

Composite Fracture in Al Li Cu Alloy

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Abstract

Commercial Al Li alloy plates have a tendency to form intergranular delamination cracks extending in the rolling direction during fracture. The poor grain boundary strength induces low toughness failures when the principal stress acts through the thickness. On the other hand, a delamination toughening mechanism occurs when the stress is applied in longitudinal and transverse directions. During fatigue crack growth at low R load ratios a strong closure effect occurs. AES analyses on freshly broken surfaces reveal that intergranular fracture occurs also with the absence from the grain boundaries not only of Li, but also of K or Na impurities.

Riassunto

I laminati in lega di Al Li hanno la tendenza a manifestare fratture intergranulari di delaminazione. La scarsa resistenza dei bordi di grano è responsabile di un comportamento poco tenace quando la sollecitazione agisce nella direzione del corto ma anche di un aumento della tenacità quando sono coinvolte le altre due direzioni. Nella propagazione della cricca di fatica si manifesta un notevole effetto di chiusura ai più bassi valori di rapporto di carico R. Le analisi AES sulle superfici di frattura intergranulari indicano l'assenza dai bordi di grano non solo di Li, ma anche delle eventuali impurezze di K e Na.

Introduction

Commercial Al-Li alloys are currently produced by many Companies (Alcan, Alcoa, Pechiney...) in two main classes: the high strength 2090 and 8091, and the damage tolerant 2091 and 8090. The physical, mechanical and tensile characteristics of these alloys are well known; this paper deals with the fracture features and the toughening mechanisms, as they involve intergranular delamination processes along planes in the rolling directions [1-4].

Commercial plates show a typical unrecrystallised structure with strongly textured pancake shaped grains elongated in the rolling direction. Grain boundaries are particularly weak and promote an intergranular failure if a stress in the short direction is present. The poor grain boundaries strength causes therefore low toughness if the plate is tested in the short transverse. Nevertheless the same mechanism can improve the measured toughness in the longitudinal and transverse orientations. In TL and LT cracked specimens (stress applied in the transverse (T) direction on a crack propagating in longitudinal (L), and stress applied in the longitudinal direction on a crack propagating in transverse, respectively), intergranular delamination, sustained by the triaxial stresses, divides a monolithic thick section into thin sheets, thus relaxing through thickness constraint. The change in stress state, from plane strain to plane stress, due to the presence of stress-free internal surfaces, produces an "extrinsic toughening" of the alloy. This mechanism, termed "Crack divider delamination" [3] or "Thin sheet toughening" [5], is analogous to the one occurring in laminated composites. K.S. Chan suggests [5] that an overvaluation of $\sqrt{3}$ in experimental K_{IC} , due to the larger fracture strain within the process zone in plane stress conditions, can be attained by this way.

Materials and Methods

A commercial 13 mm thick plate of 2091 has been studied in the T8×51 temper condition. Chemical and mechanical characteristics are reported in Table 1 and 2. The optical metallography in fig. 1a) reveals the structure with small degree of recrystallisation, sub-grain structures and high inclusion content.

TABLE 1 - Chemical composition (wt%) of the 2091 T8 × 51 alloy plate

Li	Cu	Mg	Zr	Fe	Si
2.0	1.9	1.5	0.09	0.05	0.03

TABLE 2 - Mechanical properties of the 2091 T8 × 51 alloy plate, at room temperature

	long	transv.	short
$R_{p0.2}$ (MPa)	425	379	—
R_m (MPa)	497	507	—
A (%)	11.0	12.5	—
K_Q (MPa $\sqrt{m}$)	35.6	34.3	—
K_{Icsb} (MPa $\sqrt{m}$)	—	36.2	24.5

Toughness tests have been performed with CT specimens ($B = 13$ mm, $W = 40$ mm) machined in LT or TL orientations. No valid plane strain K_{Ic} results have been obtained because neither P_{max}/P_Q nor B conditions are satisfied. Therefore only the lowest K_Q values are reported in Table 2.

Fatigue (long) crack propagation tests have been performed on the above mentioned CT specimens, with an electromagnetic load system in ambient air at 10 Hz. Crack growth has been monitored with a traveling microscope. Constant load amplitude sinusoidal cycles were applied at load ratios in the range $R = 0.17 \div 0.67$.

Chevron notched short bar tests ($B = 2H = 13$ mm, $W = a_1 = 24$ mm, $a_0 = 8$ mm) [6] for the determination of K_{Icsb} have also been performed in TL and SL orientations. K_{Icsb} results reported in Table 2 have been obtained as mean values from many tests; as usual they are slightly higher than K_Q or K_{Ic} .

Auger electron spectroscopy (AES) analyses on freshly broken surfaces have been done in a PHI Scanning Auger Microscope apparatus with the electron beam at 3 keV. The specimens were machined in the short orientation as notched bar 3.2 mm in diameter, and fractured at room temperature. The analytical results on these fracture surfaces have been considered transferable to the delaminated surfaces of TL or LT specimens, too tough for being broken inside the spectrometer. The quantitative analyses have been done by measuring the peak-to-peak heights from $dN(E)/dE$ curves and correcting by the relative sensitivity factors.

Crack morphology in CT specimens

In fig. 1 a three dimensional optical metallography together with a SEM fractography in the field of the static fracture are reported. Fracture surfaces are characterised by the intergranular failure along the rolling direction. Delamination in lateral faces of the cube (TL and LT orientations) opens the surfaces shown in the upper face.

In fig. 2 the results of fatigue crack propagation tests are reported with the fracture morphology. Varying the load ratio R from 0.67 to 0.17, crack propagation rates decrease and show a larger platform in the intermediate region. At the crack length corresponding to these ΔK values, fracture surfaces appear macroscopically rougher at midthickness, as shown by the dark fretting products, thought to be rich in Li oxides [4]. The tortuosity of the crack path in this area promotes either mixed modes of fracture or premature wedging of crack faces on unloading. The contribution to closure effect from fretted oxide debris in the highly zig-zagged fracture profile should not be so insignificant as commonly reported [2-3] for Al Li alloys. Besides, the larger closure effect at low R reduces the effective load range contributing to the lower crack propagation rates. All these effects account for the superior fatigue resistance of Al Li alloys compared with traditional 2000 and 7000 series aluminum alloys [1-3].

P.S. Pao et al. [7] suggested that the different through-the-thickness fracture morphology is connected to variations in crystallographic texture and microstructure. They measured the mechanical properties at different depths and demonstrated the significant influence on both tensile and fatigue behaviours. Our results suggest for specimen at lower R levels a "three layer composite laminate" behaviour where the intermediate layer supports the resistance to fatigue crack propagation.

In Table 3 the results of the whole fatigue crack propagation tests are summarised. The C and m coefficients of the Paris power law relationship have been evaluated from a mean curve obtained by two or more tests at each R value:

$$da/dn = C \Delta K^m$$

TABLE 3 - Fatigue crack propagation. Coefficients of Paris law

$R =$		0.17	0.3	0.5	0.67
LT	C (m/cycle)	$10 \cdot 10^{-10}$	$9.5 \cdot 10^{-10}$	$4.7 \cdot 10^{-10}$	$12 \cdot 10^{-10}$
	m	2.24	2.43	2.93	2.93
TL	C (m/cycle)	$11 \cdot 10^{-10}$	$4.3 \cdot 10^{-10}$	$5.0 \cdot 10^{-10}$	$8.3 \cdot 10^{-10}$
	m	2.00	2.87	2.77	3.02

The transition between fatigue and final fracture clearly appears in fig. 3 for an LT specimen. Delamination doesn't occur during fatigue crack growth where the stress, and the K_I level, are not high enough. During plane strain fracture test the fatigue cracked CT specimen is slowly loaded up to the final failure; the specimen, up to this time monolithic, suggests a fracture surface self-similar to the already formed one. Nevertheless, the triaxial stress state in the process zone ahead of the crack tip promotes the failure in the weakest orientation, i.e. along grain boundaries, via delamination. The new internal surfaces change the stress state from plane strain to plane stress, allow the onset of shear lips inside the ligament, thus requiring more energy for crack propagation. Moreover, as it happens in the external surfaces, traces of crack bifurcation appear as secondary cracks parallel to the main crack front, connected to these internal surfaces.

High magnification micrograph of the delaminated fracture surfaces, shows in fig. 4 a fine microdimpled substructure, typical of intergranular ductile failure. Following Starke, Sanders and Palmer [8], the slip bands developed in front of the crack tip localize the strain in the soft precipitation free zones along grain boundaries, where easy failure occurs. In fig. 5 the slip bands emerging sideways of the crack in a CT specimen are shown. During fatigue crack growth the stress level is low without any modification of the external surface; when the overload is applied, the slip bands modify the external surface near the crack tip where the local plastic deformation occurs. The same is suggested to happen at the internal surfaces.

It must be noted that shear lips are more pronounced in the mid-thickness area than in the lateral layers, though a plane stress state should operate. The internal layer appears more prone to utilize the toughening mechanism offered by the delamination rather than the external ones, where a surface is always available. A local chemical analysis of Li has not revealed any composition gradient along the thickness, thus supporting the model proposed by P.S. Pao et al. [7].

AES analyses

The specimens broken inside the chamber of the spectrometer at $4 \cdot 10^{-9}$ Torr, room temperature, have been analysed *in situ* within the first 40 min. In fig. 6 a general scan of the fracture surface up to 1200 eV shows an high Al peak with O, Cu, Mg and C. No low melting point metal impurities such as Na or K have been detected. Li peaks have been investigated in the range of low electron energies at a scanning rate of 0.2 eV/channel instead of 1 eV/channel. An overlapping with Mg and oxidised Al peaks causes some difficulties in Li detection. Additional analyses have been taken on deeply ion etched Al Li binary alloys where neither Mg nor O could hinder Li peak.

No Li has been detected in fracture surfaces, except after a long permanence of the specimen in the spectrometer, where an oxidation assisted diffusion occurs.

Auger spectra on inclusions reveal a composition which is roughly Al_2Cu with a Mg content higher than the nominal one. These results on the inclusions have been confirmed by EDS analyses.

Fracture surfaces from Auger point of view is therefore an Al Mg Cu alloy with Al_2Cu second phases with poor O and C vacuum-system contaminations.

Conclusions

Fatigue crack at higher load ratios R proceeds transgranularly through the elongated grains with a macroscopical fairly rough feature. In this load ratio range, where closure effects are not relevant, Al Li alloys are not superior to conventional Al alloys.

At lower R values fatigue crack surfaces show an highly tortuous profile at mid-thickness which induces crack closure. The fatigue crack rate curves shift toward lower values. At this stage the specimen acts like a three layer composite laminate with the internal layer more resistant to fatigue.

If the crack is stressed up to the maximum resistance, as in K_{Ic} tests, a strong delamination occurs and the specimen acts like a multi layer composite laminate. Like in this class of materials, no load must be applied in the short direction.

AES analyses reveal that the delaminated surfaces are Li-free and that fracture occurs at room temperature also without contamination of low melting metal impurities such as Na or K.

Aknowledgements

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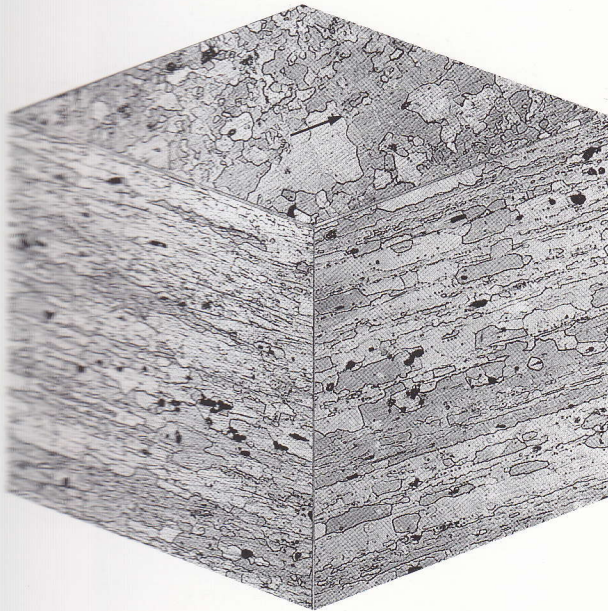


Fig. 1a:
Three dimensional optical metallography;
arrow indicates the rolling direction. The vertical
edge of the cube measures 0.8 mm.

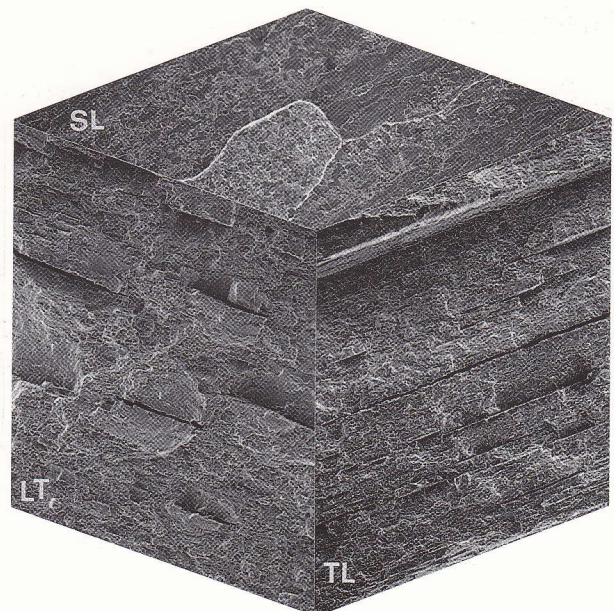


Fig. 1b:
Three dimensional map of fracture surfaces.
The vertical edge of the cube measures 3 mm.

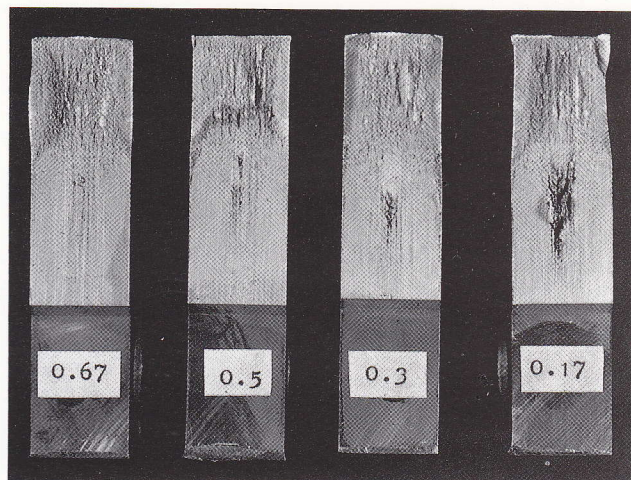


Fig. 2a:
Morphology of fatigue crack fracture surfaces.

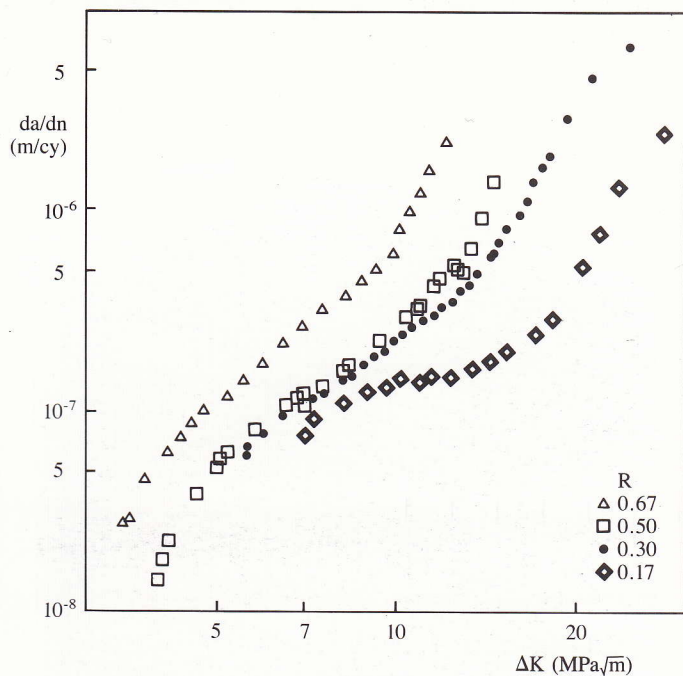


Fig. 2b:
Fatigue crack propagation tests on LT specimens.



Fig. 3:
Transition in fracture between fatigue (lower part) and overload (upper) in a CT specimen in LT orientation.

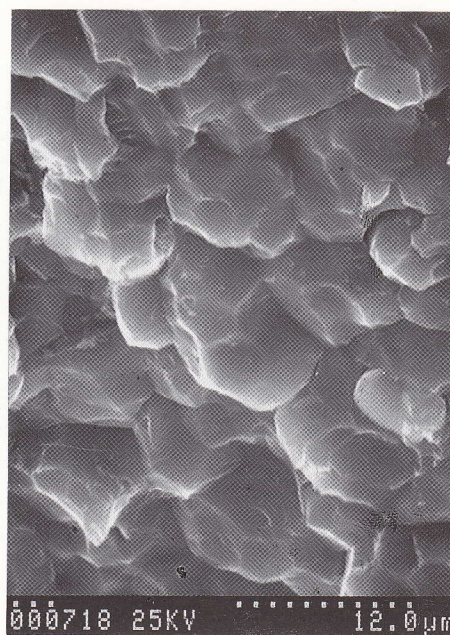


Fig. 4:
Delaminated fracture surfaces at high magnification.



Fig. 5:
Shear bands emerging on lateral surface near the crack after overloading.

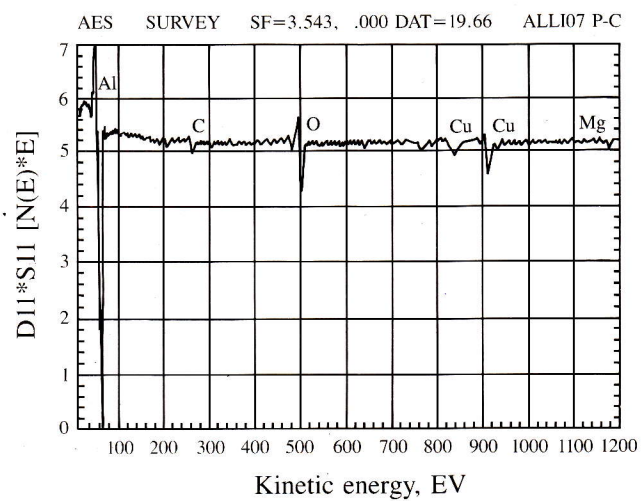


Fig. 6:
AES scan of an *in situ* fractured surface perpendicular to the short direction.