FRACTURE TOUGHNESS OF HIGH STRENGTH AA 2090 THIN SHEET

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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 Feddersen-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 correspondance of the first significant pop-in.

INTRODUCTION

For a long time, Aluminium-Lithium alloys have been in many cases considered as possible substitutes for current aerospace alloys such as AA 2024-T3 or T8, AA 7075-T6 and AA 7475-T7. Although Al-Li alloys have been commercially successfull 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 mentionned 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 publicated [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 approachs: 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 $2 \cdot 10^{-5}\ s^{-1}$. 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 $W \cong 100$ 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 T62 treatment is characterized by an equiaxed grain (*aspect ratio* close to unit), with a 5-10 µm average grain diameter, whereas the T83 temper yields slightly elongated grains (*aspect ratio* in the 1÷1.5 range) again with 5-10 µm 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 several 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 enucleate 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.

ALLOY	E [MPa]	σ_{YS} [MPa]	σ_{TS} [MPa]	e [%]	n
2090-T83 L	77700	530	559	7	0.030
2090-T83 LT	78500	506	537	10	0.031
2090-T62 L	78300	467	522	4	0.059
2090-T62 LT	78000	416	477	7	0.061

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 stable 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-Δa 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 unusual 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_∞) and K values at crack propagation instability (K_c) were evaluated as critical fracture parameters. The average results are reported in Table 2. According to

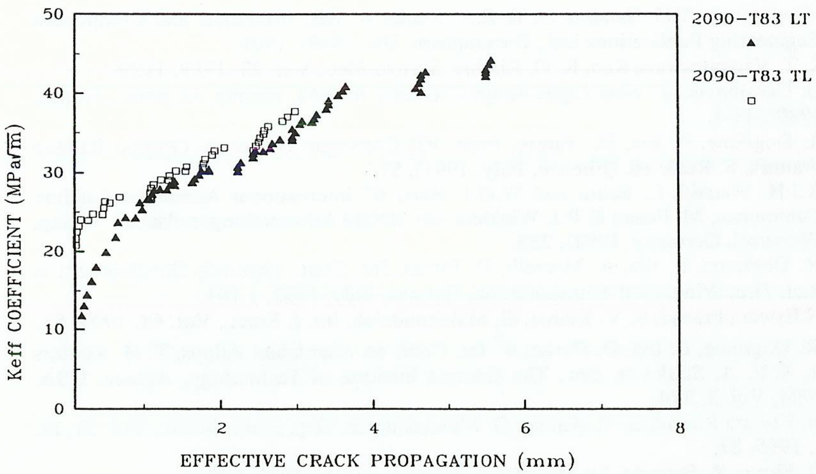

Figure 1 - R-curves for AA 2090-T83 tested in the TL and LT directions.

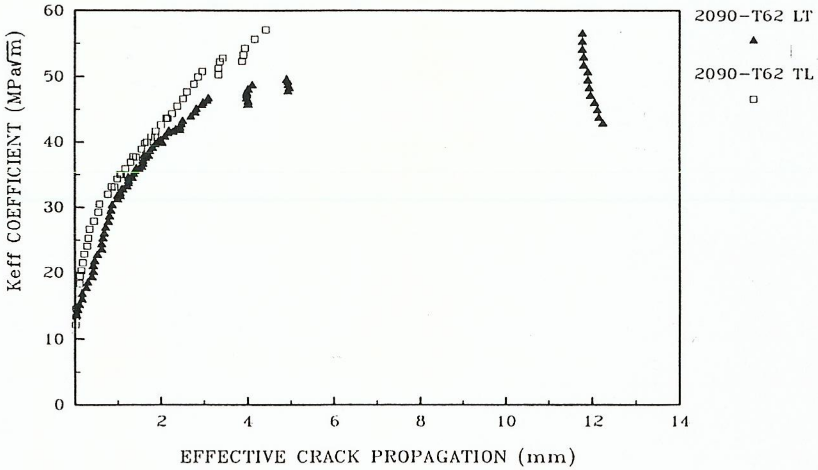

Figure 2 - R-curves for AA 2090-T62 tested in the TL and LT directions.

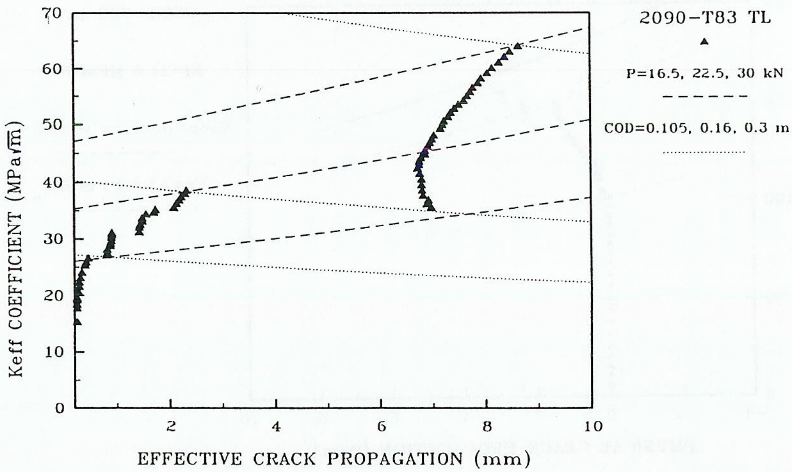

Figure 3 - Typical driving force curves for the two test configurations (load control and COD control) superimposed to an AA 2090-T83 R-curve in the TL direction.

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_c 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_∞ 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.

ALLOY	K_∞ [MPa√m]	K_c [MPa√m]	K_i [MPa√m]	K_{pop-in} [MPa√m]
2090-T83 LT	41.3 ± 2	43.5 ± 1	25.8 ± 2	39.3 ± 2
2090-T83 TL	34.9 ± 3	40.8 ± 14	26.4 ± 1	32.7 ± 3
2090-T62 LT	43.6 ± 3	46.3 ± 5	30.0 ± 1	41.7 ± 2
2090-T62 TL	45.8 ± 7	49.4 ± 7	28.7 ± 1	47.6 ± 2

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_i), where the curves go out of verticality; the first this application is reported in Figure 4. Three events have been evaluated: the

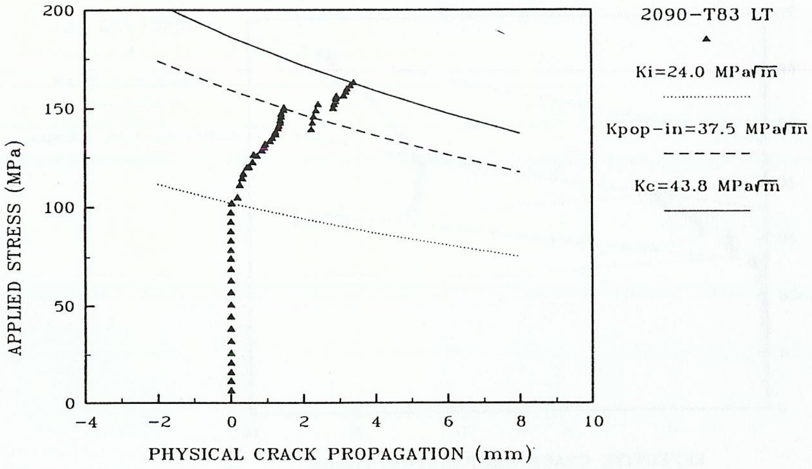

Figure 4 - Feddersen-type approach for an AA 2090-T83 specimen, tested in the TL direction.

(K_c). The previous considerations about R-curves K_c values hold also here. Instead the K_{pop-in} levels have a good reproducibility. They are apter than K_c and K_∞ to be used for design because they are a good evaluation of fracture toughness and assure a reasonable conservativity margin. Finally the K_i 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.

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