3D CREEP MODELLING OF A SHORT FIBRE REINFORCED ALUMINIUM ALLOY: INTERCONNECTIVITY AND LOAD SEQUENCES

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Abstract. Long-term isothermal creep with load changes is investigated by means of experimental tests and computational mechanics on two composite materials, commercially pure Al and AlSi-based alloy reinforced with 15 vol% of Al₂O₃ short fibres. Three-dimensional periodic unit cell models are developed based on statistical parameters, and for the AlSi composite two interconnectivity conditions for Si and short fibres are considered. Simplified materials consisting of Al, eutectic Si (except for the Al composite) and short fibres are proposed. Finite element method is applied in order to compute the stationary creep behaviour of each model. Results obtained from simulations compared to measured creep tests are in agreement. These results confirm the sensitivity of the creep behaviour with respect to load sequencing and interconnectivity of the rigid phases.

Keywords: creep, finite element method, metal matrix composite, unit cell, load sequences

1. INTRODUCTION

Short fibre reinforced metals (SFRM) have shown promising mechanical properties at elevated temperature (Schnabl, 2002), leading to applications for combustion engines where some components locally reinforced with short fibres (SF) have been developed (Henning et al., 1994). To ensure the reliability of such materials under long-term temperature/load exposure, the mechanisms controlling their thermomechanical behaviour are to be known.

In previous studies (Requena and Degischer, 2006), a short fibre reinforced AlSi12CuMgNi alloy showed a decrease in stationary creep rate after a sequence of loads and with the creep exposure time extending several thousand hours at 300 °C. Microtomographic evaluations revealed microstructural changes of the Si phase, especially of the interconnectivity between Si, SFs and intermetallics as reported in (Requena et al., 2008). A commercially pure Al-based composite was also studied in order to elucidate the role of Si during long-term creep exposure, when compared to the SFR Al-alloy.

Models of creep behaviour of SFRM have focused on the spatial arrangement of the fibres (Dragone and Nix, 1990), the influence of damage (Dun and Taya, 1994), the work hardened zone between matrix and fibres (Dlouhy and Eggeler, 1994), and the constitutive creep law of the matrix material (Lilholt, 1985). There are few studies on the influence of interpenetrating architecture of rigid phases on the creep behaviour and on the role of the changes of loads during creep. Dragone and Nix (1992) have modelled the steady and transient creep properties of an Al-alloy reinforced with a self-interconnected Al₂O₃ SF network, showing a high sensitivity in rigid phase connectivity.

In the present investigation three-dimensional unit cell finite element (FE) models are proposed in order to study the influence of the 3D connectivity between Si and SFs, and the load sequence on the creep resistance of SFR Al and Al-alloy. These models are based on 3D microstructural features and are correlated with experimental results.

2. DESCRIPTION OF THE MATERIAL

A piston alloy AlSi12CuMgNi reinforced with 15 vol.% of random-planar oriented Saffil® fibres was studied under creep conditions in (Requena and Degischer, 2006). The lengths of fibres vary from 10-200 µm, with diameters ranging between 1 to 10 µm.

The SFRM was solution treated at 480 °C/4h and oil quenched, aged at 190 °C/4h and finally overaged at 300 °C/3h to establish a stable precipitation condition at the beginning of the creep tests at 300 °C.

Another composite with commercially pure Al (99.85% purity) matrix reinforced with 15 vol.% of Saffil® fibres was studied under the same creep conditions. The arrangement and morphology of the short fibres was similar to the material previously described.

The creep tests were carried out isothermally at 300 °C with changes of load. This sequence could be described as an increase or decrease of load after achieving stationary (secondary) creep rate. Typical external load sequences, σl, are for example: 20 MPa → 40 MPa → 20 MPa, and 30 MPa → 40 MPa → 30 MPa.

The microstructure was characterised using synchrotron microtomography as explained in a previous work (Requena et al., 2008).

In the AlSi12CuMgNi composite, the morphology of the eutectic Si changes by diffusion during creep, resulting in a higher interconnectivity between Si and SFs. The interconnection of Si and SFs was present in all conditions, but
increases with time and temperature exposure. This effect became noticeable after 2000 hours. The load usually was changed after a time step of thousands of hours, with a typical creep test consisting of 3 to 5 different load conditions.

3. EXPERIMENTAL RESULTS

Figures 1a and 1b show a characteristic creep curve of strain rate vs. time obtained during one of the creep tests performed on the AlSi-based and pure Al-based composite, respectively. Each step is under a constant load, indicated in the diagrams. Primary creep stage is present during the beginning of the test, followed by secondary creep stage exhibiting a stationary strain rate. As reported in (Requena and Degischer, 2006), a decrease in the stationary creep rate of the piston alloy was observed after returning to a previous load condition. This behaviour is not observed for the pure Al matrix (see Fig. 1a-b). The stationary creep rate after a load increase and more than 1000 hours of creep decreases to 10-25% of the original creep rate for all the SFRM specimens (Requena and Degischer, 2006). This was attributed to the formation of a 3D hybrid network by Si-bridges between SFs. The Si diffusion at 300 °C is intensified by the high number of grain/phase boundaries, as well as by the external load and as a result the Si coalesces between the SFs (Requena et al., 2008).

4. MODELLING

The finite element method (FEM) was used to study the influence of interconnectivity between Si and SFs, and the role of load changes on the creep behaviour. The actual AlSi-based composite contains 5 phases: Al-matrix, SFs, Si, intermetallics and voids; while the SFRM with the pure Al matrix contains 3 phases: Al-matrix, SFs and voids. The main target was to analyse the role of the hybrid structure formed by Si and SFs during long-term creep exposure, using a model material of Al-matrix, Si (if needed) and SFs. In order to simulate the load sequences, 2 combinations were chosen: 20 MPa → 30 MPa → 20 MPa, and 40 MPa → 60 MPa → 40 MPa. Each step elapses 1000 hours, a period of time considered long enough to achieve stationary creep regime.

4.1. Unit cell

Three unit cells were developed representing two extreme conditions of Si-SFs connectivity (see Fig. 2) and a third without eutectic Si (AlSF). The method followed for their design can be found in (Marks et al., 2009). Volume fraction of phases, relative 3D particle density, mean length and diameter of SFs, orientation of SFs, and interconnectivity between SF and Si were used as input parameters for the design of the models. Basically, of the two models with Si content, one was created to resemble a fully disconnected Si-SFs composite (0% interconnectivity), and the second a fully interconnected Si-SFs composite (100% interconnectivity). The third unit cell is based on the aforementioned models, but without eutectic Si (AlSF). The unit cells are identical in size and SFs arrangement. A rectangular prism of 108 x 108 x 18 µm³ was chosen as unit cell in agreement with the statistical analysis described in (Marks et al., 2009). The 18 µm size of the edge on the z-axis was chosen to represent a periodicity perpendicular to the plane of randomly distributed SFs.
The SFs were placed considering 3D symmetrical boundary conditions applied to solve the FE model. This aspect affects the geometrical design, and as a consequence the SFs were placed to match this criterion. The SFs were oriented in 4 directions in the plane 1-2, resembling the random-planar layout in the actual material. A perfect interface between all phases was assumed neglecting damage mechanisms.

4.2. Finite element modelling

The geometrical unit cell models were meshed using two type of elements (see Fig. 3): only linear hexahedra and only linear tetrahedral, coded as C3D8 and C3D4 elements respectively, a terminology used in Abaqus® input files (Abaqus, 2006). To mesh the hexahedra models, a simple Matlab algorithm was developed capable of converting the TIFF® format unit cell model directly into an Abaqus® input file. The result was a mesh of 54 x 54 x 9 elements, cubic hexahedra of 2 µm by side. The tetrahedral meshing procedure was done using Amira® Tetragen package (Amira, 2005) resulting in a variable size between 154000 and 168000 elements. Three-dimensional symmetrical boundary conditions were applied in order to create an infinite periodic model.

Two and three phases were considered and their material properties at 300 °C were applied. Si and SFs phases were considered ideally elastic, while Al was considered to behave elastoplasticly in the static regime and following the power-law in the creep regime (see Tab. 1). On the latter, the time-hardening option in the Abaqus® user routine CREEP was selected. A 6-point plastic region of stress-strain curve was incorporated in the materials algorithm. The Al properties for the matrix in the models were extracted from AA6061 tensile and creep tests reported in (Prader, 2000) and in (Requena, 2004). The 6061 alloy was chosen because of the absence of eutectic Si, and the presence of dissolved Si and Mg in similar quantities to the AlSi12CuMgNi alloy. Silicon and SFs properties were taken from (Huber et al., 2006) and (Saffil, 2003).

A first step was computed in order to obtain the static stress distribution in the model and a second step was then applied to simulate the creep behaviour, and this procedure was repeated 2 more times to simulate the 3 step sequence. Loads were applied on the top plane of the models, i.e. within the plane of random fibre distribution (plane 1-2).
Table 1. Mechanical properties of Al, Si and SFs at 300 °C.

<table>
<thead>
<tr>
<th>Phases properties</th>
<th>Al</th>
<th>Si</th>
<th>Al₂O₃ Saffil® SFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young modulus E [GPa]</td>
<td>50</td>
<td>163</td>
<td>370</td>
</tr>
<tr>
<td>Poisson’s ratio ν</td>
<td>0.3300</td>
<td>0.2081</td>
<td>0.2200</td>
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<tr>
<td>Power creep multiplier A</td>
<td>10⁻¹¹</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Equivalent stress order n</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

5. COMPUTATIONAL RESULTS AND DISCUSSION

The computationally determined creep behaviour of AlSi and Al reinforced with 15 vol.% of short fibres under long-term creep exposure is presented in Fig. 4a-b, where the creep strain rate in the load direction is plotted for the 3 studied conditions (0% and 100% Si-SFs interconnectivity, and AlSF). The results show the same tendency and similar creep rates for both meshing elements.

During all sequences, the creep rate of AlSF is shown to be consistently higher than those of the AlSi matrix. The fully interconnected Si-SFs models present the lowest creep rate among all in every stage. When comparing the stationary creep rate of the first step with the third one, the difference between them becomes significant for the 100% Si-SFs interconnectivity. In the case of the AlSF, this difference is small. This behaviour correlates with experimental results shown in Fig. 1 and in more detail in (Requena and Degischer, 2006).

The results from models constituted by hexahedra are used hereafter to simplify further analysis, since the type of meshing elements hardly influences the behaviour of the models as seen in Fig. 4a-b.

Figure 4. Creep strain rate for the three unit cell models: a) using tetrahedral elements b) using hexahedral elements

Figure 5. Computed stationary creep rate vs. applied load for the SF reinforced AlSi (0% and 100% of Si-SF int.) and Al composites. The bold symbols indicate the stationary creep rate after a load sequence.

Stationary creep rate results are depicted in Fig. 5 as a function of the applied load. The variation, before and after changing loads, is accentuated for the fully interconnected Si-SFs model. For a given load, the stationary creep rate after
1000 h at higher load decreases with an increase of interconnectivity of the rigid phases. Figures for 30 MPa were calculated using a single step approach, without load permutation (Marks et al., 2009).

The statistical distribution of stress in the load direction for each element, $\sigma_{22}$, in the Al matrix is plotted in Fig. 6 for the 3 models, following a loading sequence of 20 MPa → 30 MPa → 20 MPa. Figure 6a illustrates the distribution of internal stresses $\sigma_{22}$ of the AlSF model, showing a broadening and a shift of the curve to lower values after 1000 h of creep exposure. In Fig. 6b, the curve is shifted to higher values (compared with bold symbols in (a)) due to an increase of the external load. After another 1000 h of creep the distribution moved towards lower stresses. After decreasing the external load to 20 MPa, as seen in Fig. 6c, the stresses in the matrix show a reduction compared to the previous step. The shape of the histogram of $\sigma_{22}$ does not change even after further 1000 h.

![Figure 6](image.png)

**Figure 6. Histograms of internal stress $\sigma_{22}$ in Al:**
a) to c) for AlSF during 20 MPa → 30 MPa → 20 MPa loading; d) to f) idem for fully disconnected Si-SFs; g) to i) idem for fully interconnected Si-SFs

Figures 6d-f present the histograms of $\sigma_{22}$ in the AlSi-matrix with 0% interconnectivity between Si and SFs. The results are similar to those of the AlSF model with the exception of the Fig. 6d, which presents a more homogeneous distribution.

The histograms for the fully interconnected Si-SFs model are shown in Fig. 6g-i. While the mean stress value (centre of the curve) for all the loading conditions matches the $\sigma_{22}$ of the other geometries, the distribution is always narrower than that corresponding to Fig. 6a-f. When Fig. 6g and Fig. 6i are compared, the distribution shows a displacement from a mean value of 11 MPa in the first step, to 6.9 MPa in the third step. In order to compensate for this decrease in the Al matrix, part of the load is transferred to the rigid phases. For all the steps, regions under higher stress values than the external load $\sigma_A$, show a lower frequency on the fully interconnected Si-SFs model respect to the other geometries, meaning that more Al volume in the AlSF and in the fully disconnected Si-SF model creep at higher rate than when the Si and the reinforcements are interconnected.
6. CONCLUSIONS

Experimental creep results carried out for an AlSi12CuNiMg alloy reinforced with 15 vol.% of Al2O3 SFs showed an increase in creep resistance after time exposure and a temporary increase of the external load. The interconnectivity between eutectic Si and the Al2O3 SFs is increased after several thousand hours of creep exposures (Requena et al., 2008). Creep tests carried out on a composite of a commercially pure Al matrix reinforced with 15 vol.% of Al2O3 SFs showed no substantial difference in stationary creep rate after changing loads. Three simple 3D unit cell models were developed, resembling two Si-SFs interconnectivity conditions of the AlSi-alloy and one Al-SF composite. This approach can be useful to simulate creep behaviour of complex microstructural architectures. The FEM models confirmed the experimentally determined decrease in stationary creep due to an increase in interconnectivity between Si and SFs, as well as the effect of load sequences. Both factors are shown to be important, especially when combined.

After long-term creep exposure, the fully interpenetrating Si-SFs model presented a narrower distribution of stress $\sigma_{22}$ in Al than the other models. The AISF model and the disconnected Si-SFs one presented a similar distribution of stresses $\sigma_{22}$. On both models and for all steps, a significant Al-matrix volume is subjected to higher stresses than the external load and thus creeps at a high rate when compared to the fully interconnected model.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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