ON THE APPLICABILITY OF J_{Ic} STANDARDS TO THE POP-IN BEHAVIOUR OF AN Al-Li 8090-T8 ALLOY

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Fracture toughness (J_{Ic}) tests were performed on AA 8090-T8 peak-aged Al-Li alloy with difficulties arising on the identification of the critical event on the J-R curve which exhibits a great number of pop-ins followed by reblunting. The application of existing Standards leads to very conservative J_{Ic} values, whose reproducibility is low. However, fractographic analyses have allowed to explain the pop-in phenomena by the formation of multiple local delaminations inside the specimen and to single out the end of the first significant reblunting stage as the reference point for J_{Ic} evaluation.

INTRODUCTION

Al-Li alloys have been developed to increase stiffness and reduce weight in aircraft structures as compared to traditional Al alloys. Thus AA 2090, 2091, 8090 and 8091 alloys have been commercially produced in recent years.

Fracture toughness (K_{Ic}) of these alloys has been widely investigated with results showing a certain degree of scatter depending on the different microstructures induced by varying thermal or thermo-mechanical treatments. Moreover, commercial thickness ranges often impede valid K_{Ic} determinations so that test results may pose questions on the applicability

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of the ASTM E 399 Standard . Therefore, the J_{Ic} tests up to now were performed mainly to the purpose of indirect K_{Ic} evaluation, e.g. Suresh et al (1). As a consequence, in-depth analyses of J-R curves features are almost non-existent.

The 8090 alloy in the T8 condition is one of the most promising for aircraft applications and its use is foreseen in view of its adequate strength coupled to a satisfactory damage tolerance. Quite recently, a series of published works has investigated the correlation among microstructure, testing temperature and fracture toughness, K_{Ic} (2-8). It was shown that the fracture behaviour is controlled by delaminations appearing at high angle grain boundaries. The validation of fracture toughness values according to the requirements for plane strain tests is therefore, at a time, adventurous. In fact, it was found by Venkateswara Rao et al (5), mainly for the 2090 alloy, and then confirmed by Doglione et al (2) for the 8090-T8 alloy, that K_{Ic} values do not follow the thickness dependence foreseeable in the case of a material behaving as a continuous body and seem to identify an horizontal plateau beginning at thickness values much smaller than those accountable on the basis of ASTM E 399 Standard. The scatter is however remarkable, with unpredictable dispersions as large as 30%. Moreover, Doglione et al (2) observed an evident pop-in behaviour, which gives rise to doubts about the very significance and engineering relevance of the stress intensity factors that can be determined.

Trial experiments have shown that analogous difficulties could arise during J_{Ic} tests. Within a large research program on the effect of Li additions to Al alloys, Firrao et al (9), a thorough study of physical events occurring during fracture nucleation and early stage propagation under quasi-static loads has been therefore undertaken to the purpose of recognizing, on a real physical base, an engineering meaningful crack initiation event.

MICROSTRUCTURE AND FRACTURE OF 8090-T8 ALLOY

The 8090-T8 is a peak-aged Al-Li alloy; the thermomechanical heat treatment consists of: solubilization for 2 hours at 535°C, water quenching, 3% stretch, ageing for 16 hours at 190°C. The alloy shows a highly anisotropic unrecrystallized grain structure, with pancake-shaped grains elongated in the rolling direction; crystals are coarse, about 1 or 2 mm long, 350 μm wide and 40 μm thick.

On ageing to a peak strength T8 condition, one sees the formation of the following precipitates : δ' (Al_3Li) spherical-shaped, strengthening; S (Al_2CuMg) lathlike-shaped, strengthening; T_1 (Al_2CuLi) lathlike-shaped, strengthening; ß' (Al_3Zr) dispersoid, suppressing re-crystallization. The presence of T_2 (Al_6CuLi_3) was also recently mentioned in the literature (7,8), although no wide consensus has been reached.

The precipitation occurs quite uniformly through the Al matrix. However, ageing produces a preferential precipitation, mainly of δ', at the grain boundaries, with consequent formation of PFZ's (Precipitate Free Zones) nearly 0.5 μm wide.

In the 8090-T8 Al-Li alloy, peak-ageing produces not only the maximum strength, but also, in contrast to 2000 and 7000 Al alloys, high fracture toughness in the TL and LT directions. A decrease in toughness was found only in the short transverse direction, where the fracture mechanism is fully intergranular. In the TL and LT direction the fracture is transgranular, with deep and frequent delaminations along high angle grain boundaries, which are parallel to the plane formed by L and T directions. Thus, low K_{IC} values in ST and SL directions result; on the contrary, a delamination toughening occurs along LT and TL directions, where, due to a loss of through thickness constraint (2,3), delaminations give rise to an alternance of plane strain and plane stress conditions, which finally leads to an improvement of the fracture resistance characteristics.

EXPERIMENTAL PROCEDURE

The material tested was provided in the form of 12 mm thick plates. Fracture tests and fractographic analyses were performed. CT specimens were machined from the plates for both LT and TL directions. Fracture toughness (J_{IC}) tests were carried out at room temperature using a MTS servohydraulic system under strain control, according to ASTM E 813-87 Standard, employing the unloading compliance single specimen technique. Two values of specimen thickness, B=6mm and B=10 mm, were tested, specimen width W=50 mm. At that selected thicknesses, the K_{IC}-B plot, according to Doglione et al(2), is already horizontal.

J-R curves were determined according to E 813 and E 1152 ASTM Standard; owing to the peculiar form of the load-COD diagrams, which were characterized by a great number of pop-ins, the Ernst plastic J formula (10) was modified in order to account for variations in plastic areas during pop-ins.

RESULTS AND DISCUSSION

The tensile properties of the 8090-T8 alloy are reported in Table 1. As already mentioned, fracture toughness test records show indication of several and, at times, large pop-in phenomena. In this case, the applicability of existing or proposed standards for J_{IC} determination is doubtful; in fact, the ASTM E 813 Standard specifies that the critical event aimed to is the "initiation of slow stable crack growth", whereas the newly proposed EGF P 1-90 Standard specifically excludes materials which exhibit a pop-in behaviour. Nevertheless, in an engineering sense, it is meaningful to try to characterize new materials, in view of their applications, with well established and physically based toughness parameters like J_{IC}. A verification of the applicability of the Standards to the 8090-T8 alloy pop-in behaviour follows.

Experimental points from two typical tests on specimens loaded in the TL and LT directions are reported in Figure 1 and 2, respectively. Both J-R curves show lo-cal broad scatterbands. Moreover the LT curve exhibits, at low applied J values, a set of points far displaced from the rest. Similar features have been observed in most of the plots, although not always with such a large evidence.

TABLE 1 - Tensile properties of AA 8090-T8.

Crack Plane Orientation Code	σ_{YS} (MPa)	σ_{TS} (MPa)	e_f (%)
LT	474	547	6.2
TL	482	543	7.5

Without duly account of fractographic analyses, low applied load crack propagations followed by self healing should be supposed. Instead, SEM observations allow to formulate a different mechanism. In fact, upon loading even at low initial levels, multiple delaminations occur along high angle grain boundaries and are confined in the high strained zone at the crack tip: this event produces a through thickness constraint relaxation in the process zone, thus dividing the thick plane strain sample in a set of thinner subsamples whose edges, adjacent to the delaminations, are in plane stress. Due to the large number of local delaminations, the proportion of the crack tip undergoing blunting in plane stress increases remarkably, thus showing a sudden rise of the global COD that reflects high local CTOD's. The stiffness of the sample is therefore reduced without a comparable crack advance having taken place. Besides, due to the local different stress states, the crack tends to propagate more easily at the centre of each subsample. When the crack tip finally advances beyond the locally delaminated material, the specimen can resume a global stiffness directly related to the initial one. Thus, many of the points which, at almost constant J integral level, are located on the right, do not represent points deriving from larger crack propagations. Furthermore, the subsequent apparent crack closure does not really occur, because compliance decreasing points represent the failure of the plane stress resisting ligaments and the recovery of plane strain condition along the entire crack front.

The explanation of the pop-in behaviour is more complex. The pop-ins occurring in the first stage of loading are little and without significant changes in compliance. In the later loading stages, the pop-ins give rise to larger loading drops and to significant increases of compliance. Before the onset of the instability the crack propagates only in the plane strain zones of the subsamples: the load-COD curve flattens and the COD increases because the resisting ligaments are in plane stress. Finally, a sudden pop-in occurs when the resisting ligaments fail by plastic instability. In fact, fractographic examinations reveal that the fracture surface shows an alternance of flat plane strain zones and slant plane stress zones adjacent to the delaminations. In this period, the above described different effects of pop-ins and delaminations cannot be easily distinguished, although some "apparent" crack closure may also be seen.

As regards J_{Ic} determination we have to note that in the case of the tested alloy the crack propagation occurs in two ways: continuous slow stable propagation and sudden unstable pop-in crack growths. Moreover, it is impossible to recognize the classical ductile fracture overall mechanism, consisting of blunting, initiation and slow stable crack propagation; J-R curves and fractographic examinations show clearly that more than one blunting stage exists. The first lies near zero crack propagation values, corresponding to the stretched zone linking the fatigue front with the fracture propagation zone. The end of the first blunting stage can correspond to the J_i value of the EGF P 1-90 Standard, which is very low (near 5 kN/m), and is not representative under an engineering point of view. Later, other blunting stages are observed on the J-R curve as groups of points vertically located; also fractographic examinations reveal the presence of more than one stretched zone. J_{Ic} values determined in accordance with ASTM and EGF Standards, displacing the blunting line by 0.2 mm, do not correspond to a physically real event. It is then reasonable to locate the critical event at the end of the first significant reblunting stage, as shown in figures 1 and 2. This leads to J_{Ic} values which are not too conservative, as in the case of J_i, and are still significant from an engineering point of view. Besides, this criterion provides J_{Ic} values which are reproducible.

The J_{Ic} values determined with the above proposed criterion have been found equal to 18.3 kN/m for the TL direction and 16.3 kN/m for the LT direction, with a ±7% dispersion around the average value. Corresponding ASTM and EGF values show a larger range of variability: from 8.3 to 13.4 kN/m.

CONCLUSIONS

The 8090-T8 peak aged Al-Li alloy is characterized by the formation under load of multiple local delaminations along high angle grain boundaries at the crack tip. The phenomenon induces several uncommon features in the J-R curves, which show "apparent" crack extensions at low applied J levels and several pop-ins at later stages, followed by crack tip reblunting. The application of existing Standards leads to J_{Ic} values that are both very conservative and scarcely reproducible. A criterion for J_{Ic} determination in correspondance of the first significant reblunting stage is proposed.

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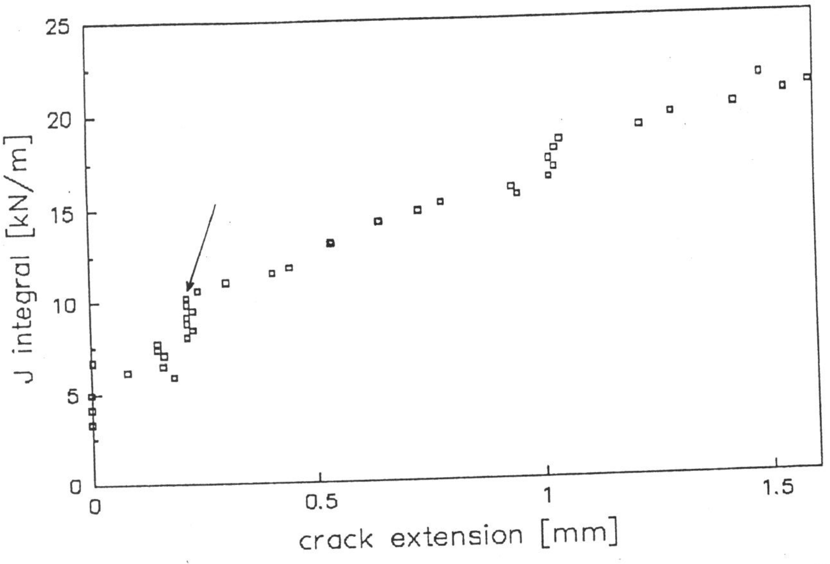

Figure 1 Plot of J-Δa points for a 6 mm thick 8090-T8 TL direction specimen. Arrow indicates J_{IC} level.

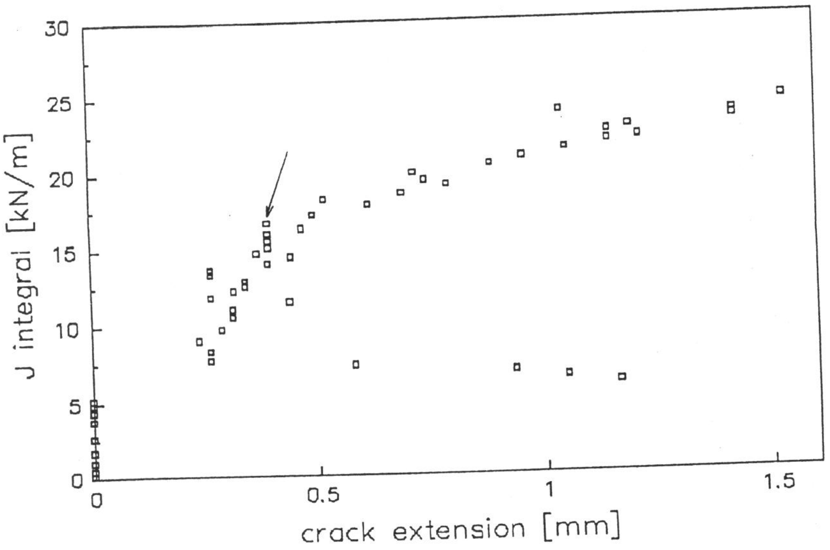

Figure 2 Plot of J-Δa points for a 10 mm thick 8090-T8 LT direction specimen. Arrow indicates J_{IC} level.