18th International Conference Metal Forming 2020

Investigation of anisotropic creep-ageing behaviour of Al-Cu-Li alloy AA2050

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Abstract

Creep age forming (CAF) of an Al-Cu-Li alloy (AA2050-T34) considering its anisotropic creep-ageing behaviour has been experimentally and numerically investigated in this study. A series of uniaxial creep-ageing tests of AA2050-T34 has been carried out in both tension and compression conditions. The creep-ageing results in longitudinal and transverse samples show some anisotropic behaviour in both the room temperature yield strength and the creep strain, in which more strengthening occurs at the intermediate stage and less creep strain is produced in the transverse samples than the longitudinal samples under the same loading condition. It is also found that compressive loading results in much higher anisotropic behaviour than tensile loading. A material model has been adopted for the creep-ageing of AA2050 and shows a good fit to experimental data. Based on the model, a four-point bending virtual test has been developed in PAM-STAMP for simulating the CAF process of AA2050. The results indicate that the anisotropic behaviour contributes an apparent effect on both creep-aged properties and springback of the CAF process and need be considered for CAF manufacture of AA2050 components.

Keywords: Creep age forming; Al-Cu-Li alloy; anisotropy; creep-ageing behaviour; springback; modelling.

1. Introduction

Creep age forming (CAF) is a forming technology typically applied for the aluminium alloy production of large panels [1]. Many researches have been carried out on CAF of conventional aluminium alloys, such as AA7075 [2] and AA7050 [3], and various creep-ageing constitutive material models have been proposed for different aluminium alloys at various temper conditions [4-6] which have been implemented into finite element (FE) solvers for CAF simulations [7, 8].

Al-Li alloys have the unique combination of a lower density, higher strength and very high elastic moduli as compared to conventional ones [9] and are good candidates for CAF. However, these materials suffer from apparent anisotropic behaviour, which limits their potential application [10, 11]. More recently, efforts have been made on reducing anisotropic behavior and the third-generation Al-Li alloys, have been developed. El-Aty et al. [12] summarised the main shortcomings of previous Al-Li alloys (1st and 2nd generations) and the development of the 3rd generation Al-Li alloys which offer superior properties including mechanical properties, fatigue resistance and corrosion resistance, but the anisotropy in tensile properties cannot be ignored. Jata et al. [13] have experimentally shown that anisotropy still exhibits at some level in mechanical properties of Al-Cu-Li alloys, but the anisotropic behaviour in creep-ageing is still unknown. Li et al. [14-16] have investigated and modelled the creep-ageing behaviour of a 3rd generation Al-Li alloy AA2050 with T34 initial temper, building a foundation for its CAF application in industry. However, only the creep-ageing behaviour in longitudinal direction was considered and possible anisotropic behaviour has not been investigated.

In this study the anisotropic creep-ageing behaviour of a 3rd generation Al-Cu-Li alloy, AA2050-T34, has been investigated. The specific anisotropic creep-ageing behaviour has been experimentally characterised by comparing the test
results in the transverse direction with those in the longitudinal direction previously reported in [14]. Based on the experimental data, a unified constitutive material model has been calibrated for the microstructural evolution and creep-ageing behaviour during CAF. Finally, numerical simulations of four-point bending test have been conducted in both the longitudinal and transverse directions to further characterise the effect of anisotropic behaviour on springback of the alloys after CAF.

2. Experiments

AA2050 is the material used in this study with chemical compositions of Al-3.6Cu-0.9Li-0.35Ag-0.34Mg (wt.%). The as-received state is in T34 temper and the 12.7 mm thick hot rolled plate has undergone 1-hour solution heat treatment at 500 °C, water quenching to room temperature, 3.5-4.5% pre-stretching and natural ageing. The geometry and the dimensions of the specimen used for the creep-ageing tests are shown in Fig. 1, which is machined from the plate in the transverse direction.

2.1. Uniaxial creep-ageing and tensile tests

The experimental programme used for the uniaxial creep-ageing tests is shown in Fig. 2. Both tension and compression creep-ageing tests were carried out under constant load conditions on an Instron 5584 machine with an assisting furnace. Three stress levels of 125, 150 and 175 MPa, which are below the yield strength of the AA2050 at the elevated temperature of 155 °C, were selected for the elastically loaded ageing tests. All ageing tests were performed at a temperature of 155±3 oC with a heating rate of 0.05 oC/s, ageing behaviour. Both tension and compression creep-ageing tests were carried out under constant load conditions on an Instron machine at a strain rate of 10-4 s-1 to acquire the yield strength of the CAFed alloys. Different creep-ageing time (0, 2, 5, 12, and 18 h) were used, so as to obtain the yield strength dependency on the creep age time.

2.2. Tensile test

Room temperature tensile tests were performed on the same Instron machine at a strain rate of 10^-4 s^-1 to acquire the yield strength of the as-received and aged materials. The tensile test specimen was machined from the plate in the transverse direction.

3. Materials modelling and FE simulation

3.1. Material model for creep-ageing of AA2050

A constitutive model has been developed to predict the tensile/compressive creep-ageing behaviour of AA2050 alloy in the longitudinal direction [15]. The material is summarised in Fig. 3 and is adjusted and valid for the creep-ageing conditions (155°C) tested in this study. The creep strain rate (ε_cr) is determined by both the applied stress (σ) and the microstructural constituents including the normalised dislocation density (ρ̅), normalised radii of newly nucleated precipitates (ρ̅_n) and dissolving precipitates (ρ̅_d), and normalised solute concentration (c). The normalised dislocation density is defined as ρ̅ = (ρ - ρ₀)/ρ₀ where ρ₀ and ρ are respectively the initial and the saturated dislocation density. At the beginning, ρ = ρ₀ and β₀ = 0. At saturation, ρ = ρ₀ and β = 1. Therefore β varies from 0 to 1. The yield strength (σ_y) of the creep-aged material at room temperature is comprised of three hardening components, including precipitation hardening (both new precipitate and dissolving precipitate), solid solution hardening (σ_ss) and dislocation hardening (σ_dis).

The initial values and materials constants for the transverse direction were determined based on the experimental data, following the same method as in [15] for the longitudinal direction. The initial values of variables for AA2050-T34 in the transverse direction is listed in Table 1. The determined
material constants and the stress direction-dependent constants are listed in Table 2 and Table 3 respectively.

### Table 2. The determined stress direction dependent material constants in the constitutive model for AA2050-T34 in the transverse direction at 155 °C.

<table>
<thead>
<tr>
<th>Material constants</th>
<th>B (MPa)</th>
<th>k1</th>
<th>k2</th>
<th>k3</th>
<th>σ_{th} (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>1.04E-2</td>
<td>0.615</td>
<td>0.615</td>
<td>0.183</td>
<td>15</td>
</tr>
<tr>
<td>Compression</td>
<td>4.0E-3</td>
<td>0.560</td>
<td>0.670</td>
<td>0.185</td>
<td>56</td>
</tr>
</tbody>
</table>

### Table 4. Experiment programme for four-point bending test in PAM-STAMP.

<table>
<thead>
<tr>
<th>Plate dimension (mm)</th>
<th>Test No.</th>
<th>Maximum surface flexural stress (σ_f, MPa)</th>
<th>Constant applied force (N)</th>
<th>Initial loading deflection (d_{0}, mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>220 x 20 x 3</td>
<td>1</td>
<td>75</td>
<td>75</td>
<td>2.08</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>200</td>
<td>200</td>
<td>5.56</td>
</tr>
<tr>
<td>220 x 20 x 5</td>
<td>3</td>
<td>125</td>
<td>347.2</td>
<td>2.08</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>200</td>
<td>555.6</td>
<td>3.33</td>
</tr>
<tr>
<td>220 x 20 x 8</td>
<td>5</td>
<td>200</td>
<td>1422.2</td>
<td>2.08</td>
</tr>
</tbody>
</table>

3.2. FE model for creep age forming process

The determined constitutive model for the transverse direction was then implemented into FE software, PAM-STAMP, for simulating four-point bending test, so as to analyse the effect of anisotropy on springback behaviour by comparing to the same simulation with the constitutive model in the longitudinal direction [17]. Fig. 4 shows the x-y and x-z plane views of the overall appearance of the four-point bending model. Both the loading and supporting heads were modelled with a half-cylinder surface and meshed with rigid shell elements, and the specimen was modelled with four-node quadrilateral shell elements. During the simulation, four steps were performed, including (i) specimen under gravity-only without loading, (ii) loading applied on the specimen by the loading heads, (iii) creep age forming, (iv) unloading and springback of the specimen. All freedoms of the supporting and loading heads were constrained except the y translational freedom of the loading head.

As shown in Table 4, five tests were simulated in both longitudinal and transverse directions. The three major parameters of the tests are the maximum surface flexural stress (σ_f), the applied load (N) and the initial maximum loading deflection at loading heads (d_0). The applied load is a setup parameter of the experiment and the others can be calculated by the theoretical four-point bending equations. After the simulations, the total deflections after springback, d_f (the final formed deflection after unloading and springback) for the specimen were recorded and used to analyse the effect of anisotropic creep-ageing behaviour on springback of AA2050-T34.
4. Results and discussion

4.1. Anisotropy in creep-ageing behaviour

The room temperature yield strength in both longitudinal and transverse specimens of AA2050-T34 under tension and compression conditions after creep-ageing under 150 MPa and pure ageing is shown in Fig. 5. All exhibit very similar strengthening behaviour. The yield strength tends to decrease within the first 2 h of creep-ageing and strengthening occurs after that until reaching the peak state at about 18 h. The biggest difference of yield strength between longitudinal and transverse directions occurs during the intermediate stage (2-15 h) and the maximum value is below 50 MPa (within 10% of the yield strength), which shows that anisotropic behaviour is present in the room temperature yield strength and dependent on creep-ageing time.

Previous investigation of the creep-ageing behaviour of AA2050-T34 at 155°C [14] showed that the behaviour was mainly controlled by the combined dislocation hardening, solute hardening and precipitation hardening. The initial decrease in yield strength is due to dissolution of the pre-existing precipitates formed at natural ageing. This is followed by nucleation and growth of different precipitates, including Guinier-Preston (GP) and Guinier-Preston-Bagaryatsky Zone (GPB) zones, $\theta'$, $T_1$, $S$, $\delta'$ precipitates [18]. After the primary stage, the solute in the matrix tends to be exhausted and forms $T_1 (Al_2CuLi)$ precipitates, which are reported as the main contributor on the variation of the anisotropy of yield strength during ageing [19, 20]. The strengthening contribution of $T_1$ precipitates along the transverse direction was reported about 1.5-2 times higher than that along the longitudinal direction [21, 22]. Thus, the larger increase of the yield strength in the transverse direction than that of the longitudinal direction could be due to this different strengthening contribution during the formation period of $T_1$ precipitate.

The effect of anisotropy is more obvious in compression than in tension, as shown in Fig. 5. The averages of the strength difference between the two directions over 5-12 h are respectively 1.7% and 6.5% under tensile and compressive conditions. The precipitate characteristics, such as their orientations, might be the major factor which are affected by the direction of stress [23]. Previous studies [24, 25] showed that different precipitation orientations are related to the precipitate-matrix misfits of precipitates. The preferred orientation of precipitates in creep-ageing tended to be parallel to the stress direction under tension; while the orientation has the tendency to be perpendicular to the compressive stress direction. This has also been observed in the longitudinally oriented specimens of AA2050-T34 after both tensile and compressive creep-ageing tests [14]. It has been reported that the dislocation movement is strongly hindered by the interfaces of precipitates if they are perpendicular to the loading direction [26, 27]. Therefore, the strengthening contribution of $T_1$ precipitates along transverse direction may be augmented by the increased impediment to dislocation, leading to an increased anisotropy in compression condition. The external stress level also seems to play a role on anisotropy since higher density of $T_1$ precipitates could be formed under a higher stress level to facilitate the heterogeneous distribution of $T_1$ precipitates to reduce the anisotropy [10]. The strength differences between the two directions under tension at 12 h of creep-ageing are 6.3% and 2.5% respectively at 0 MPa and 150 MPa. Similar behaviour appears under compression and the differences are larger than the tension case, with 8.7% and 4.3% for 0 MPa and 150 MPa respectively.

Fig. 5. Room temperature yield strength curves for both longitudinal and transverse specimens of AA2050-T34 after (a) tension and (b) compression creep-ageing tests under indicated loads at 155°C.

Fig. 6 compares the creep-ageing deformation curves in both longitudinal and transverse directions, showing a similar overall appearance for all conditions under stress levels of 150 and 175 MPa and different stress direction. Slight differences in creep strains between the two directions were found during the early period (0-2 h) of creep-ageing, and the difference tended to grow in the intermediate period (2-10 h). After that, the creep strain gradually flattened out
and this behaviour is more obvious in the compressive condition. After a full creep-ageing test of 18 h, creep strain at 150 MPa is 0.069% and 0.063% for the longitudinal and transverse directions, respectively, which shows a difference of 8.7%. The disparity at 175 MPa is approximately 3.8%. On the other hand, the differences are more prominent under compressive conditions, which are 16% and 12.7% respectively at 150 and 175 MPa.

In general, the anisotropy in creep-ageing behaviour is consistent with the overall tendency of the yield strength dependency on the creep-ageing and can be directly relating to the yield strength curves. Since a larger increase happened in the yield strength in the transverse direction at the intermediate stage (5-12 h), the increase of the creep deformation in the transverse direction is slower than that of the longitudinal direction. Anisotropic creep-ageing behaviour is also more obvious in the compressive condition.

4.2. Materials modelling results

Fig. 7 shows the comparison between the modelled creep strain curves and the experimentally measured data for the transverse AA2050-T34 samples respectively under the tension and compression conditions with stress levels of 125, 150 and 175 MPa at 155 °C. In general, the modelling curves fit well with corresponding experimental results for both stress directions, which indicates that the developed material model with the determined material constants is valid to simulate the creep age forming process of AA2050-T34 along the transverse direction at 155 °C and predict both creep-ageing and springback behaviour.

Fig. 6. Creep-ageing deformation curves for both longitudinal and transverse specimens of AA2050-T34 from (a) tension and (b) compression creep-ageing tests under 150 and 175 MPa at 155°C.

4.3. Anisotropy in springback

Fig. 8a compares the simulation results of the total deflections after springback ($\Delta \delta$) along the length of four-point bent specimens of 5 mm plates in longitudinal and transverse directions under an initial loading deflection of 2.08 mm. It shows that the largest deflection occurs at the centre point and the final deflection of the plates after CAF in the transverse direction is generally smaller than that of the longitudinal direction, indicating anisotropic behaviour in springback.

To characterise the anisotropy in springback behaviour, a springback difference ($\Delta \Delta \delta$) is defined as the difference of $\Delta \delta$ at the centre between the longitudinal and transverse directions, normalised by corresponding initial loading.
deflection ($d_1$), i.e., $\Delta S_p = \left( d_{\Delta,\text{longitudinal}} - d_{\Delta,\text{transverse}} \right) / d_1 \times 100\%$. A larger $\Delta S_p$ value indicates larger anisotropy in springback which is the result of different creep-ageing behaviour in the longitudinal and transverse directions. Fig. 8b presents the springback difference ($\Delta S_p$) under different testing conditions listed in Table 4, showing that the anisotropic behaviour in the springback changes with plate thickness under constant initial loading deflection ($d_1$) and constant initial loading stress ($\sigma_f$). It shows that under a constant initial loading deflection of 2.08 mm, the anisotropy in springback gradually increases with increasing plate thickness. The springback differences between longitudinal and transverse directions are 5.2%, 5.6% and 6.4% for 3, 5 and 8 mm plates respectively. The anisotropy in $d_\Delta$ increases with a higher rate with increasing thickness when a constant maximum flexural stress ($\sigma_f$) of 200 MPa is applied, and the values are 2.5%, 4.0% and 6.4% respectively for 3, 5 and 8 mm plates. Moreover, the anisotropy in the springback is reduced by higher maximum flexural surface stresses (larger initial loading deflections) for the same thickness plate, as shown in Fig. 8b for the 3 mm or 5 mm plates.

In creep age forming process, the most frequent practice is using a fixed die surface, i.e., with constant loading deflection. From above, it can be seen that this would lead to 5.2-6.4% springback difference for the initial loading deflection of 2.08 mm. This difference is affected by the stress level (or initial loading deflection) and material thickness. It is well known that springback is less for thicker plates during creep age forming for the same die shape because of higher surface flexural stress for thicker plates [17], which has also been observed in the current simulation results. On the other hand, it has been reported that machining induced residual stress may play an important role in the springback behaviour of thin plate, like the 3 mm plate used in this study, and generally reduce the springback [28]. This, in effect, is an increase in the applied load or initial deflection. Because of the anisotropic behaviour during creep-ageing, all these will affect the springback difference. Thus, it can be concluded that both CAF processing conditions and the initial state of the material affect the anisotropy in the springback. The springback difference is up to 6.4% in the conditions studied, indicating that the anisotropic behaviour needs to be considered when manufacturing AA2050 components with CAF process.

5. Conclusions

The anisotropic behaviour in creep-ageing and springback of a 3rd generation Al-Li alloy, AA2050-T34, has been experimentally and numerically investigated in this study. The following conclusions can be drawn:

- Anisotropy exists in both the yield strength and the creep deformation during creep-ageing of AA2050-T34, presumably due to various strengthening contribution of T1 precipitates with different directions.

- Compressive stress contributes slightly more effect to anisotropy than tensile stress since the precipitates tend to be perpendicular to compressive loading direction while parallel with tensile loading direction.

- Specimen thickness influences the anisotropy of creep-ageing behavior. The springback difference between longitudinal and transverse directions increases with plate thickness, from 5.2% for 3 mm plate to 6.4% for 8 mm plate under initial load deflection of 2.08 mm.

- The stress level plays a role in the anisotropic behaviour probably by facilitating the heterogeneous distribution of T1 precipitates during creep-ageing. Consequently, higher loading stress results in a reduction of springback difference. For 3 mm plate, the springback difference is reduced to 2.5% under constant stress of 200 MPa.

Acknowledgements

The authors would like to thank ESI group (France) for financial support and Embraer (Brazil) for the provision of test material.

References


