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Evaluation of Sc-Bearing Aluminum Alloy C557 for Aerospace Applications

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Abstract. The performance of the Al-Mg-Sc alloy C557 was evaluated to assess its potential for a broad range of aerospace applications, including airframe and launch vehicle structures. Of specific interest were mechanical properties at anticipated service temperatures and thermal stability of the alloy. Performance was compared with conventional airframe aluminum alloys and with other emerging aluminum alloys developed for specific service environments. Mechanical properties and metallurgical structure were evaluated for commercially rolled sheet in the as-received H116 condition and after thermal exposures at 107°C. Metallurgical analyses were performed to define grain morphology and texture, strengthening precipitates, and to assess the effect of thermal exposure.

Introduction. Wrought, non-heat-treatable aluminum-magnesium alloys are potential candidates for structural applications because of their low density, good weldability, and excellent corrosion resistance [1]. The addition of scandium has been shown to increase the strength while maintaining the ductility of aluminum-magnesium alloys [2, 3]. Additions of scandium and zirconium to Al-Mg alloys synergistically promote strengthening and result in higher strengths than either Sc or Zr additions produce alone [4]. In wrought Al-Mg-Sc alloys with Zr additions, strengthening occurs primarily by development of coherent Al₃Sc and Al₃Zr dispersoids. Additional strengthening is achieved by grain refinement, as the dispersoids inhibit recrystallization during working [4].

The moderate strength level achieved in Al-Mg-Sc alloys combined with the inherent corrosion resistance of the Al-Mg system makes these alloys attractive for airframe structural applications. Sc-bearing dispersoids are inherently thermally stable [5], which enables consideration for structural applications where extended elevated temperatures are anticipated. However, in alloys with magnesium levels above about 3.5%, precipitation of the β phase, Al₈Mg₅, can occur during thermal exposure and has been shown to be detrimental to corrosion resistance [5]. Limited data available at cryogenic temperatures [2] suggests that Al-Mg-Sc alloys are suitable for service down to liquid hydrogen temperatures.

In the current study, the Al-Mg-Sc alloy C557 was evaluated to assess its potential for a broad range of aerospace applications. Particular emphasis is placed on strength-toughness behavior at temperatures from -184°C to 107°C to establish service temperature applicability and after exposures up to 10,000 hours at 107°C to evaluate thermal stability.

Materials

The material evaluated was produced by Alcoa as a 4,500 kg (10,000 lb) commercial scale ingot. Proprietary thermomechanical processing was used to produce rolled sheets, 1.22 m x 3.66 m, both 1.6 mm and 2.3 mm thick, in the H116 condition. The thermomechanical processing schedule was tailored to optimize the sheet for superplastic forming and the H116 heat treatment [1] was chosen to ensure good stress corrosion resistance. The chemistry of the rolled sheet, provided in Table 1, is very similar to the Russian alloy 1535 [2]. As shown in

Table 1. Chemical Composition of C557 Rolled Sheet (in weight percent).

Sheet Thickness	Mg	Sc	Mn	Zr	Zn	Fe	Si
1.6 mm	3.94	0.22	0.62	0.100	0.016	0.099	0.052
2.3 mm	4.02	0.24	0.62	0.096	0.015	0.095	0.062

Fig. 1, the resulting sheet exhibits very thin pancake shaped grains, aligned in the rolling direction and uniform throughout the thickness. Mg-bearing particles approximately $2\mu\text{m}$ in size were observed at grain boundaries with occasional Fe, Si-bearing inclusions, ranging from 5 to $20\mu\text{m}$ in size, as shown in Fig. 2. Results from orientation distribution function (ODF) texture analysis were similar for both sheets and revealed a strong deformation texture, dominated by Brass and shear components, and moderate recrystallization texture.

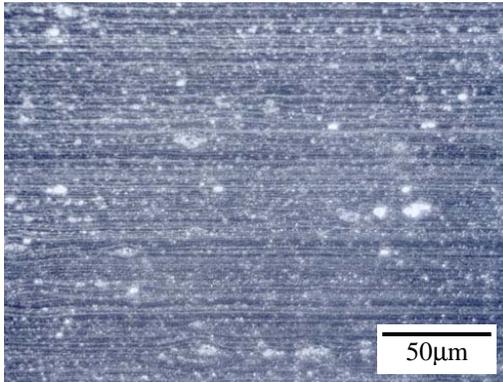


Fig. 1. Typical microstructure of the C557 sheets evaluated.

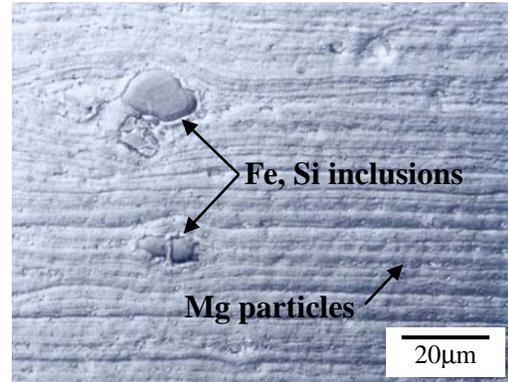


Fig. 2. Nomarski image of the C557 sheet illustrating particle distribution.

Procedures

Tensile and fracture toughness properties were determined for material in the H116 condition and after isothermal exposures at 107°C , for times up to 10,000 hours. Properties were measured for material in the H116 condition at 25°C , -184°C , and 107°C . Ambient temperature properties were evaluated after thermal exposure for 1,000, 3,000, and 10,000 hours at 107°C . The material was isothermally exposed as pieces of sheet from which specimens were machined after exposure.

Tensile properties were measured using sub-size, full sheet thickness specimens in both the longitudinal (L) and transverse (T) orientations. All test procedures were in accordance with ASTM E8-96. For each test, yield strength, ultimate tensile strength, percent elongation to failure (gauge length = 2.54 cm), and elastic modulus were determined.

Trends in fracture toughness with temperature and thermal exposure were evaluated for both LT and TL orientations using full sheet thickness compact tension (CT) specimens with width, $W = 50.8$ mm. Fracture toughness was determined by the single specimen, J-integral method according to ASTM E1152-87. Physical crack length was determined by the potential drop method. The crack initiation toughness (K_{JIC}), in accordance with ASTM E813-87, and tearing modulus (T_R) [6] were determined from the crack extension data for each test. The fracture surfaces of the C(T) specimens were examined in an scanning electron microscope (SEM) to investigate the fracture mechanisms. Examinations were concentrated at approximately 0.4 mm and 4 mm of crack growth in order to characterize fracture morphology under conditions of both plane strain and plane stress, respectively.

Additional fracture toughness tests were performed using middle crack tension, M(T), specimens to determine apparent fracture toughness, K_{app} , for material in the H116 condition. M(T) specimens nominally 102 cm wide were tested in the LT orientation and specimens

nominally 61 cm wide were tested in both LT and TL orientations. All M(T) specimens were tested at ambient temperature with procedures in accordance with ASTM E561-94. The stress intensity factor, K , was calculated using Eq. 1,

$$K = (P/BW)[\pi a \sec(\pi a/W)]^{1/2} \quad (1)$$

where P is load, B is thickness, W is width, and a is the half crack length. The specimens were fatigue precracked until the crack length to width ratio, $2a/W$, was approximately 0.33. Local out-of-plane buckling was restricted during the fracture test and physical crack length was determined by unloading compliance and visual measurement. K_{app} was calculated using Eq. 1 based on maximum load ($P=P_{max}$) and the initial crack length in the fracture test.

Results and Discussion

Effect of temperature. Variations in properties with test temperature for material in the H116 condition were similar for both gages of sheet. Tensile results shown in Fig. 3 were consistent with data reported for Al-Mg-Sc alloys [2-4]. Compared with ambient temperature, tensile strengths increased by at least 20% at -184°C and were reduced by approximately 10% at 107°C . Elongation was greater at both 107°C and -184°C , with values approximately 50% higher for the transverse orientation and nearly doubled for the longitudinal orientation. Tensile strength anisotropy was low, with values for L and T orientations within 5% at all temperatures. Variations in ductility were greater, with differences between L and T orientations exceeding 25% at ambient temperature.

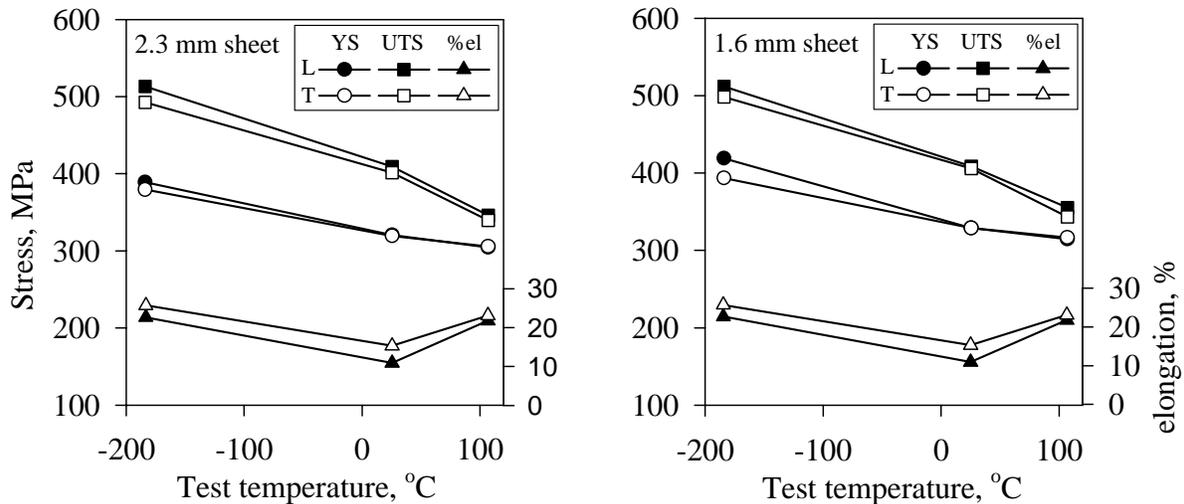


Fig. 3. Effect of test temperature on the tensile properties of C557 sheet in the H116 condition.

Both sheet gages exhibited continuously rising R-curves, shown in Fig. 4, for all temperatures and orientations tested. Higher toughness was achieved at elevated temperature, as evidenced by the overall higher R-curves, but toughness appeared comparable for ambient and cryogenic temperatures. Analysis of the R-curves indicated that initiation toughness, K_{JICi} , varied inversely and tearing modulus, T_R , varied directly with temperature over the range from -184°C to 107°C , as shown in Fig. 5, with the greatest thermal effect occurring between ambient and elevated temperatures.

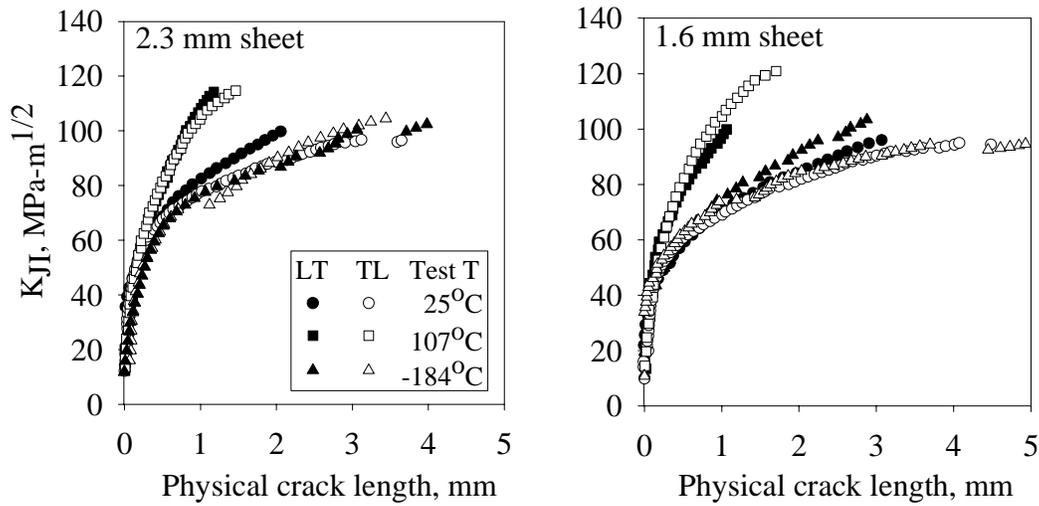


Fig. 4. Variation in K_{JICi} and T_R of C557 sheet with test temperature.

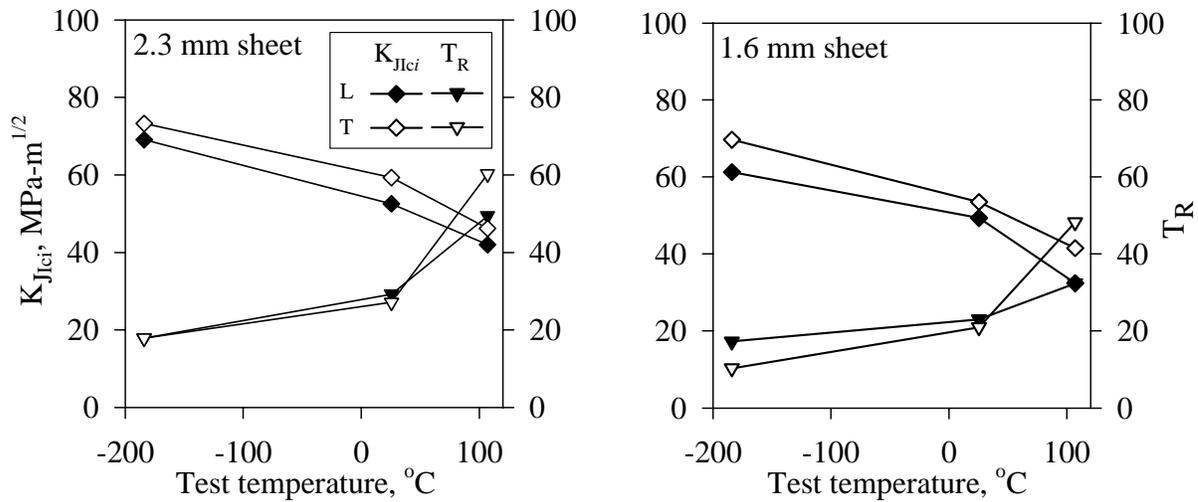


Fig. 5. Variation in K_{JICi} and T_R of C557 sheet with test temperature.

SEM examination indicated that the fracture mode was primarily transgranular microvoid coalescence (TGMVC) at ambient temperature. The example shown in Fig. 6 was typical for both plane strain and plane stress fracture. Void initiating particles ranged in size from 1-10 μm , resulting in a bimodal distribution of ductile dimples linked by apparent void sheets. The fracture mode at elevated temperature was also TGMVC, however, fracture under plane strain conditions exhibited large, shallow, equiaxed dimples, and an absence of apparent void sheets, which may indicate that the lower initiation toughness reflects primarily the reduced tensile strength at 107°C. Delaminations, linked by regions of TGMVC, were observed at cryogenic temperature, as shown in Fig. 7. The delaminations, which occur perpendicular to the primary crack plane and parallel to the crack growth direction, begin within 200 μm of the fatigue precrack and may explain the enhanced initiation toughness observed. Studies of delamination

toughening in Al-Li alloys indicate that the toughness increase occurs due to reduction of through-thickness constraint at the crack tip associated with the formation of additional free surfaces [7, 8].

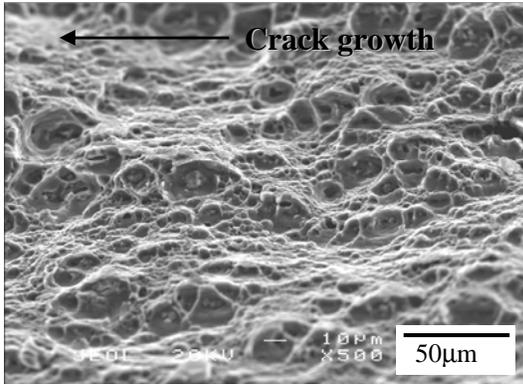


Fig 6. TGMVC typical for plane stress and plane strain fracture at ambient temperature.

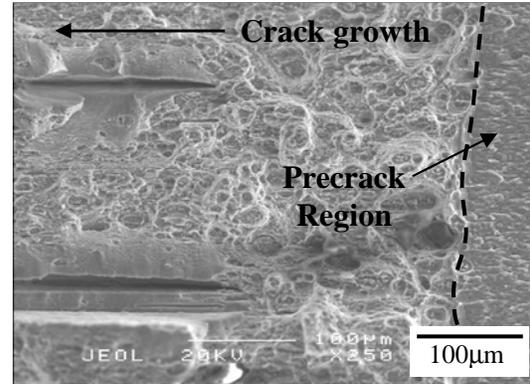


Fig 7. Delaminations observed in the region of stable crack extension at -184°C .

Effect of thermal exposure. The trends in ambient temperature properties with exposure at 107°C were similar for both sheet gages. Tensile results shown in Fig. 8 indicate that ultimate and yield strengths were reduced by about 5% and 10%, respectively, after 10,000 hours exposure at 107°C . Reductions in elongation after thermal exposure are approximately 20% for the longitudinal orientation and over 35% for the transverse orientation, with most of the

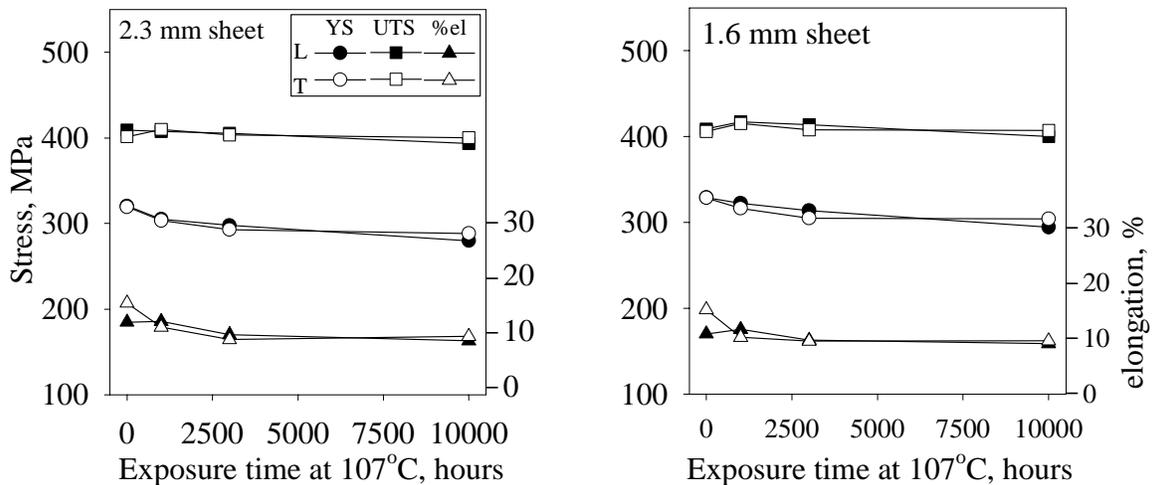


Fig. 8. Variation in tensile properties of C557 sheet with thermal exposure.

reduction occurring by 3,000 hours. Anisotropy in tensile strengths was very low, with values for L and T orientations within 3% for all exposure times. Ductility anisotropy was significantly reduced with thermal exposure. Braun [5] demonstrated that although tensile properties of a similar Al-Mg-Sc alloy remained stable with thermal exposure, corrosion resistance deteriorated due to β phase precipitation at grain boundaries.

The R-curves resulting from ambient temperature tests after thermal exposure, shown in Fig. 9, suggest that toughness remains relatively stable. However, trends in initiation toughness and tearing modulus with thermal exposure, shown in Fig.10, reflect reduction in toughness after 1,000 and 3,000 hours exposure, with recovery to pre-exposure levels by 10,000 hours.

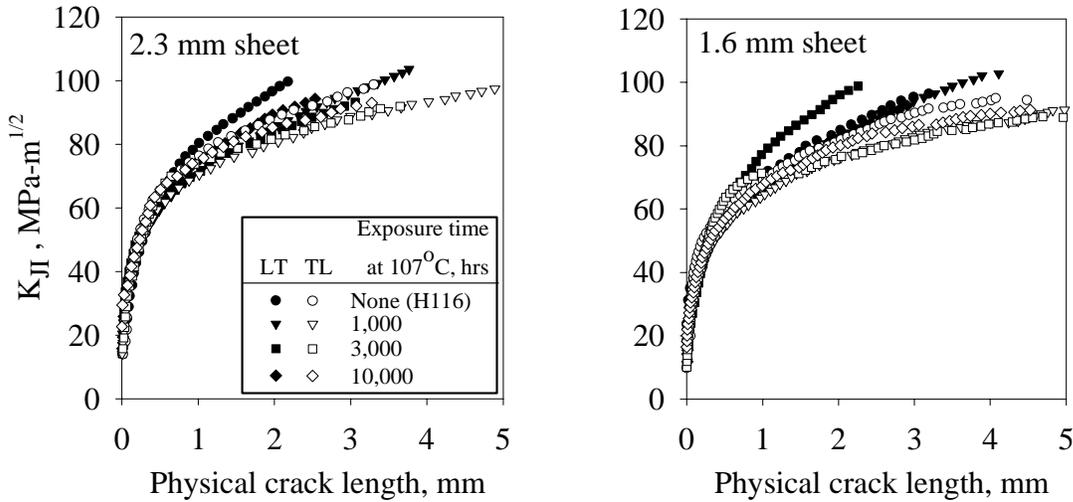


Fig. 9. Variation in R-curves of C557 sheet with exposure time at 107°C.

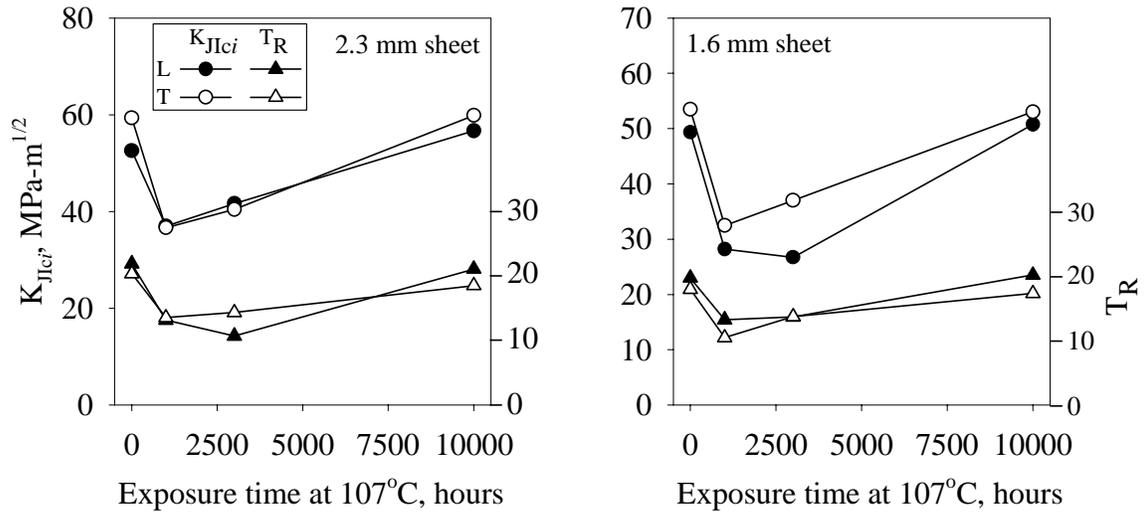


Fig. 10. Variation in K_{Ji} and T_R of C557 sheet with exposure time at 107°C.

SEM fractography indicated that the fracture morphology was similar for all exposure times. Fracture occurred by TGMVC, as shown in Fig. 11. The fraction of large dimples was greater and of apparent void sheets less than observed for unexposed materials, particularly in the plane strain fracture region. Transmission electron microscopy (TEM) analysis of material exposed for 10,000 hours at 107°C revealed grain boundary precipitation of the β phase, Al_8Mg_5 . Based on the similarity of fracture surfaces for all thermal exposure conditions, it is likely that precipitation had occurred by 1,000 hours. For specimens exposed for 3,000 and 10,000 hours, delaminations were noted in the fatigue precrack region, as shown in Fig. 12. The transition from the precrack

to stable crack extension is marked by large plastic deformation zones at the end of each delamination. The resulting crack tip blunting effect may explain the higher initiation toughness values compared with material exposed for 1,000 hours. The delaminations occur over 35% and 60% of the sheet thickness for 3,000 and 10,000 hour exposure times, respectively, which could explain the enhanced effect on toughness for longer exposure times.

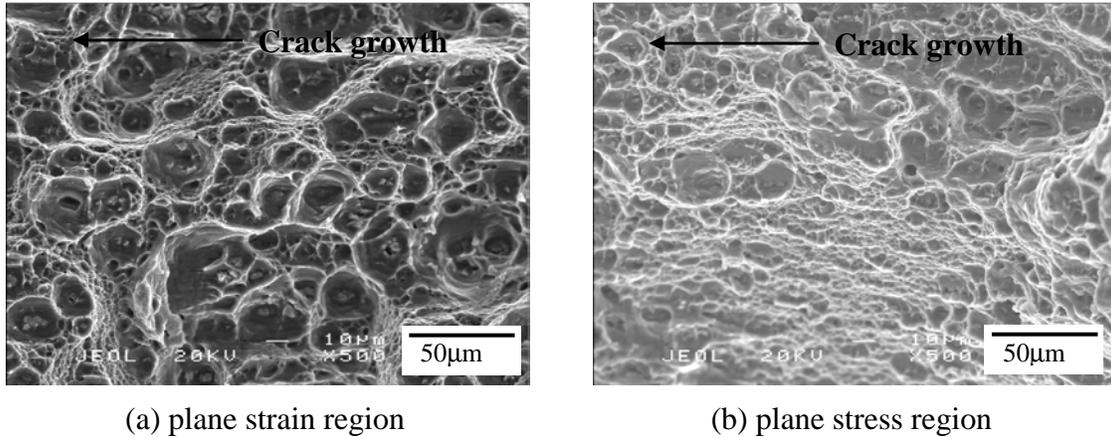


Fig. 11. Typical TGMVC morphology after thermal exposure at 107°C.

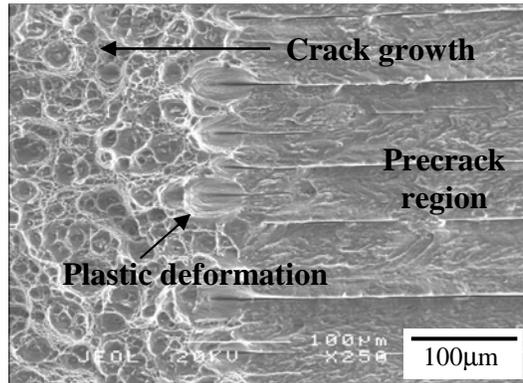


Fig. 12. Delaminations in precrack region after thermal exposure at 107°C.

K_{app} Fracture Toughness Assessment. Airframe manufacturers have traditionally relied on K_{app} for assessing the fracture toughness of large sheet structures. K_{app} and tensile yield strength results are provided in Table 2 for C557 compared with values for aerospace alloys evaluated during other in-house research programs. C557 exhibited strength and toughness values comparable to 2024-T3 based on the 61 cm panels, but exhibited about 12% lower K_{app} in the 102 cm panels. Overall, the strength-toughness combination for C557 was lower than for Al-Cu-Mg-Ag alloy, C415, and Al-Li alloy, ML377, which were developed in the High Speed Research program for elevated temperature aircraft service [9]. The toughness level for C557 compared well with 7050 and 7475, but strengths were lower.

Table 2. Fracture toughness results from 61 and 102 cm wide M(T) panels.

Alloy/ Condition	Width, cm	Thickness, mm	Orientation	YS, MPa	K_{app} , MPa-m ^{1/2}
C557-H116	102	2.3	L, LT	320.4	126.2
C557-H116	102	1.6	L, LT	328.7	124.0
2024-T3	102	1.6	L, LT	310.1	142.7
7475-T7	102	1.6	L, LT	458.9	117.2
C557-H116	61	1.6	L, LT	328.7	104.7
C557-H116	61	1.6	T, TL	328.0	115.5
C557-H116	61	2.3	L, LT	320.4	108.6
C557-H116	61	2.3	T, TL	319.0	118.0
2024-T3	61	1.6	L, LT	310.1	116.5
C415-T8	56	2.3	L, LT	503.0	124.1
ML377-T8	56	2.3	L, LT	526.4	120.3
7050-T73	56	2.3	L, LT	468.5	111.1

Conclusions

Measured mechanical properties for the Al-Mg-Sc alloy C557 and trends with both test temperature and thermal exposure were similar for both 1.6 and 2.3 mm gage sheet. While strength and toughness both increased at cryogenic temperature, suggesting that C557 is viable for low temperature service, delaminations occurred during fracture at -184°C and must be better understood prior to structural application. Thermal stability in tensile properties was demonstrated by less than 5% variation in ambient temperature tensile strengths with exposure at 107°C . Fracture toughness decreased with thermal exposure and was primarily due to β phase precipitation at grain boundaries. Improvement in fracture toughness with extended thermal exposure was associated with the occurrence of large plastic deformation zones at fatigue precrack delaminations prior to the onset of stable cracking. Yield strength and apparent fracture toughness values of C557 were within 10% of established values for 2024-T3 sheet, but strength and toughness were somewhat lower than that of alloys developed specifically for elevated temperature service.

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