FRACTURE TOUGHNESS OF HIGH STRENGTH AA 2090 THIN SHEET

R. Doglione, F. Arena, D. Firrao

Dipartimento di Scienza dei Materiali e Ingegneria Chimica, Politecnico di Torino - C.so Duca degli Abruzzi, 24 - 10129 Torino, Italy

ABSTRACT

To identify an univocal critical fracture parameter for AA 2090-T82 and T62 thin sheet fracture mechanics tests were performed and showed random and frequent pop-ins which render not well reproducible the R-curves of this material to be used for design. Moreover a catastrophic failure always occurs, even performing tests under COD control configuration. Therefore, R-curve analyses and Feeddersen-type approach were successfully attempted so that it has been possible to single out, with an excellent reproducibility and satisfactory conservativity margin, a critical fracture parameter in correspondence of the first significant pop-in.

INTRODUCTION

For a long time, Aluminium-Lithium alloys have been in many cases considered as possible substrates for current aerospace alloys such as AA 2024-15 or 18, AA 7075-T6 and AA 7475-T7. Although Al-Li alloys have been commercially successful in the last years, their potentiality was not fully exploited owing to an often singular fracture behaviour. Even if excellent fracture toughness levels are often achieved, the application of specific standards has often met with difficulties. In fact in this material, owing to its particular microstructure, there are phenomena (delaminations [1], fatigue crack ramifications [2], pop-ins under quasi-static load [3]) which are much more frequent than in traditional aluminium alloys. Thus, the evaluation of suitable and reliable parameters for design have been so difficult that aeronautic constructors consider Al-Li alloys somehow unreliable. In the special case of high strength thin sheet, one of the most important characterizing datum is the R-curve. The mentioned problems and the complicated experimental procedure to R-curves determination have limited researches in this field, with very few reported data in literature [4-12]. In this respect, the case of Al-Li 2090 high strength thin sheet is very representative: pop-in occurrence and strain rate sensitivity of the fracture mechanisms have been reported [4-9].

In this work the problem of high strength AA 2090 (that is in T8 and T6 conditions) thin sheet fracture toughness is faced. Till now, only the AA 2090 R-curve or his comparison with classical aluminium alloys has been published [5, 7, 8], but there is a complete lacking of the use of R-curve to predict the instability conditions of components in different loading configurations or to single out a critical fracture parameter for design. From a theoretical point of view it's not difficult to discuss the stability of fracture according to the driving force and to enucleate a critical value of toughness if it exists: in
fact the Griffith’s and Irwin’s classical energetic approach can be used. Instead it’s very
difficult to evaluate an univocal and reliable solution of this problem when the pop-in
phenomenon occurs. Thus the analyse of this critical condition was made comparing the
results reached by two classical approaches: the Feddersen construction and the R-curve.

EXPERIMENTAL

AA 2090-T82 was received by Alcoa in the form of 1.6 mm thick sheet. Then part of the
lot was subjected to a complete T62 heat treatment. Plate specimens for tension tests and
M(T) specimens for fracture mechanics tests, according to ASTM E 561-92a standard,
were fabricated. Tension tests were performed in both L and LT directions under strain
control at strain rates of $10^{-4}$ and $2.10^{-3}$ s$^{-1}$. The average results are reported in Table 1. A
small anisotropy in L and LT directions is evident.

The M(T) specimens, taken in LT and TL fracture directions, were W=100 mm wide
and the initial fatigue crack length ($2a_0$) was always kept inside the 0.3$\leq 2a_0$/W$\leq 0.4$
range, according to the cited standard. The fracture toughness tests to determine the
Feddersen construction and R-curves were performed under crack opening displacement
control by a 250 kN MTS system. This provides a decreasing crack growth driving
force, which allows to follow a ductile fracture process entirely, thus limiting the
possibility of global instability arising. The single specimen method was used. For the
physical crack length determination the compliance method was employed, performing
partial unloading during the tests, and the effective crack length evaluation was made by
the secant reciprocal slope technique. The microstructure was analyzed on
metallographic samples for both treatments by optical microscopy and finally the failure
mechanisms were studied on the fracture surfaces by SEM microfractographic
observations.

RESULTS

Metallographic analyses indicate for both tempers a fine recrystallized grain structure.
The T82 temper is characterized by an equiaxed grain (approximately close to unit), with
a 5-10 $\mu$m average grain diameter, whereas the T83 temper yields slightly elongated
grains (aspect ratio in the 1.5 range) again with 5-10 $\mu$m average diameter, measured
on the direction perpendicular to rolling. The rolling direction is also noticeable since it
yields alignment along the grain boundaries of Al, Cu, Li, Fe, Si intermetallic
compounds. In conclusion, both lots of this material have a rather similar microstructure.

The P-COD diagrams obtained during fracture mechanics tests show a variable number of
pop-ins with different extensions not related to the tempers or fracture directions. The
material has a globally stable behaviour only at the beginning of crack growth; after the
first pop-ins localized phenomena of unstable crack propagation occur. Although the
fracture tests were performed under crack opening displacement control, it has been
impossible to control the fracture process after a certain load level. Moreover, a
noticeable variability was found in the location of failure point on the P-COD diagrams;
sometimes it happened quite before achieving horizontal tangency, sometimes near it and
occasionally beyond the maximum load, usually following a large pop-in. Most R-curves
show a flat plateau at high load level, thus reaching approximately a toughness plateau
(Figure 1 and 2). In some cases, especially for T62 temper and TL direction, this
plateau hasn’t been reached clearly (Figure 2); a premature failure occurring, or it was
reached and followed immediately by a catastrophic crack propagation. This
unpredictable fracture behaviour renders impossible to emulate an univocal critical
parameter to use for design unless to accept large conservativity in the values.

Table 1 - Tensile characteristics of the AA 2090-T83 and T62.

<table>
<thead>
<tr>
<th>ALLOY</th>
<th>E  [MPa]</th>
<th>$\sigma_{YS}$ [MPa]</th>
<th>$\sigma_{UT}$ [MPa]</th>
<th>e  [%]</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>2090-T83</td>
<td>77700</td>
<td>530</td>
<td>559</td>
<td>7</td>
<td>0.030</td>
</tr>
<tr>
<td>2090-T83</td>
<td>78500</td>
<td>506</td>
<td>537</td>
<td>10</td>
<td>0.031</td>
</tr>
<tr>
<td>2090-T62</td>
<td>78300</td>
<td>467</td>
<td>522</td>
<td>4</td>
<td>0.059</td>
</tr>
<tr>
<td>2090-T62</td>
<td>78000</td>
<td>416</td>
<td>477</td>
<td>7</td>
<td>0.061</td>
</tr>
</tbody>
</table>

DISCUSSION

In order to evaluate the material fracture behaviour in service two main load
configurations are usually taken as reference: load control and displacement control. The
first gives in any case the fracture instability before reaching the toughness plateau,
the second always assures a reliable crack propagation unless a fracture mechanism change
occurs. To check the situation for AA 2090 thin sheet, the R-curves were compared with
the two typical driving force configurations, the displacement control being assured by
the COD control on the sample centre line. As known, under load control the driving
force curves increase in the K-$\Delta$a plane, whereas under displacement control they
decrease. A typical representation of driving forces is reported in Figure 3. It’s obvious
that near the toughness plateau the load control can’t avoid a catastrophic fracture. From
the same figure, it’s apparent that in this configuration the first pop-ins will not lead to a
global instability: this statement may be non-conservative since under load control kinetic
effects may trigger a catastrophic failure more easily than under COD control. Moreover,
the final instability point reached by the COD control may not be valid as the critical
point in load control, where failure may occur before. The conclusion is that in load
control it isn’t possible to single out a reproducible and reliable critical point. Another
usual point is that by the COD control the final instability is unavoidable. This
phenomenon was explained recently [9, 11] by a change of fracture morphology owing
to a progressive acceleration of crack propagation, switching from ductile intergranular
fracture to brittle intergranular.

Taking into proper consideration the variability and shape of these R-curves and the
previous phenomenology causing catastrophic failure, K values at the toughness
plateau (K$_c$) and K values at crack propagation instability (K$_f$) were evaluated as
critical fracture parameters. The average results are reported in Table 2. According to
Figure 1 - R-curves for AA 2090-T83 tested in the TL and LT directions.

Figure 2 - R-curves for AA 2090-T62 tested in the TL and LT directions.

Figure 3 - Typical driving force curves for the two test configurations (load control and COD control) superimposed to an AA 2090-T83 R-curve in the TL direction.

Pop-in may occur or may not occur early enough to trigger a catastrophic failure. Because of the accidental and not foreseeable nature of pop-ins, the choice of $K_p$ values for design doesn’t assure conservativity and may over-estimate fracture toughness when such an event doesn’t occur near the plateau. Thus, it may be proposed to consider the $K_p$ values: their scatter decreases but it isn’t completely satisfactory since in several cases the full plateau is not reached.

Table 2 - Fracture parameters evaluated with reference to the physical crack length for AA 2090-T83 and T62.

<table>
<thead>
<tr>
<th>ALLOY</th>
<th>$K_0$ [MPa√m]</th>
<th>$K_p$ [MPa√m]</th>
<th>$K_{max}$ [MPa√m]</th>
<th>$K_{pop-in}$ [MPa√m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2090-T83 LT</td>
<td>41.3 ± 2</td>
<td>43.5 ± 1</td>
<td>25.8 ± 2</td>
<td>39.3 ± 2</td>
</tr>
<tr>
<td>2090-T83 TL</td>
<td>34.9 ± 3</td>
<td>40.8 ± 14</td>
<td>26.4 ± 1</td>
<td>32.7 ± 3</td>
</tr>
<tr>
<td>2090-T62 LT</td>
<td>43.6 ± 3</td>
<td>46.3 ± 5</td>
<td>30.0 ± 1</td>
<td>41.7 ± 2</td>
</tr>
<tr>
<td>2090-T62 TL</td>
<td>45.8 ± 7</td>
<td>49.4 ± 7</td>
<td>28.7 ± 1</td>
<td>47.6 ± 2</td>
</tr>
</tbody>
</table>

In order to get over the problem of uncertainty and scatter of $K$ values at plateau or at catastrophic point, a Feddersen-type approach has been employed [13]. A typical example of onset of crack propagation ($K_p$), where the curves go out of verticality; the first this application is reported in Figure 4. Three events have been evaluated: the
Figure 4 - Feddersen-type approach for an AA 2090-T83 specimen, tested in the TL direction.

(K). The previous considerations about R-curves K values hold also here. Instead the $K_{\text{pop-in}}$ levels have a good reproducibility. They are aper than $K_c$ and $K_{\text{pop-in}}$ to be used for design because they are a good evaluation of fracture toughness and assure a reasonable conservativity margin. Finally the $K_c$ values are the most reproducible and can have the best use when structures need higher safety levels.

CONCLUSIONS

The study of fracture behaviour of AA 2090-T83 and T62 thin sheet has showed the presence of pop-ins. The variability and randomness of this event does not assure a good reproducibility of the R-curves and lead always to catastrophic failure not related to test configurations. The resulting uncertainty made difficult to identify reliable critical values of toughness by an energy balance (i.e. equilibrium between R-curve and driving force).

In spite of this fact, the opportunity to choice K levels on the first significant pop-in was displayed by an engineering approach, leading to fracture toughness values reproducible and suitable for design.

REFERENCES