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Fatigue fracture tests on Al-Li 2198-T851 specimens under mixed-mode conditions

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Abstract

Aluminum-lithium alloys deliver numerous benefits for applications in which weight represents a key concern, thanks to their reduced mass density and enhanced mechanical properties compared to more traditional aluminum alloys. From the first generation of these alloys, significant anisotropy was observed in mechanical properties that was responsible of unpredictable failures during manufacturing. This paper reports an experimental campaign on the fracture anisotropy for the third generation aluminum-lithium alloy Al-Li 2198-T851. Particularly, fatigue crack-growth tests were carried out on the Middle Tension M(T) specimens with an initial central notch having different angles (30°, 45° and 60°) with the normal to the loading axis, in such a way to highlight the potential anisotropic characteristics of the material. Two types of specimen were manufactured: longitudinally (*L*) and transversally (*T*) with respect to the rolling direction of the sheets. crack gauges and strain gauges were glued on specimens to measure the crack-growth rates and central alignment of load during tests.

A significant difference of the crack-growth rates was observed for the two types of specimen, while cracks propagated perpendicularly to the loading axis irrespective of the angle of the central notch. Additionally, larger scatter of paths was observed for (*L*) specimens, while (*T*) specimens presented crack paths almost perpendicular to the loading axis, suggesting that cracks tended to propagate between the grains of the material.

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1. Introduction

The aerospace industry is always demanding innovative materials to cope with the continuously increasing requests for advanced processes (Citarella et al., 2021) and innovative materials with higher specific strength, i.e. strength-to-weight ratio. The Aluminum-Lithium (Al-Li) alloys constitute a promising group of metallic material with noteworthy prospective applications in this field. Al-Li alloys deliver great advantages for use in aero-structures thanks to their lower mass density, higher stiffness, higher fracture toughness and fatigue crack-growth resistance, as well as enhanced corrosion resistance. This is due to the addition of Li that produces a specific mass reduction of the alloy: for each 1 wt% of Li added to Al, mass density is reduced by 3% while the elastic modulus is increased by almost 6%, see Lavernia et al. (1987), Rioja et al. (2012) and Heinz et al. (2000).

The first generation of Al-Li alloys, such as 2090, 8090 and 2091, exhibited significant in-plane and through-thickness anisotropy of mechanical properties, and were responsible of unpredictable failures during manufacturing, e.g. during cold hole expansion, see Rioja et al. (2012). Further generations of damage tolerant Al-Li alloys were developed in the last decade by trying to recover these disadvantages and, eventually, a third generation of Al-Li alloys with highly desirable combinations of mechanical properties was successfully developed and commercialized, see Steuwer et al. (2011). Among these alloys, AA2198 represents an Al-Li alloy that is known to present extremely high strength levels, due to the precipitation hardening mechanisms, presenting a Cu % ranging from 2.9% to 3.3% and a Li % ranging from 0.9% to 1.1% (relatively lower Li level if compared with first generations of Al-Li alloys).

Mechanical performances of AA2198 are scarcely reported in literature. Most of the available data refers to S-N curves of AA2198 for T8, see De et al. (2011) and Alexopoulos et al. (2013) for a comparison between plastic and fracture behaviors of two different heat treated AA2198 (T3 and T351). Further researches on Al-Li alloys can also be found with reference to their high weldability, e.g. through friction stir welding, see Cavaliere et al. (2009), Bitondo et al. (2010) and Astarita et al. (2012).

The aim of the current work was to investigate the potential fracture anisotropy of the third generation Al-Li alloy 2198-T851. Fatigue crack-growth tests were carried out on Middle Tension M(T) specimens with an initial central notch having different angles (30°, 45° and 60°) with the normal to the loading axis, in such a way to highlight the anisotropic characteristics of the material.

2. Materials and methods

The material under investigation was a 2198-T851 aluminum–lithium alloy produced by ALCAN (Toronto, Canada) under the form of rolled sheets of 3.2 mm thickness with the chemical composition and mechanical properties reported in Tables 1 and 2 respectively.

Table 1 Chemical composition of aluminum alloy Al-Li 2198-T851 (wt%).

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Zr	Pb	Li	Al
0.03	0.04	3.3	0.01	0.32	0.01	0.01	0.02	0.03	0.11	0.01	1.0	Bal.

Table 2 Mechanical properties of aluminum alloy Al-Li 2198-T851.

Rolling direction	E [MPa]	σ_y [MPa]	σ_u [MPa]	A_f [%]
L	74560	460.8	512.4	13.3
T	74903	438.4	499.0	14.0

Specimens were cut out from the rolled sheets longitudinally (*L*) and transversally (*T*) with respect to the rolling direction (Figure 1) in rectangular plates with sizes of 200 x 90 mm × mm, according to ASTM E647 (2015).

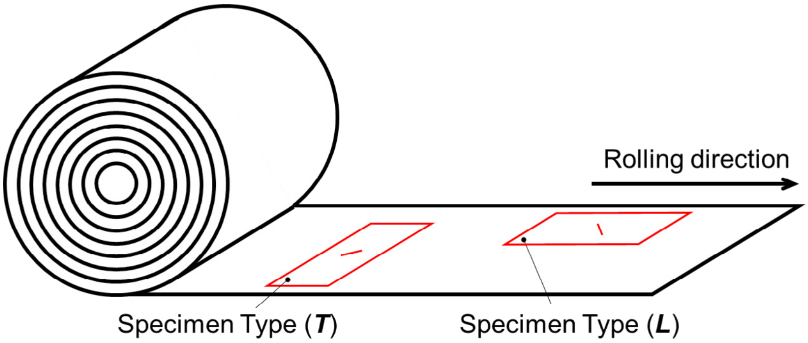

Fig. 1. Manufacturing direction definition.

The initial notch were produced through Electrical Discharge Machining (EDM) giving a notch radius of about 0.15 mm and three different inclinations of the initial central notch (30°, 45° and 60° with the normal to the loading axis) were considered for each type of specimen, for a total of 6 different specimens tested.

For all tests the specimens were instrumented with strain gauges and crack gauges. The size of specimen, the geometry of the notch and the loading conditions were illustrated in Figure 2.

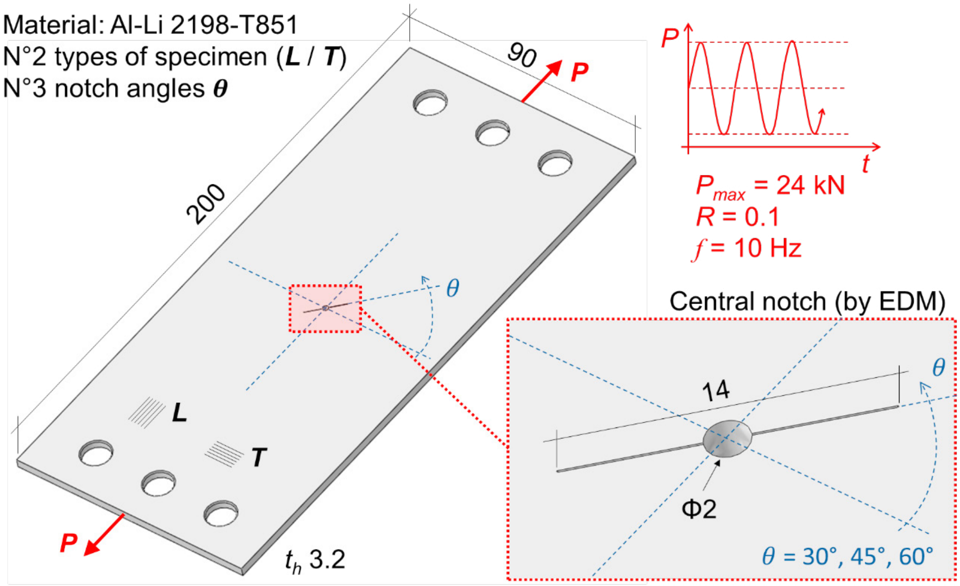

Fig. 2. Specimen dimensions and loading conditions.

All tests were carried out at room temperature, with a loading frequency of 10 Hz, onto a servo-hydraulic testing machine INSTRON 8502 equipped with a load cell of 50 kN, see Figure 3. Stress ratio of R = 0.1 with a maximum load P_{max} = 24 kN for all tests were adopted. Four strain gauges (6/120LY43) of HBK, two for each side, were glued on the specimen to check the absence of secondary bending during tests. Two crack gauges (TK-09-CPA01-005/DP) of Vishay were glued close to the notch tips (see Figure 3), so as to measure the crack advancing at small crack lengths. At longer crack lengths, tests were stopped every few thousand cycles so as to measure the advancing crack through a digital camera. Each test was stopped until the total failure of the specimen was reached.

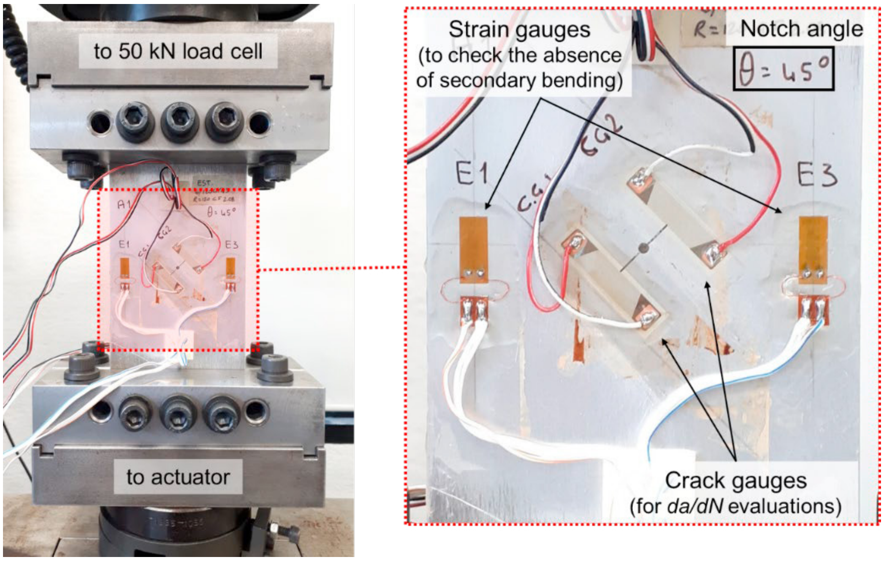

Fig. 3: Experimental setup with reference to a 45° inclined notch.

3. Results and discussion

Six specimens were tested, one for each combination of the two types of specimen and the three notch inclinations. Crack length vs. fatigue cycles curves were reported in Figure 4. Very similar crack lengths were measured by the crack gauges at the two crack tips (“CG1” and “CG2” in Figure 4). A significant difference of the crack-growth rates for the two types of specimen was observed, with the (*T*) direction reporting crack-growths nearly 25% faster than those of the (*L*) direction. Faster crack-growths were measured for the lower values of the notch inclination angles.

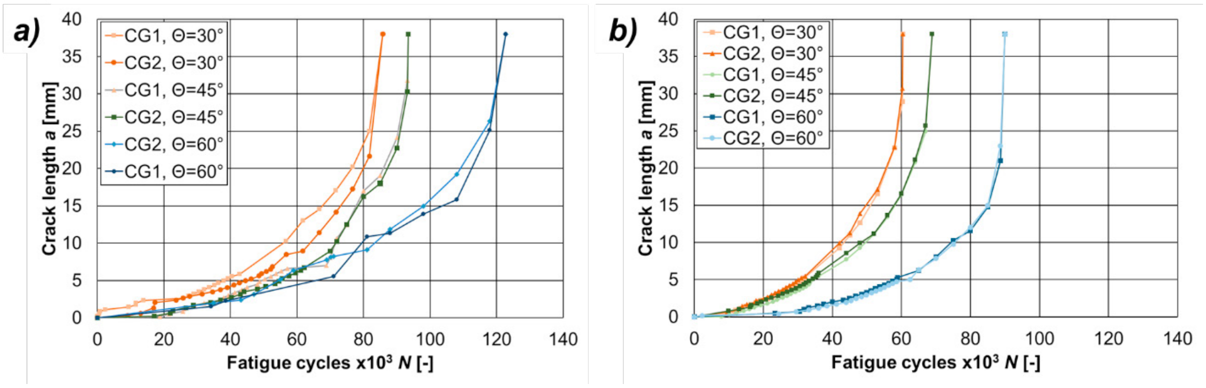

Fig. 4. Crack length vs. fatigue cycles curves for (a) *L* and (b) *T* specimens; “CG1” and “CG2” stand for the single crack gauge monitoring the crack at the two notch tips.

The obtained crack paths were reported in Figure 5. Although the high inclinations of the central notch were aimed at driving the propagation toward the loading direction, all cracks propagated perpendicularly to the loading axis irrespective of the notch angle. Additionally, larger scatter of paths was observed for (*L*) specimens, due to the through-the-thickness anisotropy already observed by Rioja et al. (2012) and Heinz et al. (2000). (*T*) Specimens presented crack paths perfectly perpendicular to the loading axis with a mostly negligible curvature at the notch tips. This suggested that cracks propagated perpendicular to the loading axis, but also tended to propagate between the grains of the material as shown in Figure 6.

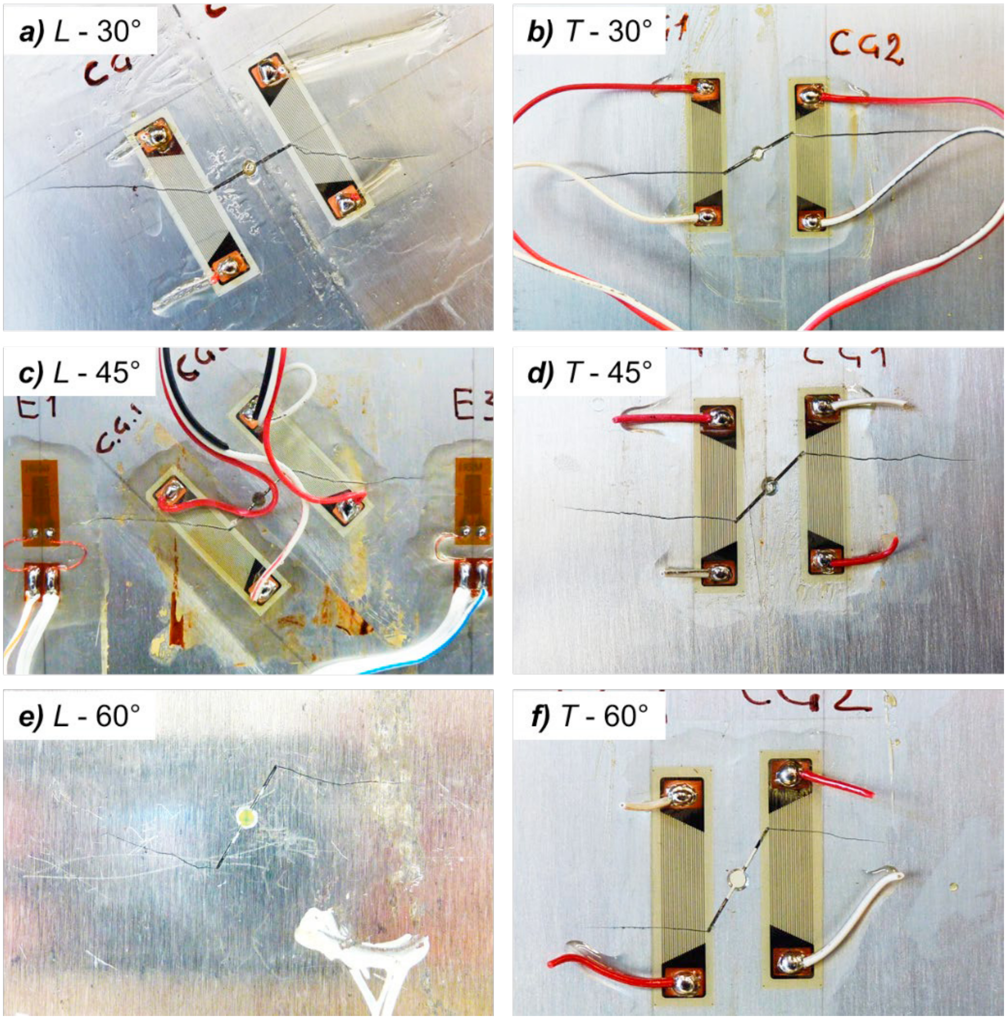

Fig. 5. Crack paths related to the three notch inclination angles and the two types of specimen: (a) *L* - 30°, (b) *T* - 30°, (c) *L* - 45°, (d) *T* - 45°, (e) *L* - 60°, (f) *T* - 60°.

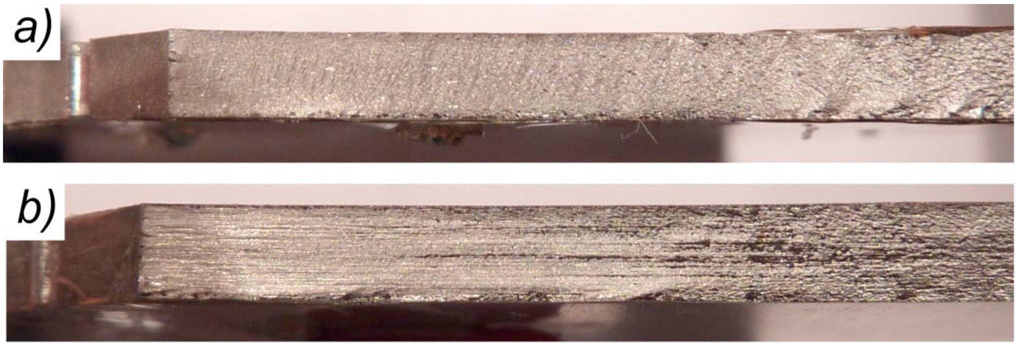

Fig. 6. Typical fracture surfaces: (a) *L* specimen, (b) *T* specimen.

4. Conclusions

Aluminum-lithium alloys deliver numerous benefits for applications in which weight represents a key concern, thanks to their reduced mass density and enhanced mechanical properties compared to more traditional aluminum alloys. This document reports the first results of an experimental campaign on the fracture anisotropy for the third generation aluminum-lithium alloy Al-Li 2198-T851.

Fatigue crack-growth tests were carried out on M(T) specimens with a initial central notch having different angles (30°, 45° and 60°) with the normal to the loading axis, in such a way to highlight the anisotropic characteristics of the material. Specimens were manufactured longitudinally (*L*) and transversally (*T*) with respect to the rolling direction of the sheets.

Although the high inclinations of the central notch were aimed at driving the propagation toward the loading direction, all cracks propagated perpendicularly to the loading axis irrespective of the notch angle. Large scatter of the crack paths was observed for (*L*) specimens, due to a significant through-the-thickness anisotropy. On the other hand, (*T*) specimens presented crack paths almost perpendicular to the loading axis, suggesting that cracks propagated perpendicular to the loading axis but also tended to propagate between the grains of the material.

Further studies on this line of research are intended to be notably developed.

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