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Influence of microstructure on the fretting resistance of Al-Cu-Li alloys

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The resistance of two Al-Cu-Li alloys (2050 and 2196) to fretting has been investigated. For each material two heat treatments have been studied (T8 and low temperature ageing). Fretting tests with a cylinder-plane configuration have been performed in the partial slip regime. The results obtained show that the low temperature temper gives a better resistance to fretting crack initiation and propagation than the T8 temper for both alloys. The 3D shape of the fretting cracks has been observed by high resolution synchrotron X-ray tomography. Multiple initiation sites were observed below the contact. In their early stages of development, the fretting cracks grow approximately radially within the material leading to thumb nail cracks which eventually merge laterally. The difference in fretting resistance is analysed with respect to the 3D fracture surface of the fretting cracks in relation with the alloys precipitation state.

Keywords: Fretting, Al-Cu-Li, fretting damage, X-ray tomography, crack

Introduction

Confronted by the increasing use of composite materials in aircrafts, aluminium alloys have to be constantly improved. From a weight saving point of view, lithium addition offers interesting perspectives, as it reduces the density while improving at the same time mechanical properties like elastic stiffness and strength-damage tolerance compromise. Originally, Al-(Li,Cu) alloys were developed between the 60's and 90's but their commercial applications were limited due to technical problems, such as a very low corrosion resistance. Nowadays a new generation, with alloys containing a lower fraction of lithium, is being developed. A key issue in aircraft design is the use of rivets to join components which highly contribute to the risk of failure by fatigue. Higher fatigue stresses (induced by the presence of a hole) can become limiting in the case of riveted or bolted joints. Fundamentally, this problem can be considered from at least two points of view:

- First, through the influence of the rivet hole which acts as a stress raiser and therefore promotes fatigue crack initiation.
- Second, through the presence of a contact between the rivet and the fuselage material which can generate sub-surface damage through a fretting fatigue phenomenon. It is generally observed that fretting leads to premature crack nucleation compared to classic fatigue loading.

Although considerable research has been carried out on the initiation and growth of fatigue cracks from notches or holes in a vast range of Al alloys including early Al-(Li,Cu) alloys, the fatigue properties of the recently developed Al-Cu-Li alloy has been poorly investigated not to mention their fretting properties. Besides, very few studies have focused on the influence of microstructure on the fretting resistance of Al alloys [1, 2, 3]. This is mostly due to the fact that the characterisation of fretting cracks is generally destructive: sub contact cracking does not allow direct crack visualisation; instead the fretting test must be stopped and the samples cut in order to analyse the extent of damage. In this paper, the fretting resistance of two Al-Cu-Li alloys with different Cu/Li ratios and different heat treatments is studied.

Materials and methods

Materials

Two Al-Cu-Li 15 mm thick plates of alloys 2050 and 2196 were supplied by Constellium, Voreppe Research Centre (Constellium CRV). The chemical compositions of the alloys are detailed in Table 1. The following processing route has been used: casting, homogenization, hot rolling, solution heat treatment, quenching, stress relieving by controlled tension and artificial ageing. Two ageing conditions have been investigated: peak aged (T8) and under aged (UA - 96h at 120 °C). The corresponding mechanical properties are given in Table 2.

	% Cu	% Li	% Mg	% Mn	% Ag	% Zr	% Zn	% Si	% Fe
2050	3,2-3,9	0,7-1,3	0,2-0,6	0,2-0,5	0,2-0,7	0,06-0,14	< 0,25	< 0,08	< 0,1
2196	2,5-3,3	1,4-2,1	0,25-0,8	< 0,35	0,25-0,6	0,04-0,18	< 0,35	< 0,12	< 0,15

Table 1: Chemical composition of the studied alloys (wt%).

After heat treatment, a mixture of semi-coherent T_1 and coherent δ' precipitates has been observed by transmission electron microscopy [4] in the 2196 alloy in the T8 condition while δ' are predominant in the UA condition. In the 2050 alloy a majority of T_1 precipitates has been found in the T8 condition while no significant precipitation could be observed in the UA condition. Both alloys exhibit a classical rolling texture with a low fraction of recrystallised grains in the 2050 alloy [4]. Those grains have a classical pancake shape with a very large dimension along the rolling direction (L). The number of Fe-rich intermetallic particles per unit volume (as studied by X-ray tomography - see below for a short presentation of the technique) in the 2050 alloy is slightly larger than in the 2196 alloy but volume fractions are comparable (0.32% and 0.23 % respectively). The average size of those particles (radius of a sphere of equivalent volume) is slightly larger in the 2196 alloy (3.1 μm) than in the 2050 (2.6 μm).

Alliage	Treatment	TYS (MPa)	UTS (MPa)	$\epsilon\%$	E (MPa)	ν	σ_d (MPa)
2196	T8	559	594	5,9	79000	0,305	140-150
	UA	428	520	11,1			
2050	T8	525	550	6	77000	0,305	150
	UA	360	463	18,9			

Table 2: Mechanical properties of the two alloys in UA and T8 conditions. σ_d is the fatigue strength at 10^6 cycles for $R = 0, 1$.

Fretting tests

The experimental setup used for the fretting experiments is shown schematically in figure 1. The flat Al specimen is maintained in contact with a cylindrical counter-body in titanium alloy thanks to the normal force P , which is kept constant during the test. A relative sinusoidal displacement δ is imposed, with a 10 Hz frequency, between the two bodies giving rise to a contact shear force of amplitude Q . Al-Cu-Li specimens have a controlled planar surface with a roughness R_a of $0.2 \mu\text{m}$. The pads which form counter-body are machined from bars of a titanium alloy (TIMETAL 6-4 from Timet company: 4.1%wt of V, 6.5%wt of Al and $R_{p0,2}$ of 952 MPa). They have a cylindrical surface with a constant radius of $R=80 \text{ mm}$ and a roughness R_a of $0.45 \mu\text{m}$. The normal force P was fixed at 346.5 N/mm along the contact corresponding to a calculated maximum Hertzian contact pressure of 300 MPa (Hertz law). Tests were conducted at different values of the tangential force Q ranging between 75 and 275 N/mm.

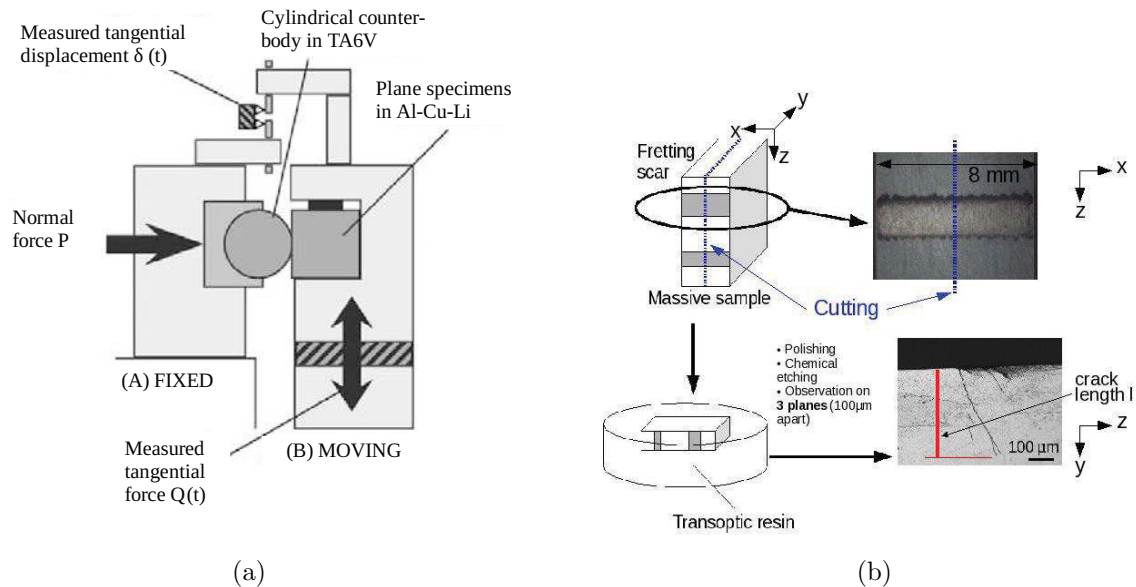


Figure 1: a) Schematic representation of the fretting device for the cylinder (Ti)/plane (Al-Cu-Li) configuration. b) Experimental method to investigate cracking after the fretting test ($X//ST, Y//LT, Z//L$)

During the tests, P , Q and δ values were recorded. A constant number of cycles N of amplitude δ /tangential force Q is imposed on the sample; in the present case, N was fixed at 100 000 cycles. Several values of δ have been investigated. All the tests are carried out in partial slip conditions which are characterized by no relative movement between the cylinder and the plane at the centre of the contact and, simultaneously, a relative movement (slip) at the edges of the contact area. Depending on the contact loading conditions, cracks may or may not nucleate in these slip zones. As mentioned above, this cannot be detected by direct observation of the cycled sample, as cracking occurs below the contact surface. Therefore when the test is stopped ($N=100\ 000$), the sample is cut in two in the middle of the fretting scars. One of the new surfaces thus created is mechanically polished and the crack length measured by optical observation after Keller etching. The surface is further polished and etched twice (approximately $100 \mu\text{m}$ of material removed along the X direction between each observation) in order to evaluate the homogeneity of the crack length in volume. The crack

length is defined as the projected length along the Y axis (see figure 1 for a schematic of the whole process and for a definition of the X, Y and Z axis). The location of fretting damage versus macroscopic directions of the rolled plate (L: rolling, LT: long transverse, ST: short transverse) is defined in figure 2.

Tomographic imaging of fretting cracks

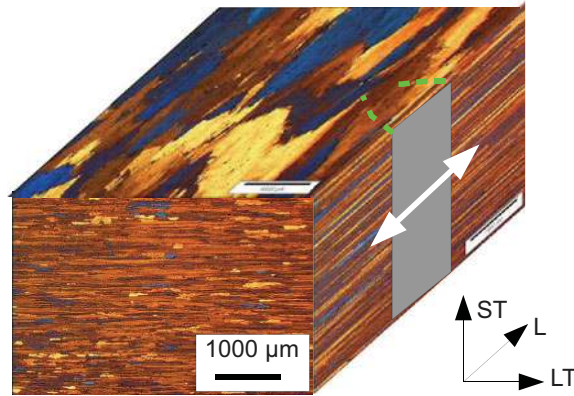


Figure 2: Schematic drawing illustrating the orientation of the fretting cracks with respect to the sample rolling directions and test conditions (L-T configuration in this case). The rectangular gray shape shows the fretting scar. The double arrow indicates the direction along which the fretting pad is oscillating. The hashed lines show schematically the crack orientation below the contact.

The 3D shape of the fretting cracks has been characterized by X-ray micro-tomography at the European Synchrotron Radiation Facility in Grenoble, France (beamline ID19). Given the voxel size used ($0.7 \mu m$) the whole fretting pad cannot be observed in tomography. Needle-like specimens with a $1mm^2$ square section have been extracted at the surface of the fretting pads. Each needle contains a fretting crack in its central part and is set in tension with a dedicated device in order to open the crack and facilitate its observation as explained in Proudhon et al. [5]. The result of the tomographic observation is a 3D image of the fretting crack. Note that with this method only a restricted part of the fretting crack which has formed along the X direction can be observed.

Results and analysis.

Fretting damage

Figure 3 shows a plot of the average crack length measured below the contact as explained on figure 1 b. From this figure, by extrapolating the crack length to a zero tangential force, one can determine a shear stress threshold below which no crack initiation occurs. This threshold is found to be larger for the UA alloys (124 N/mm for the 2050 alloy and 113 N/mm for the 2196 alloy) than for the T8 alloys (96 N/mm for the 2050 alloy and 102 N/mm for the 2196 alloy). Besides the crack growth rate (given by the slopes of the curves on figure 3) is lower for the UA heat treatment.

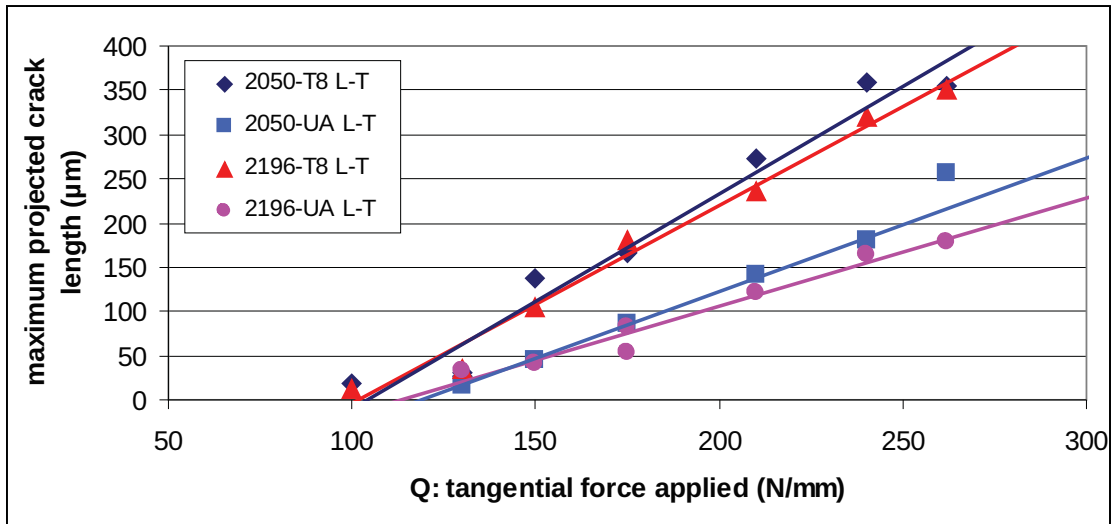


Figure 3: Comparison of the crack nucleation and propagation under fretting for the alloys 2050 (T8 and UA) and 2196 (T8 and UA).

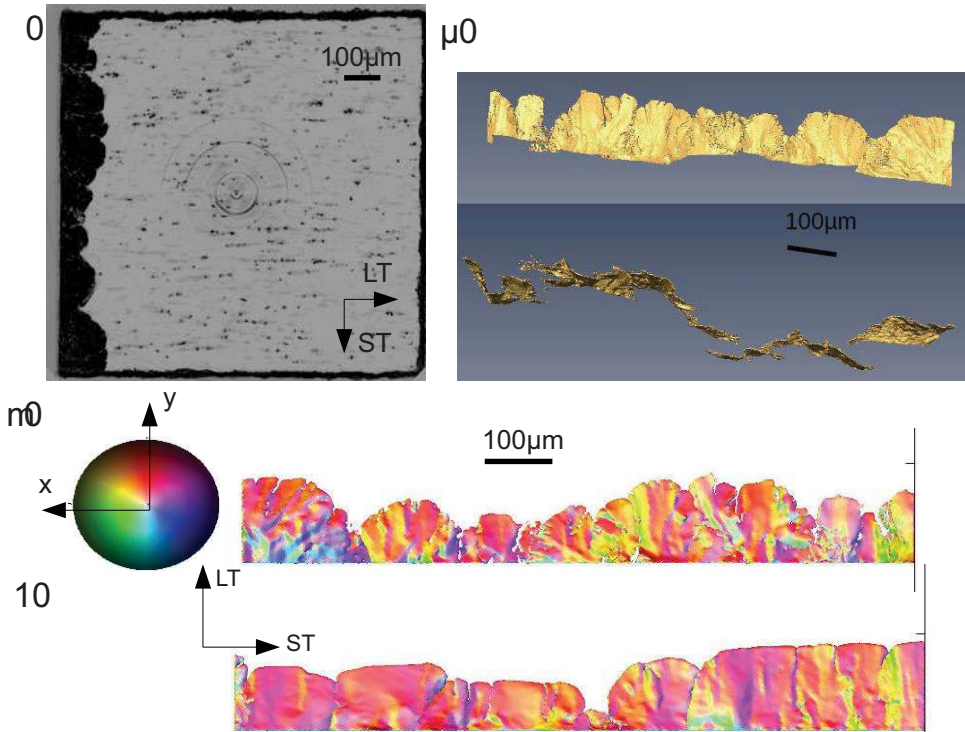


Figure 4: Example of 3D observations of the fretting cracks as obtained by X-ray tomography ($Q=210\text{N/mm}$) a) 2D projection of the crack (in black) in LT-ST plane (2050-T8 L-T) b) 3D rendering of the crack observed below the contact (2050-T8 L-T) c) and d) : 3D rendering of the crack normal in the XYZ axis system; the color indicates the evolution of the local orientation of the crack surface (c : 2050 UA L-T, d: 2050 T8 L-T)

3D observation of fretting cracks

The 3D characterisation of the fretting cracks shows that various small cracks initiate at different locations, and finally join to form one macroscopic crack as already observed in a

2024 alloy [5]. The local orientation of the crack during fretting propagation are different depending on the alloy temper (T8 or UA) for alloy 2050 (see Figure 4) : while in the T8 conditions the average orientation of the crack tend to stabilise (in a zone probably corresponding to one grain) at a depth of about 50 μm below the contact (Y/LT direction) it remained very "chaotic" for the UA condition. This qualitative observation which has been consistently made on the different samples observed in 3D could account for the better resistance of the UA treatment and could be a result of the microstructure induced by the heat treatment. Similar observations have been conducted during fatigue tests of samples with a central hole on the same materials/heat treatments : the UA microstructure induced a more tortuous crack path (with the crack following crystallographic directions) than for the T8 microstructure [4]. In UA temper, the slip mode is probably more crystallographic in fatigue but also in fretting conditions.

Summary

For the experimental conditions investigated, the two alloys in the UA conditions exhibit a better resistance to fretting damage which is attributed to a more tortuous crack path observed in 3D below the contact. This higher tortuosity can be linked to a microstructure which promotes planar slip (shearable precipitates), as observed on larger fatigue samples [4].

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