibit a strengthening, but in region (2) the nearly constant strain rate depends strongly on the initial heat treatment condition of the composite, which determines the cycles to failure. The T4 and T6 conditions exhibit modest life-times of N_f= 1078 and N_f=372, respectively, but with the stabilizing T4-S and T6-S treatments, life time is increased significantly to N_f=3472 and N_f =2078. This is unexpected because at least during the experiments on T4 specimens the thermal loading should overage the matrix similar to the additional stabilization at 300°C (3s exposures at maximum test temperature sum up to almost 1h during the complete test).

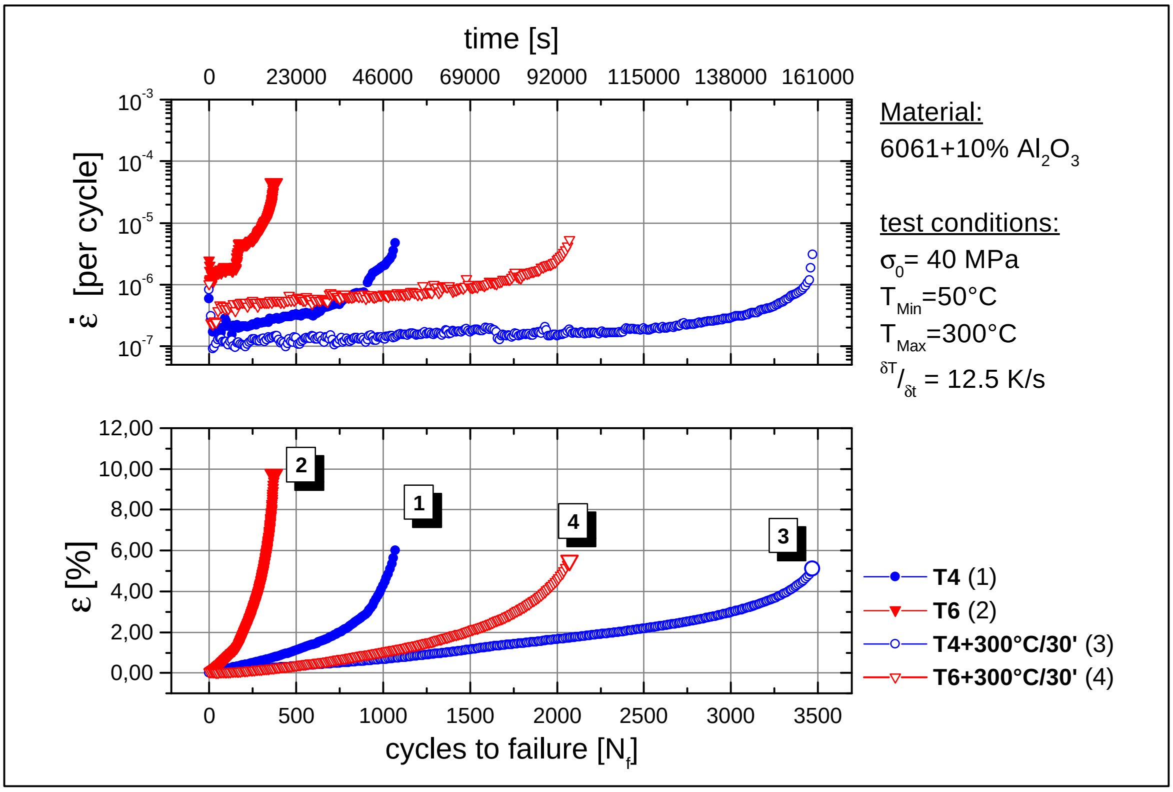


Fig. 3: Thermal cycling creep diagram and corresponding creep rate per cycle of W6A10A at 40 MPa external stress.

Although the T4 and T6 specimens progressively overage during thermal cycling the creep rate within the experiment does not approach the values of the stabilized specimens. In spite of the increased life time of the stabilized specimens their elongation at rupture is reduced to below 6%.

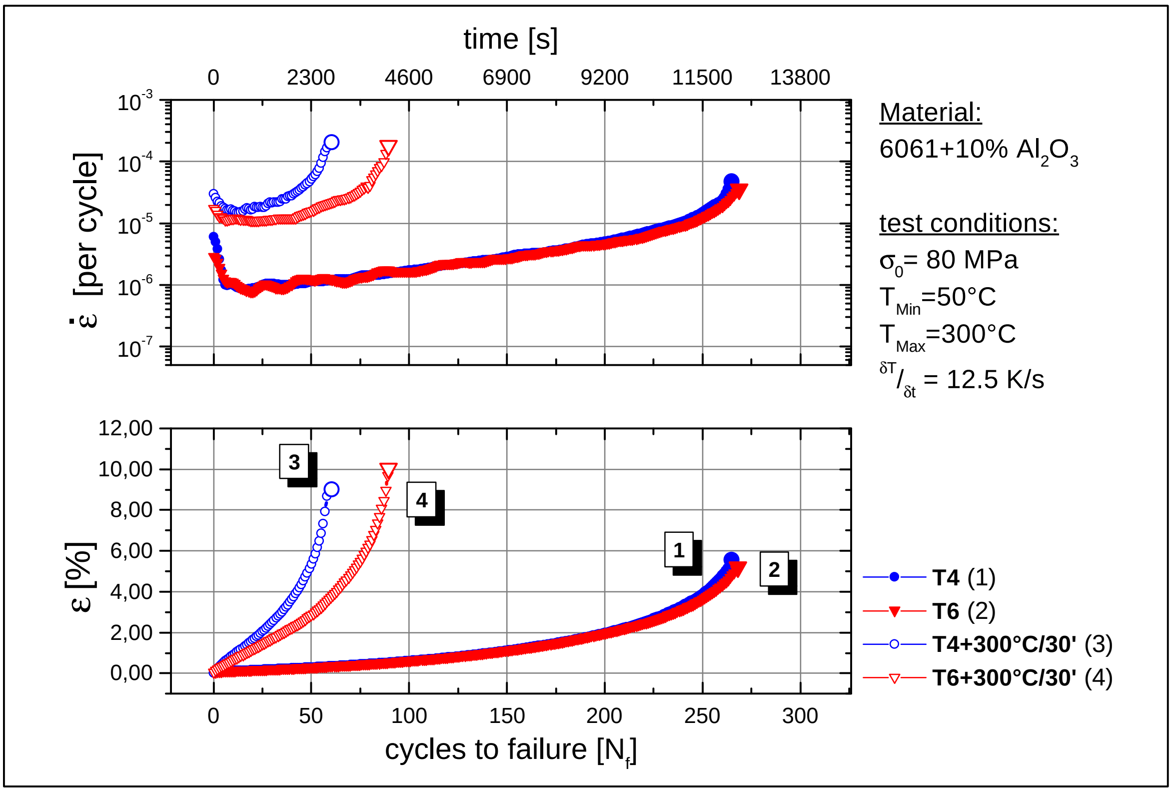


Fig. 4: Thermal cycling creep diagram and corresponding creep rate per cycle of W6A10A at 80 MPa external stress.

As a first approach, it can be assumed that a soft, overaged matrix reduces the internal stresses attributed to the difference in thermal expansion between matrix and reinforcement and thus reduces the creep rate increasing the life time. Detailed investigations are done to clarify the mechanisms responsible for this a behavior.

Whereas the creep rates for the composite in the T4-S and T6-S conditions at 40 MPa are significant lower than those for the T4 and T6 specimens the opposite is true for thermal cycling conditions at 80 MPa (see Fig. 4). The T4 and T6 conditions exhibit identical behavior with reduced cycles to failure of N_f=266 (approx.1/4 of N_f at 40 MPa) and N_f=269 (approx.3/4 of N_f at 40 MPa), respectively. The artificial aging treatments T4-S and T6-S reduce the lifetime significantly to N_f=59 and N_f=90, respectively, which are only e few % of N_f at 40 MPa. Under this higher external load the matrix strength is governing the life time and thermally induced residual stresses are supposed to have a minor influence.

Fracture surface

The SEM image obtained from the fracture surface of a thermal cycling creep specimen (Fig. 5) clearly exhibits extensive interface debonding between matrix and the spinel layer of the Al_2O_3-particles and void formation, but no significant particle cracking. Generally, Fig. 5 is representative for all conditions and test parameters.

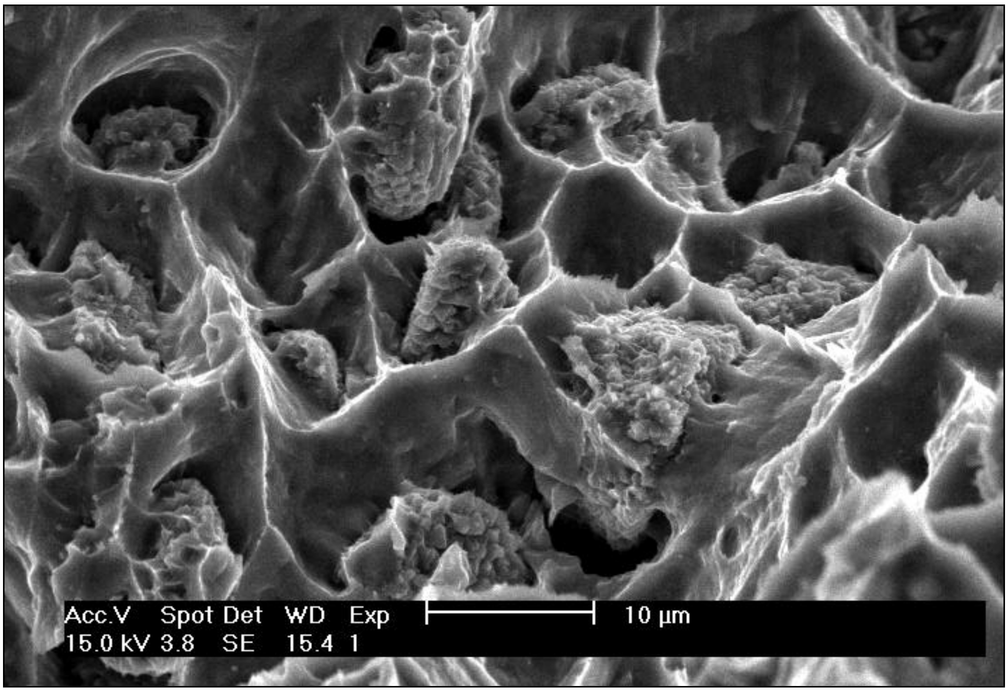


Fig. 5: Fracture surface of T6 condition after thermal cycling creep

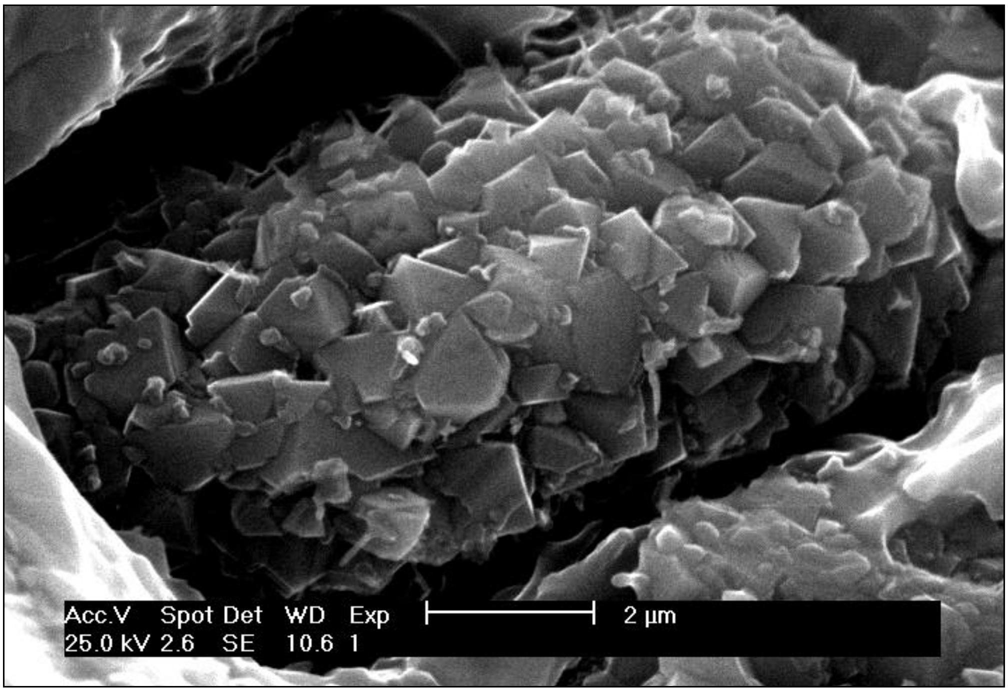


Fig. 6: Completely debonded interface showing spinel crystalls ($MgAl_2O_4$) on particle surface

The higher magnification in Fig. 6 reveals that there is no matrix in between the spinel crystals. This indicates, that during thermal cycling creep the thermal stresses, caused by the different thermal expansion between matrix and reinforcement, may promote debonding and void formation at the spinel/matrix interface, which can be assumed to be the main damage mechanism under thermal cycling creep loading. In addition, Fig. 7 shows the matrix region around an extracted particle, showing a fine dimple structure due to interface debonding between the aluminium alloy and the spinel layer.

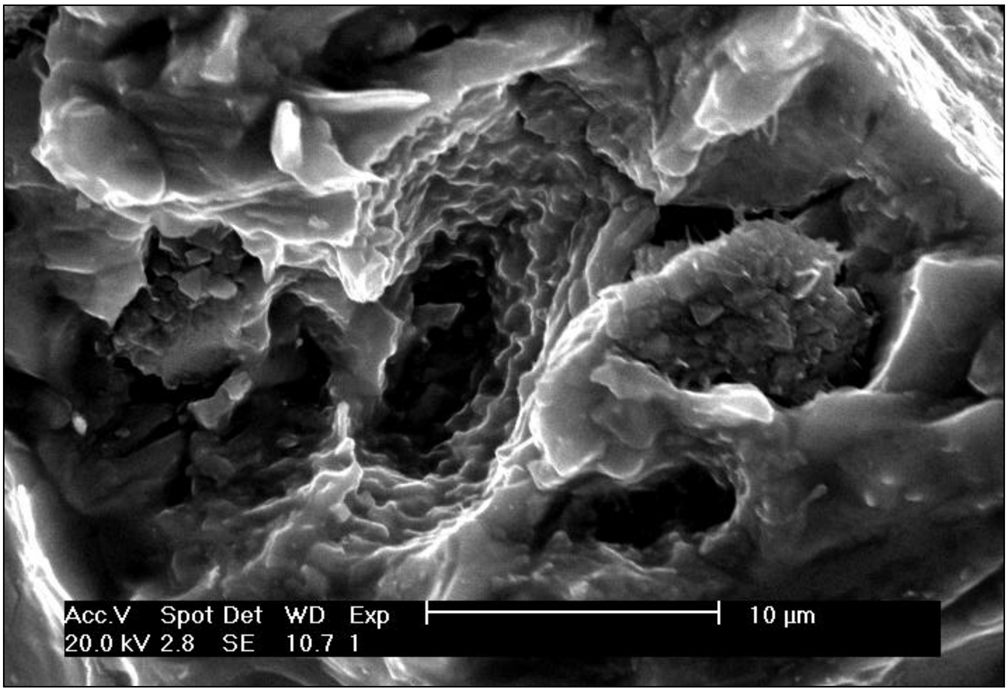


Fig. 7: Matrix region around an extracted particle, showing dimples due to interface debonding.

SEM investigations on longitudinal cross sections of thermally cycled samples in the vicinity of the fracture surface reveal void formation on the front faces of the particles in the loading direction (Fig. 8).

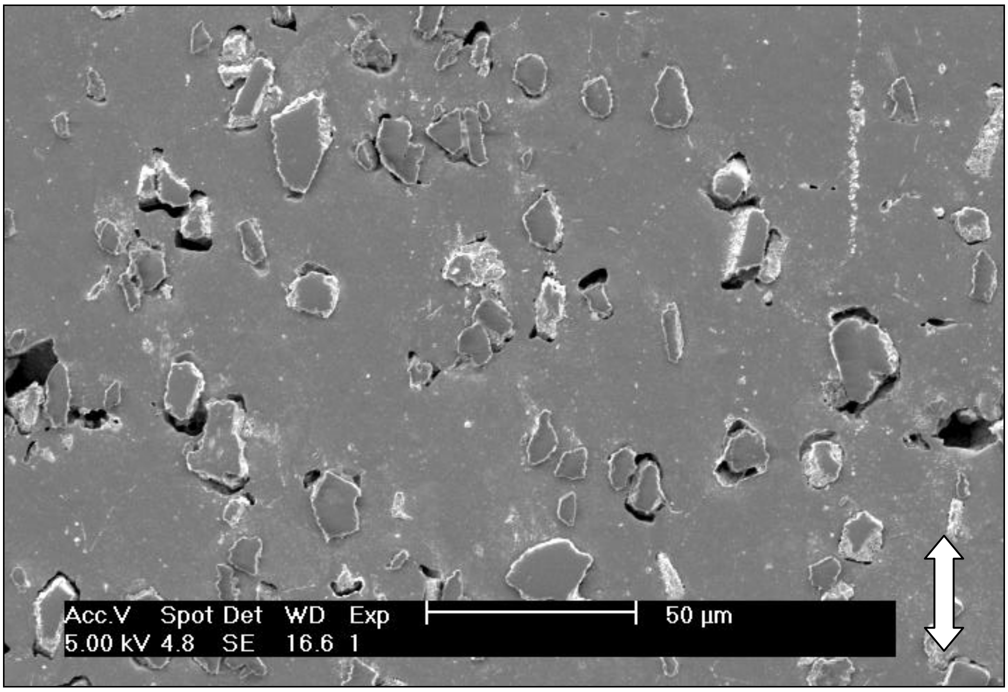


Fig. 8: Void formation on the front faces of the particles in thermally cycled W6A10A at 40 MPa (the arrow indicates the tensile loading direction)

Failure occurs as a result of transverse linkage of these voids, leading to large transverse cracks which are also present in the vicinity of the fracture surface (Fig. 9).

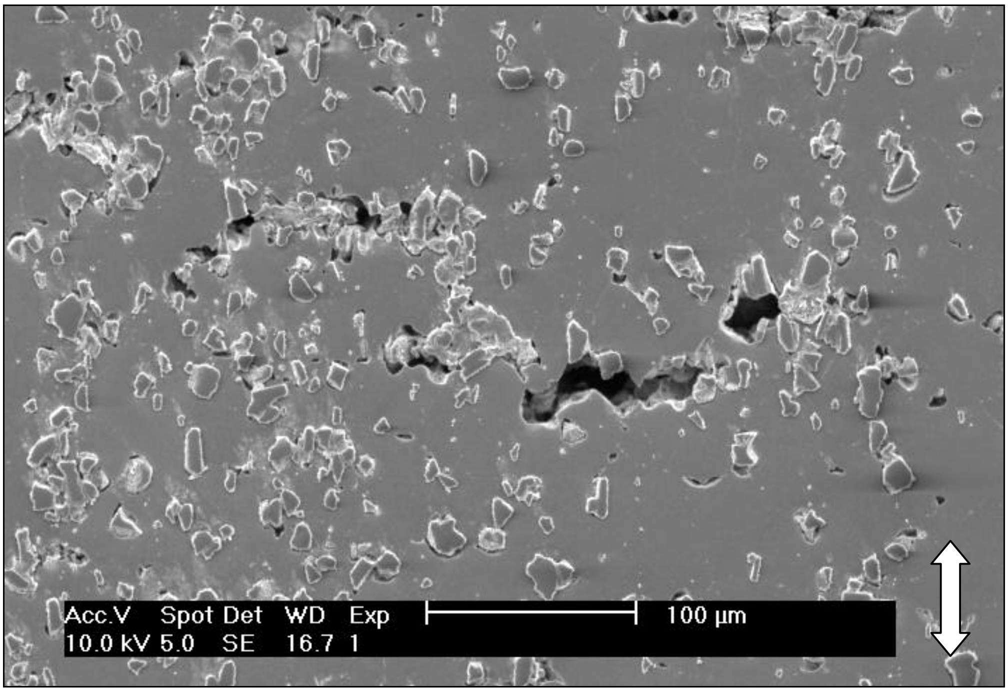


Fig. 9: Linkage of voids transverse to the loading direction, initiated at the particle/matrix interfaces.

CONCLUSION

The present results demonstrate that the thermal cycling creep behavior of the aluminium matrix 6061 reinforced by 10 vol.-% Al_2O_3 particles is strongly dependent on the heat treatment condition and creep loading. It is proposed that at relatively small applied loads (40 MPa) the lifetime is governed by thermally induced stresses, which promote void formation and a matrix softening by stabilization can increase the thermal cycling creep resistance.
At higher mechanical loads (80 MPa) the matrix strength has the main influence on life time and the specimens with T4 and T6 heat treatments exhibit higher cycle to failure values, compared to the stabilized, over aged conditions.

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