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Stress-corrosion cracking characterisation of the advanced aerospace Al–Li 2099-T86 alloy

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ABSTRACT

New alloy developments driven by aircraft industry have identified aluminium lithium (Al–Li) alloys as potential candidates for substitution of incumbent high strength aluminium alloys used for manufacturing spacecraft and launchers. Whereas properties like specific stiffness, strength and toughness are proven as superior when compared to those of currently adopted Al alloys, the Stress Corrosion Cracking (SCC) characteristics are still an open aspect if advanced Al–Li alloys are considered for space structural applications. The present paper provides a comprehensive characterisation of the Al–Li 2099-T86 SCC performances.

1. Introduction

In the last 30 years, the leading aircraft manufacturers have been posing severe demands on the aluminium suppliers to deliver alloys with improved performances in terms of mechanical properties, high specific strength, and high specific stiffness for a wide spectrum of airframe structural applications. Even earlier, from the period of 1930s to 1980s, a number of key aluminium alloys were developed which provided the backbone to aircraft production. These alloys included AA7075 and AA7050 which were predominantly used for thick plate applications such as wing spar and ribs, and AA2024 used for fuselage sheets, lower wing covers and various extrusions. For aluminium alloys used in current spacecraft and launchers applications the situation is no different. The alloys of choice for the space industry are still limited to a small number of materials including AA7075, AA2024, AA6061, and AA6082 which were mainly developed in the 1930–1950s.

Further tuning of these alloys focused mainly on strength, toughness and damage tolerance as well as stress-corrosion or corrosion performances (for the 7xxx series), but little was achieved to enhance density or elastic modulus. Promising improvements regarding these properties were found already in 1920 by adding lithium as alloying element. Being the lightest metallic element (with an atomic number of three) and having a solid solubility in aluminium (with a maximum of approximately 4% at 610 °C) lithium contributes reducing the density by 3% and enhancing the elastic modulus nearly 6% for every added weight % Li with a significant increase of strength [1]. Al–Li alloys have been found to exhibit superior mechanical properties when compared to conventional Al alloys [2–4], in terms of higher specific strength, enhanced resistance to high cycle fatigue, fatigue crack growth and fracture toughness also at cryogenic temperatures, [5–7]. The property evolution over the different Al–Li generations has been reviewed in [8–10]. After decades of poor performance issues during the implementation of the first and second generation of Al–Li alloys, the third generation could overcome many of the identified problems, including property anisotropy, low tensile elongation, poor fracture toughness, low corrosion resistance and poor thermal stability, [8]. With dropping the Li content, the first grade developed was the weldable ultra-high strength alloy Weldalite 049® [11], which is currently widely adopted in aeronautical and aerospace applications. Similar to this alloy, but with a lower copper content, the AA2195 has been used for manufacturing the NASA's Space Shuttle external fuel tank, implementing the Friction Stir Welding (FSW) process [12–14], and will be used for the Space Launch System (SLS) external tanks, currently under development. The more recent AA2050 and AA2196 alloys, considered as direct replacement without any redesign [3], have been adopted for Airbus aircraft structural parts [2], while the AA2198 is used for the Falcon 9 launcher walls and domes, also combined with FSW [14,15].

The current advanced Al–Li alloys were established at the

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beginning of the 21st century by Alcoa and Alcan separately. In particular AA2099, has been recently developed by Alcoa for use in aerospace and high performance applications requiring high strength, low density, superior damage tolerance, excellent corrosion resistance and good weldability [16]. AA2099 has a high lithium content of 1.8% which improves the specific properties. Subsequent development of controlling and refining the composition, temper, and microstructure took place in cooperation with Bombardier from 2005 onwards [1]. AA2099 was made commercially available in accordance with AMS 4458 and can already be found in the fuselage and floor structure of Airbus' A380 aircraft [17]. The manufacturer offers two tempers of the AA2099 alloy: T83 and T86 of which the high fracture toughness T86 temper is used in the present study.

If the AA2099 is considered for spacecraft and launcher structural applications, it shall comply with European ECSS standards for materials selection. Whilst strength and toughness are driving properties for aircraft industry, excellent corrosion and especially stress-corrosion resistance are key criteria for space applications. Stress Corrosion Cracking (SCC) is a critical failure phenomenon and has been investigated for more than half a century. A significant amount of work has been carried out to understand SCC behaviour of Al-alloys [18]. SCC behaviour of high strength aluminium alloys is treated in [19–23]. It can be stated that SCC generally correlates to chemistry and morphology of Grain Boundary Precipitations (GBP) [24,25], among all proposed mechanisms in aluminium alloys the most cited are two: Anodic dissolution initiated cracking [19,20,26] and Hydrogen induced cracking [27,28]. Burleigh [26] related the latter mechanism rather to effect 7xxx series, whilst anodic dissolution was observed on 2xxx series alloys.

Often related to aqueous environment it is less known that stress-corrosion cracking is also an insidious failure mechanism in aircraft [20,29] and even spacecraft applications [30–32]. Water condensation, either atmospheric or in inhabited modules, exposure to coastal environments, typically at launch sites, and the presence of aggressive chemical substances such as cleaning solvents and hydraulic fluids or rocket propellants can promote stress-corrosion cracking on space hardware. In order to prevent the occurrence of SCC failures in space programs, the European Space Agency has developed advanced testing methodologies [33] as well as dedicated standards in collaboration with the European space industry, for the determination of the susceptibility of materials to SCC and the selection of suitable alloys for space hardware manufacturing, [34,35]. Due to their inaccessibility during service and high sustained stress levels, only materials with excellent resistance to SCC can be used for spacecraft and launchers structural applications. Initial internal SCC tests have shown poor results for AA2099 according to the standard [35] and further investigations towards SCC have been performed, including alternate immersion SCC tests, Slow Strain Rate Testing (SSRT) as well as electrochemical and X-Ray Diffraction analysis. The results of this extensive test campaign are presented in the current study.

2. Material and specimens

All test specimens used in the laboratory investigations were machined from a 37 mm thick plate of aluminium Alloy AA2099 in T86 state (solution heat treated, cold-worked by thickness reduction of 6% and artificially aged). Chemical composition and mechanical properties [7] are given in Tables 1 and 2 respectively. The dimensions of the samples used for performing the whole experimental test program are shown in Fig. 1. Different samples proportions (W, B, t), reported in the table of Fig. 1, have been used as presented in the separate test descriptions.

Table 1
Chemical composition of the alloys investigated in wt% (two columns).

Alloy	Cu	Li	Zn	Mg	Mn	Zr	Ti	Fe	Al
AA 2099-T86	2.50	1.75	0.56	0.30	0.29	0.08	0.02	0.03	Rem.
AA 7075-T651	1.34	/	5.43	1.94	0.04	/	0.05	0.15	Rem.

Table 2
Mechanical properties of the alloys investigated (Values in the ST direction).

Alloy	$R_{P0.2}$ [MPa]	R_m [MPa]	E [GPa]	Elongation [%]	Density [g/cm^3]
AA 2099-T86	427 (LT)	496 (LT)	78	5	2.63
AA 7075-T651	344	420	71	3	2.81

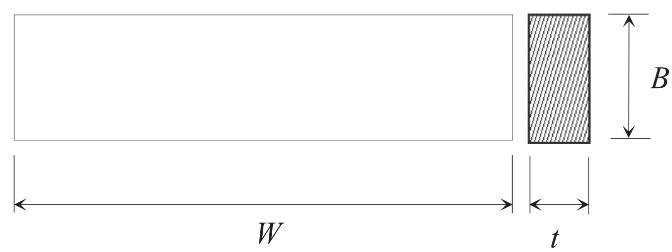

Fig. 1. Dimensions of the specimens used for performing the overall test program.

Table 3
Parameters and results of SCC testing of AA2099-T86 material.

Dimension [mm]	*Duration [days]*	*Number of samples*	*Stress level*	*Failure*	*SCC*	*Pits*
37 × 10 × 2	21	3	60% YS	0	No	x
37 × 10 × 4	21	3	60% YS	0	No	x
64 × 15 × 2	30	3	60% YS	0	No	x
64 × 15 × 4	30	3	60% YS	0	No	x
Control samples	21	2	Unstressed	0	No	x
Control samples	21	2	Unstressed	0	No	x

Table 4
Pit depth results of AA2099-T86 material.

Pit depth[μm]	*60% YS Stressed*	*Unstressed*
Tensile side	171.8	31.9
Standard deviation	± 146.0	± 21.6
Compressive side	119.3	
Standard deviation	± 64.2	

AA7075-T651 material was also used as a reference for performing the stress-corrosion cracking testing. Its composition and mechanical properties are summarised in Tables 1 and 2.

3. Experimental program

3.1. Stress Corrosion Cracking (SCC) test and subsequent Four Point Bending test

As general procedure materials for spacecraft and launchers structural applications are first tested at 75% of the yield strength under alternate immersion in 3.5% NaCl water solution according to [35] and classified in three tables based on the susceptibility to SCC, [34].