# On the Long-Term Stability of 6013-T6 Aluminium Alloy Sheet

#### R. Braun

German Aerospace Center (DLR), Institute of Materials Research, D-51170 Cologne, Germany

Keywords: AA6013, thermal stability, aging, microstructure, tensile properties, corrosion potential, intergranular corrosion, stress corrosion cracking

### Abstract

Alloy 6013-T6 sheet was thermally exposed at temperatures ranging from 85 to 150°C for time periods up to 3000 h, simulating long-term service usage. Microstructure, tensile properties, and corrosion behaviour of the sheet in the different heat treatment conditions were investigated. Transmission electron microscopy, tensile tests and various corrosion tests did not indicate a significant alteration in the microstructure and ambient temperature performance of alloy 6013-T6 after exposure to slightly elevated temperatures.

## 1. Introduction

The increasing age of the airline fleets has drawn attention to degradation due to fatigue and corrosion and to long-term stability of the material used in aircraft structure [1-3]. Designed with a life expectancy of about 20 years, growing numbers of aircraft extend their service life beyond the original life span. The major issues with aging aircraft are service loading, synergism between corrosion and fatigue, and natural aging effects. Investigations on alloy 2024-T3 currently used in fuselage skin sheet applications revealed that mechanical properties did not changed when as received sheet was thermally exposed at elevated temperature or material taken from aircraft with service usage was studied [4, 5]. However, the corrosion resistance decreased after long-term exposure. For future aircraft such as the A380, welded panels of the alloys 6013 and 6056 are incorporated into design concepts of the lower fuselage [6]. As first application of laser beam welding, an integrally stiffened shell of 6013 sheet has been built in new aircraft of the A318 [7]. The aim of the present work was to investigate the thermal stability of the alloy 6013-T6 performing microstructural examinations, tensile tests, and studies of the corrosion behaviour on sheet material thermally exposed at elevated temperatures.

## 2. Experimental

The material used was a 1.6 mm thick sheet of the alloy 6013-T6 (T6 heat treatment: 4 h at 191°C). The sheet was thermally exposed at temperatures between 85 and 150°C for time periods up to 3000 h. Microstructural examinations were performed using a transmission electron microscope operating at 300 kV. Tensile tests were carried out using transverse oriented flat tensile specimens with a width of 12.5 mm and a gauge length of 60 mm. The corrosion potential was measured according to the standard test method ASTM G69. Electrochemical tests were carried out in aerated aqueous 0.1 M NaCl solution. A potentiodynamic scan rate of 0.1 mV/s was used. The samples were polished

to 2500 grit. Susceptibility to intergranular corrosion was investigated performing continuous immersion tests in an aqueous chloride-peroxide solution according to ASTM G110 and alternate immersion tests in 3.5% NaCl solution according to ASTM G44. Exposure time periods were 24 h and 30 days in the former and latter tests, respectively. Coupons used were 25 by 30 mm in size. The stress corrosion cracking (SCC) behaviour was studied using two-point loaded bent beam specimens (ASTM G39), which were alternately immersed in an aqueous 3.5% NaCl solution (ASTM G44). The applied stress was 300 MPa in transverse direction. Constant extension rate tests were carried out applying a cross-head displacement rate of  $5.5 \times 10^{-6}$  mms<sup>-1</sup>. Transverse oriented flat tensile specimens with 16 mm gauge length and a cross section of 10 mm<sup>2</sup> were permanently immersed in an aerated aqueous solution of 3% NaCl + 0.3% H<sub>2</sub>O<sub>2</sub> at free corrosion potential. The area below the stress-elongation curve was used as parameter to determine the SCC susceptibility. Reference tests were carried out in dry laboratory air. Pre-exposure tests were performed to determine the degradation of specimens associated with immersion in the corrosive environment in the absence of stress.

## 3. Results and Discussion

Figure 1 shows transmission electron micrographs of alloy 6013-T6 thermally exposed to elevated temperatures. Fine needle-shaped and lath-shaped precipitates were observed, causing streaks in selected area diffraction pattern (Fig. 1a). These precipitates corresponded to the  $\beta$ " and Q' phases, which contribute to the strength of copper containing 6xxx series aluminium alloys in peak-aged condition [8]. A change in the matrix precipitation of 6013-T6 sheet related to the additional heat treatments was not found. Grain boundary particles were observed in 6013-T6 sheets which were thermally exposed at 150°C and, to a lesser extent, at 120°C for 1000 h (Fig. 1b).

Transverse tensile properties of alloy 6013 in different heat treatment conditions are given in Table 1. Thermal exposure at temperatures between 85 and 150°C for 1000 h did not cause significant changes in the tensile properties compared to values determined in the T6 temper. A slight reduction in the ultimate tensile strength and ductility was found for 6013-T6 specimens which were additionally aged at 150°C for 1000 h.



Figure 1: Transmission electron micrographs of 6013-T6 sheet thermally exposed (a) at 100°C for 2000 h and (b) at 150°C for 1000 h, showing matrix precipitates and grain boundary particles, respectively.

Table 1: Transverse tensile properties of 6013 sheet in different heat treatment conditions.

Heat Treatment	0.2 % proof stress [MPa]	Ultimate tensile strength [MPa]	Fracture elongation [%]
Т6	344	403	13.7
T6 + 1000 h / 85°C	353	408	14.0
T6 + 1000 h / 100°C	347	406	13.9
T6 + 1000 h / 120°C	353	409	13.5
T6 + 1000 h / 150°C	350	393	10.4

Figure 2 shows the potentiodynamic polarization curves of 6013-T6 sheet thermally exposed at 85°C for 3000 h and at 150°C for 1000 h using aerated 0.1 M NaCl solution. The corrosion potential coincided with the pitting potential, indicated by an instant sharp increase of current when anodically polarizing from the corrosion potential. Values of the corrosion potential of 6013 sheet in the T6 temper and after additional thermal exposures are listed in Table 2, obtained from polarization curves and measured according to the ASTM G69. Potentiodynamic scans indicated a slight shift of the corrosion potential to cathodic values with increasing heating. A difference of 20 mV was found between the corrosion potential of 6013 sheet in the T6 temper and after an additional thermal treatment at 150°C for 1000 h. When immersed in an aqueous chloride-peroxide solution, the corrosion potential of 6013-T6 was about 10 mV more noble than those measured for sheet after various additional heat treatments. Considering scatter in data, these small changes in corrosion potential were virtually not significant.



Figure 2: Potentiodynamic polarization curves of 6013-T6 sheet additionally heat treated at 85°C for 3000 h and at 150°C for 1000 h, using an aqueous solution of 0.1 M NaCl.

Table 2: Corrosion potential	(in mV <sub>SCE</sub> ) of 6013 sheet in different heat treatment conditions obtained from the
standard test method ASTM	G69 and from potentiodynamic polarization scans in 0.1 M NaCl solution

Heat Treatment	Corrosion Potential (pot. scan)	Corrosion Potential (ASTM G69)
Т6	-0.647	-0.732
T6 + 1000 h / 85°C	-0.650	-0.742
T6 + 3000 h / 85°C	-0.656	-0.744
T6 + 1000 h / 100°C	-0.649	-0.746
T6 + 2000 h / 100°C	-0.662	-0.746
T6 + 1000 h / 120°C	-0.661	-0.746
T6 + 1000 h / 150°C	-0.667	-0.748

Immersion tests in an aqueous chloride-peroxide solution according to ASTM G110 indicated sensitivity to intergranular corrosion for 6013 sheet in the different heat treatments studied (Fig. 3a). Pitting and intergranular corrosion were observed when coupons were alternately immersed in 3.5% NaCl solution (Fig. 3b). Maximum depth of corrosion attack measured in metallographic sections is plotted in Figure 4. As found in both immersion tests, thermal exposure at elevated temperature did not cause a significant change of corrosion type and depth of attack. Under alternate immersion conditions, a slight increase in depth of corrosion was observed for alloy 6013-T6 thermally exposed at 120 and 150°C, probably caused by grain boundary precipitates.



Figure 3: Metallographic sections of coupons of 6013-T6 sheet thermally exposed at  $100^{\circ}$ C for 2000 h, which were immersed in an aqueous chloride-peroxide solution for 24 h (a) and alternately immersed in 3.5% NaCl solution for 720 h (b).



Figure 4: Maximum depth of corrosion attack measured in metallographic sections of coupons of 6013 sheet in different heat treatment conditions, which were immersed in an aqueous chloride-peroxide solution for 24 h or alternately immersed in 3.5% NaCl solution for 30 days.

Table 3: Time-to-failure data of 6013 sheet in different heat treatment conditions obtained from alternate immersion tests in 3.5% NaCl solution using two-point loaded bent beam specimens

Heat Treatment	Time-to-Failure
Τ6	3× > 40 days
T6 + 1000 h / 85°C	3× > 40 days
T6 + 1000 h / 100°C	3× > 75 days
T6 + 1000 h / 120°C	3× > 75 days
T6 + 1000 h / 150°C	3× > 75 days

Results of alternate immersion tests in 3.5% NaCl solution according to ASTM G44 are listed in Table 3, indicating high SCC resistance for 6013 sheet in the different heat treatment conditions. At an applied stress of 300 MPa in transverse direction, failure was not observed within 40 days of exposure. For 6013-T6 sheet additionally aged at temperatures between 100 and 150°C, bent-beam specimens did not fail even during a prolonged exposure length of 75 days.

Results of the constant extension rate tests are plotted in Figure 5. Duplicate specimens were tested. Compared to the reference tests performed under inert environmental conditions, values of the area below the stress-elongation curve were lower for specimens dynamically strained in the corrosive environment. On the fracture surfaces, pitting and intergranular corrosion as well as transgranular environmentally assisted cracking were observed (Fig. 6a). Intergranular stress corrosion cracking did not occur. A severe degradation was also found for pre-exposed specimens.



Figure 5: Area below the stress-elongation curve for 6013 sheet in different heat treatment conditions. Duplicate specimens were dynamically strained in an inert environment and in an aqueous solution of 3% NaCl + 0.3% H<sub>2</sub>O<sub>2</sub>. Data for pre-exposed specimens are included.



Figure 6: Scanning electron fractographs of 6013-T6 sheet additionally heat treated at 85°C for 3000 h. The specimens were (a) dynamically strained in an aqueous solution of 3% NaCl + 0.3% H<sub>2</sub>O<sub>2</sub> and (b) pre-exposed in the corrosive environment and subsequently tensile tested in an inert environment.

Fractographic examinations of pre-exposed specimens which were subsequently tensile tested under inert environmental conditions revealed pitting and intergranular corrosion

(Fig. 6b). The deterioration related to pre-exposure was similar to that of specimens dynamically strained in the corrosive environment. Therefore, the degradation of the latter specimens was primarily caused by corrosion independent upon stress. The constant extension rate testing technique did not indicate sensitivity to intergranular stress corrosion cracking for 6013 sheet in the T6 temper and after various thermal exposures at elevated temperatures. Transgranular stress corrosion cracking has been observed in aluminium alloys when severe loading conditions were applied, such as performing constant extension rate tests [9]. The reduction of the area below the stress-elongation curve caused by this type of cracking was slight [10].

#### 4. Conclusions

Results of the present investigations indicated that alloy 6013-T6 used in fuselage applications has a stable microstructure with regard to long periods of service usage. Thermal exposures at 85°C for 3000 h and at 100°C for 2000 h, which should simulate long-term natural aging during aircraft life-time, did not result in changes of the microstructure, tensile properties and the corrosion behaviour of 6013-T6 sheet. More severe heat treatments at higher temperatures caused a slight degradation probably associated with beginning overaging effects.

#### References

- J.N. Scheuring and A.F. Grandt, Transactions of the ASME, 119, 380-386, 1997. [1]
- [2] [3] M.L. Du, F.P. Chiang, S.V. Kagwade, and C.R. Clayton, Int. J. Fatigue, 20, 743-748, 1998.
- P.Shi and S. Mahadevan, Int. J. Fatigue, 25, 457-469, 2003.
- R. Braun, C. Juricic, and G. Tempus, Progress in Mechanical Behaviour of Materials, ICM8, Vol. 2, [4] edited by F. Ellvin and J.W. Provan, Fleming Printing Ltd, Victoria, 597-602, 1999.
- G. Tempus, Airbus Deutschland GmbH, Bremen, unpublished results, 1999. [5]
- [6] H.-J. Schmidt, B. Schmidt-Brandecker, N. Ohrloff, and T. Fleischer, ICAF '99, Vol. 1, edited by J. L. Rudd and R.M. Bader, EMAS, Cradley Heath, 537-552, 1999.
- W. Zink, Advanced Aerospace Materials, edited by M. Peters and W.A. Kaysser, Deutsche [7] Gesellschaft für Luft- und Raumfahrt e.V., Bonn, 25-32, 2001.
- S. Esmaeili, X. Wang, D.J. Lloyd, and W.J. Poole, Metall. Mater. Trans. A, 34A, 751-763, 2003. [8]
- [9] N.J.H. Holroyd, Environment-Induced Cracking of Metals, edited by R.P. Gangloff and M.B. Ives, NACE, Houston, 311-345, 1990.
- [10] R. Braun, Werkstoffe und Korrosion, 45, 255-263, 1994.