INTERACTIONS BETWEEN DISLOCATIONS AND CRYSTALLINE DEFECTS DURING THE CYCLIC DEFORMATION OF A 0.7 Wt% Al-Li ALLOY

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ABSTRACT In the aerospace industry requirements for new materials with high mechanical properties and low density has stimulated research works in Al-Li alloys. For ten years numerous studies have been developed in order to promote complex alloys having convenient mechanical and physical properties, and able to replace conventional alloys /1/ and /2/. From a fundamental point of view basic researchs to study the microscopic mechanisms controlling the mechanical behaviour of Al-Li alloys have to entered upon because several microscopic mechanisms are not well understood. Such investigations were first conducted on binary Al-Li alloy in solid solution state or having a fine distribution of $\delta'(Al_3Li)$ precipitates, according to the amount of lithium atoms. Tensile properties /3/ or cyclic behaviour /4/,/5/ have been investigated. The aim of this paper is to determine in terms of dislocation-crystalline defect interactions the microscopic mechanisms involved in the cyclic deformation of a solid solution of a binary Al-Li alloy, containing 0.7 Wt % of lithium. This work is a part of a whole research program devoted to Al-Li binary alloys in our laboratory and therefore is complementary to studies presented in reference /5/.

EXPERIMENTAL PROCEDURE

A binary Al-Li alloy containing 0.7 Wt % of lithium has been used in this present investigation. After heating at 530°C for two hours, then quenching in ice water and finally ageing at room temperature for several months the 0.7 Wt % Al-Li alloy is kept in a solid solution state as can be inferred by small angle X ray scattering experiments and TEM observations. Most of fatigue studies presented here have been entered upon with fatigue specimen in this solid solution state. Some tests have been carried out with samples after undergoing to a solid solution heat treatment at 320°C so as to reduce the thermal vacancy rate and to understand better the role of solute lithium atoms.

Cylindrical specimens with 9 mm diameter and having a gauge length of 40 mm have been used in this study. Fatigue tests have been performed in a push pull mode using a specific fatigue machine with a very high displacement sensitivity, that allows to perform fatigue studies in a very large range of fatigue strain amplitude ($10^{-6} \leq \Delta\varepsilon_t \leq 10^{-2}$). In fact, this fatigue machine is very convenient for studing all types of interactions between dislocations and crystalline defects that occur during cyclic deformation. Fatigue tests are conducted by a PDP 11 Digital Computer with a linear time deformation dependence and a frequency range between 0.2 and 10^{-3} Hz. Fatigue tests have been carried out under total or plastic strain conditions. The specimen deformation is recorded from a MTS extensometer with a measurement length of 25 mm. The applied stress is deduced from data given by the loading cell. Both strain and load data are stored in the computer memory. Then, parameters of the fatigue loop (figure 1) are determined by processing the stored mechanical data :

i) the maximum fatigue stress, σ_M, of the fatigue loop (figure 1). (A symetrical behaviour in traction and compression is observed).

ii) the dissipated relative energy, Δ, given by :

$$\Delta = \frac{\text{cycle aera ABCDA}}{\text{aera OBF + aera ODE}}$$

iii) the unloading stiffness value R, determined by a least square method applied to an unloading stress range, A , which is defined by : $\Delta A = (\sigma_M - 1/3\sigma_M)$ fig1 . In addition continuous acoustic emission (C.A.E.) measurements have been carried out in real time during fatigue cycling, in order to obtain informations on the dynamic behaviour of dislocations. Technical problems and theoretical processing, concerning the acoustic emission phenomenon, are given in reference /6/.

At last, dislocation-structures have been investigated by TEM observations using a 200 CX Jeol Microscope. Thin foils have been cut off in cycled sample according a direction parallel or perpendicular to the tensile axis. Some in situ tensile experiments have been performed in the electronic microscope in order to study the local movement of dislocations within dislocation structures of thin foils obtained from a previously cycled sample.

EXPERIMENTAL RESULTS

i) Mechanical properties

The cycled 0.7 Wt % Al-Li binary alloy presents a cyclic hardening at the beginning of the fatigue process. After some ten of fatigue cycles the maximum fatigue stress, σ_M, reaches a constant value, σ_S, that corresponds to the stabilized fatigue range. However, at low strain amplitude, a very weak cyclic hardening is observed ($\varepsilon_p < 5.10^{-5}$). On figure 2, the dependence on both maximum fatigue stress σ_M and dissipated relative energy Δ, with the amplitude of the fatigue plastic strain is reported for the stabilized fatigue range. Corresponding curves of pure polycrystalline aluminium (5N) and of Al-Mg dilute alloy (100 ppm Mg) are also reported in figure 3. It can be seen in figure 3 similar variations independently of the nature of materials except in the low strain amplitude range. Therefore, a "cyclic yield strength" have been determined in order to reveal a similar behaviour in all the strain amplitude range. The cyclic yield strength is determined as follow : from results of fatigue tests at different strain amplitudes in the stabilized fatigue range, the total deformation ε_{to}, corresponding to a plastic deformation ε_p equal to zero, is obtained by extrapolation in the (ε_t, ε_p) plot (figure 4). The "cyclic yield strength", σ_o , is the particular stress value corresponding to the extrapolated strain value ε_{to}. For the three materials the stress value, σ_o , is given in table.

0.7 Wt% Al-Li	Al-Mg	Al 5N	
11.5	2.3	1.1	σ_o (MPa)

In figure 5 is reported, for the three previous materials, the difference between the stabilized stress value, σ_S , and the cyclic yield strength, σ_o, as a function of plastic strain amplitude. In this particular plot, a single fatigue behaviour is ascertained independently of the chemical composition of investigated alloys.

The Figure 6 shows the variation of the stiffness value, R, versus the fatigue strain amplitude after cycling in the stabilized stress range. In fact, we have reported a reduced stiffness value R/Ro in order to release from scattering effects resulting of the use of different specimens. For a given sample, R_0 is determined from a fatigue loop having at zero stress a width of 1.10^{-6}. At low strain amplitude the reduced stiffness remains approximatively at a constant value, quite close to one. Also a very weak level of dissipated relative energy is observed. From a strain amplitude of $\Delta\varepsilon p/2 = 5.10^{-5}$ a strong decrease in the reduced stiffness variation can be shown in figure 4. It is related with a marked increase in the value of the relative dissipated energy Δ. In spite of fatigue tests carried out in a large frequency range 0.2 -10^{-3} Hz and with different strain amplitude higher than 5.10^{-5}, no significant variations in the maximum stress or in the relative dissipated energy has been observed. Therefore, one may be considered that the fatigue behaviour of the 0.7 % Al-Li alloy presents a very pronounced athermal character.

Finally, a decrease in the temperature of the solid solution treatment leads to an increase in the cyclic hardening at the beginning of the fatigue process. However, after several thousands of fatigue cycles the fatigue stress level becomes independent on the temperature of the solid solution heat treatment.

ii) Continuous Acoustic Emission (C.A.E.)

A typical result of CAE measurements during fatigue tests is reported in figure 7. The rootmean square (r.m.s) voltage is very strongly increased just as the fatigue stress reaches the yield strength in traction as well as in compression. Then, a very marked peak is observed and the CAE evolution in the plastic domain is characterized by a slight decrease of the CAE level that is clearly higher the level that of the background noise. During the quasi elastic unloading the r.m.s. voltage presents a very weak value corresponding approximatively to the background noise level. According to the cycle number a decrement is observed in the level of CAE. When the stabilized stress domain is reached, no variations of acoustic parameters can be detected. Below a strain fatigue amplitude of 2.10^{-3} , the variations of the r.m.s. voltage have no physical significance being included in the background noise. It is noticed that acoustic emission results for the 0.7 Wt % Al-Li alloy, are quite similar to those observed in the case of pure polycrystalline aluminium /7/.

iii) MET observations

No significant difference are gernerally detected between dislocation microstructures of the 0.7 Wt % Al-Li alloy or the pure polycrystalline aluminium cycled under the same conditions. The figure 8 shows dislocation cells corresponding to the microstructural state of fatigue specimens cycled at strain amplitude between 4.10^{-4} and 2.10^{-3} . Dislocations cells of 2-5 µm sized, having straight dislocation walls ($\simeq$ 0.5 µm large) and a high density of tangled dislocations, exhibit a very weak variation in size as the cycle number or the strain amplitude are increased. However at the highest strain amplitude used in this study (2.10^{-3}), equiaxis dislocations cells have been simultaneously observed with very elongated cells. They have very narrow walls arranged such as they form a very marked "labyrinth" structure (fig 9). This structure is very similar to the one observed in cooper single crystals cycled under similar conditions. As a matter of fact, we have also observed only two activated slip systems with mainly screw dislocations components. In situ tensile experiments carried out on labyrinth structures obtained from a massive specimen previously cycled has shown that the plastic deformation occurs by creation of edge dislocations and displacement of screw components in the channel between the walls (figure 10).

DISCUSSION : The analysis of the experimental results shows a distinction between low and high fatigue strain amplitude.

i) At low fatigue strain amplitude

In this domain, a very weak level of the dissipated relative energy Δ and a small cyclic hardening suggest that dislocation creation is probably not involved in the fatigue process. This hypothesis is consislent with the fact that the reduced stiffness R/R_0 , which is sensitive to the mobile dislocations density /8/ remains constant independently of the strain amplitude. All the results suggest that the microscopic mechanisms controlling the cyclic deformation of the 0.7 Wt % Al-Li alloy is probably the interaction between dislocations and solute atoms as in 5N polycrystalline aluminium and Al-Mg dilute alloy. From the value of the cyclic yield strength determined in § **2** (σ_0=11.5 MPa) we have found a cyclic hardening value by atom per cent of lithium of 5 MPa/at %. This value is in good agreement with the one determined by P. SAINFORT /3/, in the case of tensile monotonous deformation. However, we have observed that the fatigue stress level is strongly dependent on the temperature of the solid solution heat treatment. Thus, it seems that the spatial distribution of lithium atoms in the aluminium matrix can play an important role especially at the beginning of the cyclic deformation.

ii) At high strain amplitude

This fatigue domain is characterized by a very pronounced athermal behaviour and by a rapid increase in the evolution of dissipated relative energy versus the strain amplitude. As it has been proposed by SLIMANI and al. /7/ in the case of pure aluminium the acoustic emission peak, observed just at the beginning of the plastic deformation, can be mainly interpreted by a strong rate of dislocation loop creation. All these considerations lead to assume that the interaction between dislocations controls the cyclic deformation of the 0.7 Wt % Al-Li alloy at high strain amplitude. The same cyclic behaviour in the plastic deformation domain beyond the cyclic yield strength (see figure 3) may be probably related with similar dislocation structures composed of dislocation cells. As in the case of pure polycrystalline aluminium /9/, /10/ we think that the fatigue stress in the stabilized stress range can be understood from a composite type model with a hard phase assumed to be the cell walls and a softer matrix corresponding to the interior of cells or to the channel of labyrinth structure.

The maximum fatigue stress is considered to be the sum of two components :

i) the first one is due to the interaction of emitted dislocations with trees of the dislocation forest in the walls (as well cell walls than that of the labyrinth structure).

ii) the second component corresponds to the internal stresses necessary to assume the strain compatibility between the wall and the cell inside , these two regions have not the same plastic behaviour.because the mechanical properties are strongly dependent on the value of dislocation density that depends itself on the respective degree of creation and of annihilation of dislocations. The same behaviour mentionned above for both 0.7 Wt % alloy and aluminium suggest that microscopic mechanisms wich control the creation and the annihilation of dislocations are slightly sensitive to the addition of solute lithium atoms.

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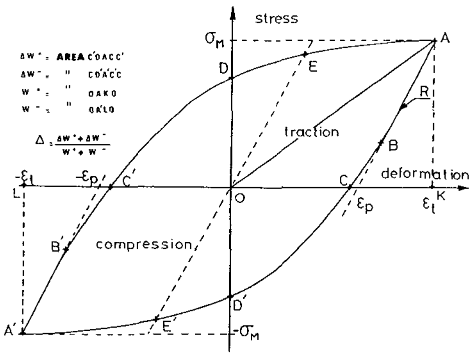


Fig 1 : Définition of the relative dissipated energy and of the maximum fatigue stress on a fatigue loop.

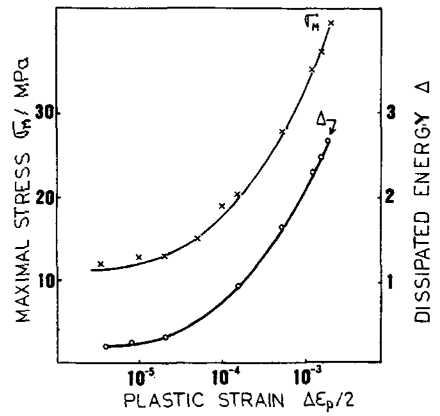


Fig 2 : Maximum fatigue stress σm and dissipated relative energy versus plastic strain amplitude Δεp/2. Experimental values determined in the stabilized fatigue range.

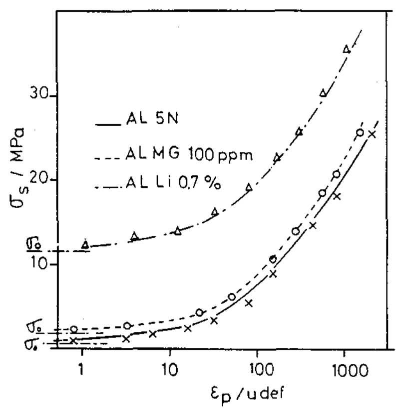


Fig 3 : Maximum fatigue stress versus plastic strain for 3 materials. AL 5N ; Al-Mg(100ppm) ; Al-Li 0,7 Wt%.

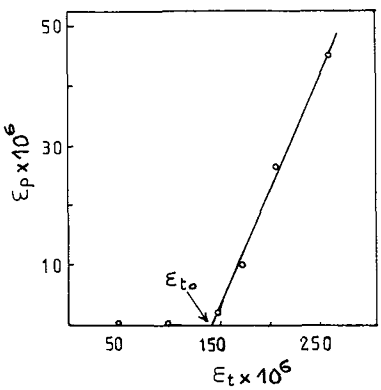


Fig 4 : Determination of the total deformation corresponding to a plastic deformation equal to zero.

Fig 5 : Variation of the stress increment in the plastic range of the stabilized fatigue cycle versus plastic strain amplitude. Observe the same behaviour independently of the investigated alloys. (Same curve for the three materials : Al5N Al-Mg and Al-Li alloys.)

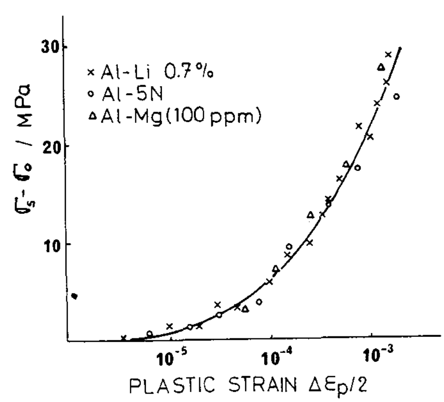
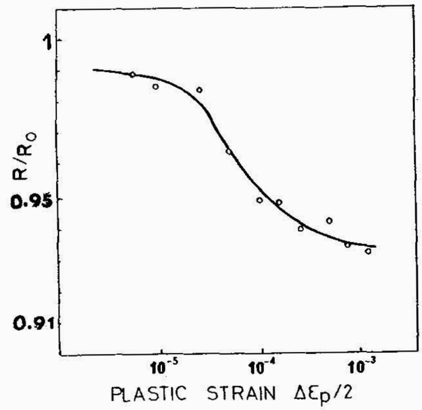


Fig 6 : Variation of the relative stiffness value R/Ro, with the fatigue strain amplitude (R/Ro definition in the text)



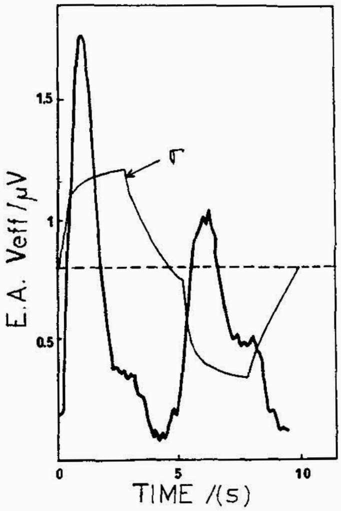


Fig 7 : Continuous acoustic Emission recorded during a fatigue cycle . Test conducted in the stabilized range at $\Delta\varepsilon_p/2 = 10^{-3}$

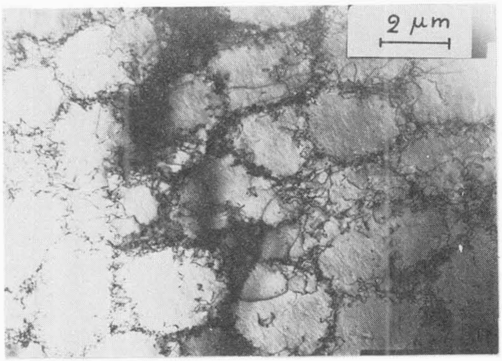


Fig 8 : Fatigue cells in stabilized stress range ; $\Delta\varepsilon_p/2 = 1.2 \cdot 10^{-3}$ cycle number N = 1000

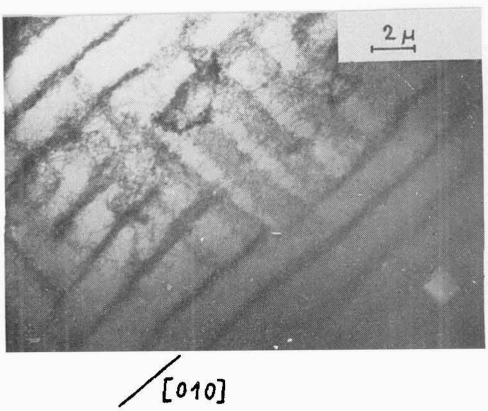
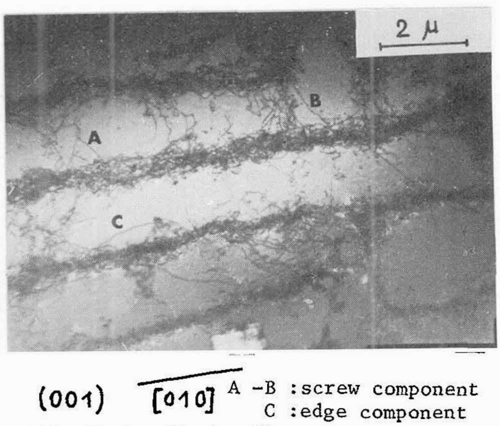


Fig 9 : Labyrinth structure
Sample cycled at $\Delta\varepsilon_p/2 = 2.10^{-3}$
Cycle number 1000



A -B :screw component
C :edge component

Fig 10: In situ tensile test . Displacement of the dislocations between the walls.