Proceedings of the 9th International Conference on Aluminium Alloys (2004) 132
Edited by J.F. Nie, A.J. Morton and B.C. Muddle

A Comparison of the Stress Relaxation Behaviour of Three Aluminium Aerospace Alloys for use in Age-Forming Applications

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Keywords: Creep, Ageforming, Stress Relaxation, 2xxx, 7475, 6056

Abstract

To date little work has been published on the stress relaxation behaviour of Al-alloys used in the age-forming of aerospace structures. This paper compares the stress relaxation behaviour of three candidate alloys, being considered for damage tolerant applications manufactured by the age-forming technique; 7475, 6056 and a new 2xxx series alloy, 2XU [1]. The effect of forming temperature and initial stress has been investigated for each alloy, on aging to a damage tolerant temper. Of the alloys studied, 2XU exhibited the greatest level of relaxation. The activation energies for creep relaxation were found to be comparable with self diffusion of Al. A similar level of stress relaxation was found to occur when using a higher temperature and shorter equivalent aging time.

1. Introduction

Age-forming (also known as creep forming or creep-ageforming) has been successfully used to produce aircraft upper wing skins for a number of years [2-4]. Recently, many of the airframe manufacturers have become interested in extending age-forming to components that require more damage tolerant properties. However, such components are traditionally manufactured in 2xxx series alloys, like 2024, using a naturally aged T351 temper. In age-forming a component is loaded onto a forming tool by vacuum bagging or mechanical clamping and is then given an artificial ageing heat-treatment [5]. During this thermal-cycle, the stresses are partly relaxed by creep and some permanent deformation occurs. The remaining elastic stresses are exhibited as “spring back” when the component is released from the tooling [4,6]. To extend the process to damage tolerant components, therefore, requires an alternative alloy/temper combination where the target properties can be obtained with an artificial ageing temper. In order to obtain a component that is accurately formed, the material used should exhibit a predictable behaviour in conforming to the shape of the tool and as little spring back as possible. The rate of stress relaxation and the amount of permanent strain that is achieved are thus key parameters that need to be known in order to predict the required tool shape. While the behaviour of non-heat treatable alloys has been extensively studied under constant load conditions, and can be predicted by established creep laws (e.g. [7-9]), to date little data has been published on the creep relaxation behaviour of high strength Al-alloys suitable for age-forming applications. The age-forming behaviour of airframe alloys is also more complex, in that the material properties change continuously during the age-forming process. For example, the creep rate will slow down if the material strengthens due to precipitation hardening, but may actually increase again if the material is over-aged to achieve a damage tolerant temper [10].

Thus, the creep relaxation behaviour in age-hardenable alloys cannot be easily predicted. However, the use of a range of temperatures and initial stresses should enable an overview to be obtained of the alloys' relative formability under creep relaxation conditions and the determination of the activation energies of the dominant stress relaxation mechanisms.

2. Experimental

The tests in this study were made on material supplied in the form of commercially produced rolled plate (2XU and 7475) or 5mm sheet (6056) in a solution heat-treated and stretched condition (~2-3%). Samples were machined from the 1/4 and 3/4 thickness positions for the plate and from the mid plane of the sheet material. Constant strain, stress relaxation, and constant load creep tests were performed inside a temperature controlled chamber. Temperature control was better than ±0.5°C and the strain was measured and controlled with a non-contact optical video extensometer, over a 25 mm gauge length. Relaxation and creep tests were performed for the 2XU and 7475 alloys using round tensile specimens with an 8mm diameter gauge section with a narrow machined flat to facilitate strain measurement with the video extensometer. For the 6056 alloy, tests were performed on flat tensile specimens with a 2 x 10mm gauge cross section. A reference heat treatment was selected for each alloy as a baseline for all the tests, which gave the target damage tolerant properties (Table 1). Each test was started immediately after the test piece had reached the final isothermal stage of the ageing cycle, i.e. after the heating ramp and any lower temperature 1^{st} stage treatment, as age-forming is conventionally carried out with the material in a similar pre-temper condition [3].

Table 1: Reference heat treatments and temper designation for each alloy.

Alloy	Temper	Heating Rate	1^{st} Stage	2^{nd} Stage
2XU	T851	75°C/hr	-	24h@173°C
6056	T7851	75°C/hr	175°C	13h@190°C [11]
7475	T7351	75°C/hr	108°C	24h@160°C

For each alloy, stress relaxation tests were performed over a range of final stage ageing temperatures and initial stress levels up to 90% of the tensile proof stress at temperature. Because there is interest in reducing the age-forming cycle time, the relaxation tests were conducted for the equivalent ageing time, as a function of temperature. This was calculated at each temperature, using well established experimental data (e.g. [12]), by integrating over the whole thermal cycle, including the heating ramp, using the following relationship, where t_f is the heat treatment time.

$$t_{eq}(T_2) = \int_0^{t_f} \frac{\exp(-Q/RT_1)}{\exp(-Q/RT_2)}.dt \qquad (1)$$

3. Results and Discussion

3.1 Effect of Temperature

Figure 1 shows the effect of temperature on the rate of stress relaxation for each of the alloys, starting from an initial stress of 70% of yield (at temperature).

In all cases the expected result was observed, in that the relaxation rate increased with ageing temperature. The relaxation rate is very high at the start of the test and gradually reduces as the test continues, in most cases exhibiting a classical logarithmic decay.

The exception to this behaviour are the lower temperature tests for the 2XU alloy (Figure 1a), which show a clear inflexion in the curve up to a test temperature of 185°C. Above 185°C, this inflexion is no longer apparent, although it may become masked by the higher relaxation rate. This inflexion is a manifestation of the complex nature of the combined effects of stress, thermally activated creep, and the microstructural changes that occur in the alloy due to ageing. As the recommended temper for the 2XU alloy is a single stage treatment, this alloy rapidly age-hardens during the first stages of the test from a naturally aged condition. In comparison, the other two alloys are nearer their peak hardness when the relaxation tests begin, since they have already undergone a 1st stage heat treatment, and their yield stresses changes less during the test.

In 2XU this inflexion therefore occurs because relaxation initially slows down, due to precipitation hardening causing the alloy to become more resistant to creep, and the curve then regains its more familiar form at longer times once the ageing kinetics approach the plateau of the peak hardness region in the ageing curve. The microstructure development in the 2XU alloy also exhibits strong interactions with the ageforming processes, which is discussed in a companion paper [13] and further below.

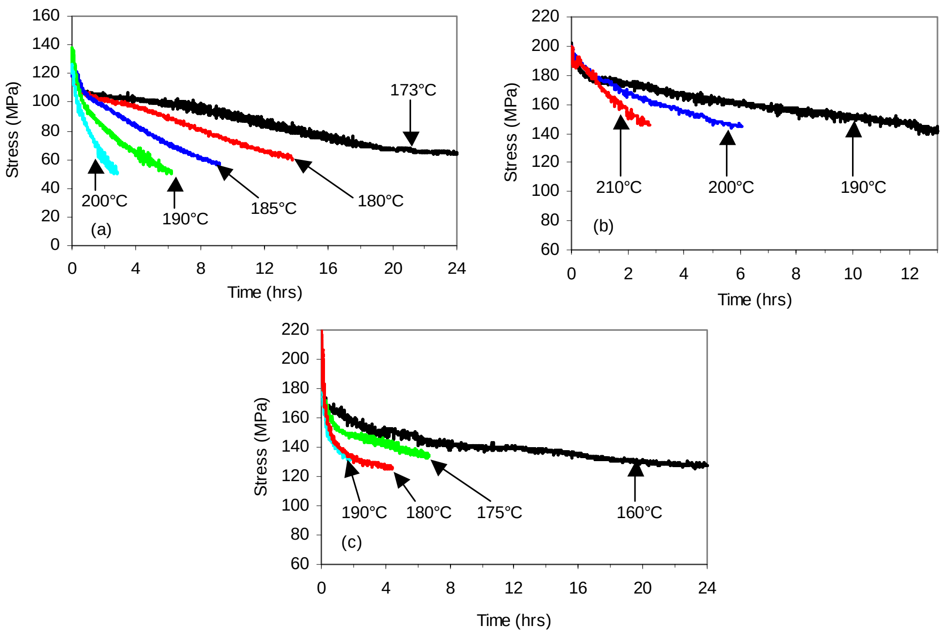

Figure 1: Effect of temperature on stress relaxation to the same equivalent ageing time, with an initial stress level of ~ 70%σ_y, (a) 2XU, $\sigma_{(\tau=0)}$ = 127 MPa, (b) 6056, $\sigma_{(\tau=0)}$ = 199.5 MPa, and (c) 7475, $\sigma_{(\tau=0)}$ = 197 MPa.

Table 2: Activation energies for stress relaxation

Alloy	Activation Energy
2XU	170 kJ mol^{-1}
6056	139 kJ mol^{-1}
7475	134 kJ mol^{-1}

Similar work on binary Al-4%Cu single crystals, aged to T6 using an equivalent ageing time, has reported that the plastic creep strain ~ doubled when the temperature was increased by 60°C [14], suggesting that creep relaxation has a different kinetic dependence to the ageing response. In terms of age-forming, this would result in less springback when components are age-formed at higher temperatures. However, these experiments were carried out under a constant compressive load. It must also be remembered that equivalent ageing times do not imply an identical microstructure, and the strengthening phases generally coarsen with increasing aging temperature even if an 'equivalent' time is used [15]. This will ultimately lead to a loss of creep resistance if the temperature rise is large enough to cause substantial microstructural coarsening. In comparison, the creep relaxation results for 6056 and 7475 (Figure 1b & c), do not shown a significant difference in the amount of relaxation that occurs when aging is carried out for the same equivalent times at higher temperatures, although there is a small increase of ~20 MPa for 2XU (Figure 1a) which is equivalent to a ~10% reduction in spring back.

This implies that the thermal activation for creep-relaxation is similar to that for the ageing kinetics, and the material's creep resistance are not substantially affected by microstructural changes, within the ageing temperature range investigated, except for the 2XU alloy.

3.2 Activation energies

From the stress relaxation data at different temperatures, values for the creep relaxation activation energy have been calculated from plotting ln(t) vs 1/T, for the time to relax to 50% (2XU) or 70% (6056,7475) of the initial stress [16] (shown in Figure 2). With the exception of 2XU, which is slightly higher (170 kJmol^{-1}), the calculated values for the creep relaxation activation energy are very similar to that for self-diffusion in aluminium, which is generally taken as 142 kJmol^{-1} [17].

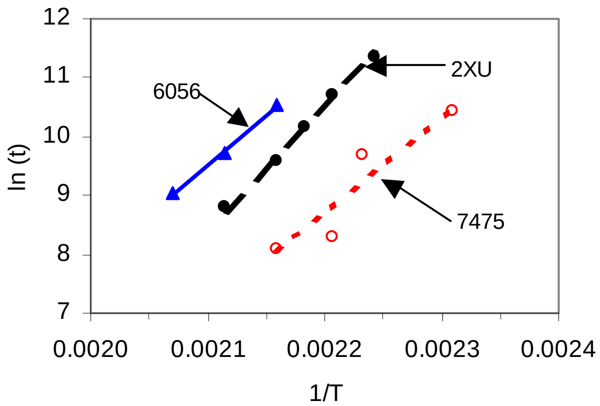

Figure 2: Activation energies for creep relaxation of the three alloys, from the time to reach 50% relaxation (2XU) or 70% relaxation (6056, 7475).

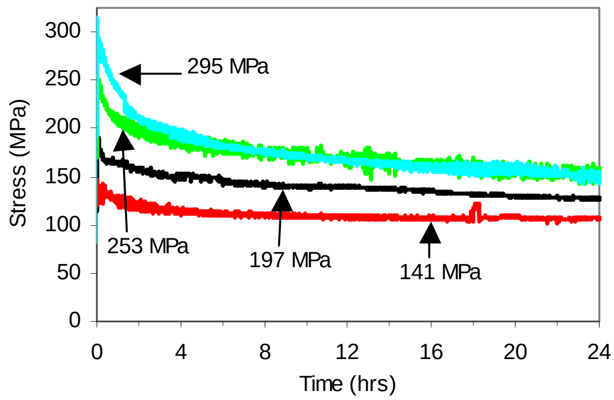

Figure 3: Example of the effect of initial stress level on the creep-relaxation behaviour of 7475, during age-forming using a 2nd stage temperature of 160°C.

3.3 Effect of Initial Stress Level

An example of the effect of the initial stress level on the creep relaxation behaviour is shown in Figure3 for the 7475 alloy, which is the strongest of the alloys tested. As the initial starting stress is decreased, the amount of relaxation that is achieved (at the same temperature) is reduced. This on its own is not surprising as during dislocation creep the creep rate is extremely sensitive to stress.

However, the time period of the test is fixed by the ageing treatment and ultimately the curves would all be expected to relax to the same level.

In the example shown, it can be seen that the test sample with the lowest initial stress level appears to relax to a minimum level of ~ 105 MPa with which, given sufficient additional time, the other curves should converge. In age-forming there, therefore, appears to be a minimum stress level, or a material and temperature dependent relaxation limit, below which only very minor permanent shape changes can be obtained, which in this case is ~ 30% of σ_{y}.

3.4 Constant load creep tests

The steady-state / minimum creep rate was determined for the alloys studied using constant load tests with the reference ageing treatment (table 1). This data is plotted logarithmically in Figure 4 as a function of the stress level to obtain the creep rate stress exponent, n [17]. Although ideally more data should be obtained, the 7475 and 6056 alloys follow the classically expected behaviour [9]. A transition can be seen from n ≈ 1 at low stresses, indicating diffusional creep, or viscous flow, to n ≈ 5-8 at high stresses, which is indicative of power law, or dislocation creep [9,18]. The creep exponents obtained from Figure 4 are shown in Table 3 in the high and low stress ranges. Interestingly, the 2XU alloy, which exhibits the greatest microstructural changes during heat treatment, appears to show a negative creep stress exponent. For this alloy, the stress range investigated was more restricted due to its lower initial yield stress.

Microstructural investigation of this alloy has also shown that the precipitation of the principal hardening phases θ′′, θ′ and Ω is altered when ageing under an applied stress, which results in these plate-shaped precipitates forming preferentially on habit plane variants parallel with the tensile stress axis [13]. For the dominant phase, θ′, the degree of alignment increases rapidly, but saturates above ~150 MPa. The influence of this effect on the creep behaviour has not yet been determined.

Table 5: Creep exponent for each alloy at high and low stresses.

	Creep exponent (n)		
Alloy	Low σ	High σ	Average
7475	1.3	6.4	4.1
6056	1.3	8.7	5.2
2XU	-	-	- 3.0

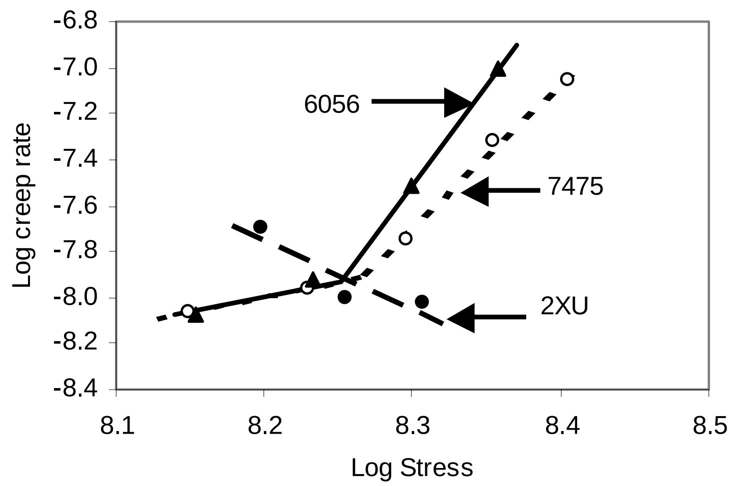

Figure 4: Steady-state / minimum creep rate as a function of stress level for the three alloys, 2XU aged at 173°C; 6056 at 190°C, 7475 at 160°C as in Table 1.

3.5 Comparison between the alloys

A comparison of the relaxation behaviour of the three alloys, for the same initial stress level of ~ 200 MPa, is shown in Figure 5 and in Table 3 the final percentage relaxation is given for each alloy at the end of its reference heat treatment. Direct comparison is difficult because of the different tempers used for each material to obtain the desired property balance. Overall, of the three alloys investigated, the 2XU alloy, in the recommended T851 condition, relaxes the most and 6056 T7851 the least. The greater relaxation exhibited by 2XU is probably related to it having the lowest yield strength and being the most dilute of the alloys investigated. Furthermore, for this alloy, relaxation testing and age–forming is carried out without a pre-temper. The 2XU alloy also has the lowest magnesium content at ~0.2% (by weight), as compared to ~0.7% for 6056 and ~2.2% for 7475. Magnesium is known to give solid solution strengthening in aluminium alloys and strongly interacts with dislocation glide and cross slip.

Table 3: Amount of relaxation achieved for the reference heat treatment (Table 1) for each alloy relaxed from 200 MPa.

Alloy	Initial Stress	Final Stress	Relaxation
2XU	202.5 MPa	105.5 MPa	47%
6056	199.5 MPa	142 MPa	29%
7475	200 MPa	123 MPa	38%

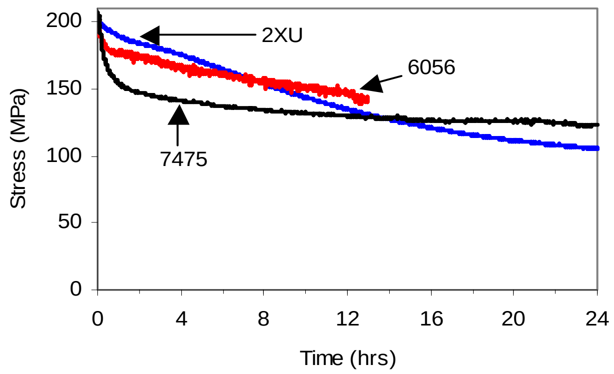

Figure 5: Comparison of the three alloys relaxation behaviours, 2XU aged at 173°C; 6056 at 190°C, 7475 at 160°C, all with the same initial starting stress of ~ 200 MPa.

More surprisingly the strongest alloy, 7475, shows a greater degree of relaxation than 6056, despite a slightly lower ageing temperature. This greater level of relaxation occurs due to a very rapid relaxation rate during the early stages of ageing, on reaching the second isothermal temperature step, which slows down dramatically after the first two hours. The reason for this behaviour has not yet been determined, but maybe related to the reversion and the dissolution of Guinier-Preston Zones as ′ starts to form during ramping to the second stage ageing temperature.

4. Conclusions

The creep-relaxation behaviour has been compared for three alloys that have potential for age-forming aerospace components requiring damage tolerant properties. Of the three alloys studied, the 2XU alloy has the greatest capacity for stress relaxation, followed by 7475, and 6056 the least, when aged to a damage tolerant temper. Each alloy showed similar levels of relaxation to that for the reference ageing treatment, when tested at higher temperatures to the same equivalent time ageing. For a given temperature, there also appears to be a threshold stress, below which very little relaxation will take place. The activation energies for creep relaxation where in the range 130 to 170 kJ mol^{-1}. Measurements of the stress exponent suggest that the creep mechanism changes from diffusion controlled or viscous flow, at low stresses, to dislocation creep at higher stresses. For 2XU an inflexion in the relaxation curve was observed due to a rapid increase in creep resistance, caused by precipitation hardening. The creep stress exponent obtained for 2XU also showed a non-conventional behaviour, but this needs to be confirmed using a wider range of stress levels.

Acknowledgements

This research was carried out under project reference G4RD-CT-2002-00743 “Ageformable panels for commercial aircraft” in the European Commission’s fourth framework programme for competitive and sustainable growth.

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