Mechanical properties of AA5083 in different tempers at low temperatures

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Abstract. Aluminium alloy 5083 was chosen for use in the critical cryogenic applications of shipboard transportation of liquefied natural gas (LNG). In the present work, the tensile, Charpy impact, bend and fatigue crack propagation behaviours of aluminium alloy 5083 in temper O, H112, and H32 were investigated both at room and cryogenic temperatures.

Keywords: AA5083, tension, Charpy impact, fatigue crack growth rate

1. Introduction

The Al-Mg alloy 5083 (AA5083), which contains 4-4.9 wt% Mg, takes advantage of exceptional combination of economy of fabrication, weldability, and corrosion resistance. The AA5083 are a medium-strength, non-heat treatable wrought aluminium alloy and its strength increases with increasing Mg content. Since AA5083 contains more than 3wt% Mg, it is supersaturated at room temperature and the excess of Mg solute atoms tend to precipitate out as β-phase (Mg_2Al_3) particles located along the grain boundaries during prolonged aging at room temperature, or after shorter periods of exposure at slightly elevated temperatures in the range 65-200 ^{o}C [1]. Thus the AA5083 is suitable for utilization at room temperature and it is highly desired for being used in fast sea transportation for commercial and military applications, for example, military vehicles and high performance vessels [2, 3]. Moreover, AA5083 is found to demonstrate extremely high toughness both at room and cryogenic temperatures. In addition, its tensile strengths, elastic moduli and fatigue properties at cryogenic temperature are as high as, or even higher than those at room temperature, which has been attributed to its very low Peierls stresses, the inherent structure containing a small number of secondary precipitates, and a high notch yield ratio [4]. These properties make the AA5083 the most widely used for critical

arctic and cryogenic applications such as bridges, marine structure, chemical processing equipment, superconducting machinery, and storage and transport tanks for cryogenic fluids.

The AA5083-O, which is strengthened by solid solution additions of Mg and used in a annealed condition, has been chosen for use in construction of large spherical tanks for shipboard transportation of liquefied natural gas (LNG) at service temperatures as low as 111 K [4, 5]. An interpretation of fatigue crack initiation and propagation behaviour of the AA5083-O at cryogenic temperature has been conducted to facilitate the design for leak-before-failure criterion for LNG tanks.

The temper designated in O state means in the annealed condition, which is applied to wrought aluminium alloys to obtain the lower strength temper but usually to increase subsequent workability. The AA5083-O has been investigated for LNG tanks and the AA5083 is also used in a temper designated H, i.e., strain hardened, which usually increases its strength by means of strain hardening. This temper may or may not have supplementary thermal treatments to produce some reduction in strength. The temper H1 represents strain hardened only, which is applied to AA5083 that has been strain hardened to obtain a desired level of strength but without a supplementary thermal treatment. The number following H1 indicates degree of strain hardening. The temper H3 represents strain hardened and stabilized, which is applied to AA5083 that has been strain hardened and then stabilized either by a low temperature thermal treatment or as a result of heat introduced during fabrication of the product. The stabilization treatment usually improves its ductility. The H3 temper is usually used only for those aluminium alloys that will gradually age soften at room temperature if they are not stabilized. The number following the H3 indicates the degree of strain hardening remaining after stabilization. In the present work, mechanical properties in terms of tensile, bend and Charpy impact at cryogenic temperatures of AA5083 in temper O, H112, and H32 were investigated. In addition, damage-tolerance fatigue life prediction methods are required for critical cryogenic components like LNG tanks, which is based on fatigue crack growth data, service loading conditions, and non-destructive inspection (NDI) results. Among these parameters, the fatigue crack propagation is mainly based on laboratory test data, thus the fatigue crack growth rates of the AA5083 in different tempers, i.e., O, H112, and H32, were investigated both at room and liquid nitrogen temperatures.

2. Experimental Details

AA5083 plates with a thickness of 30 mm in tempers O, H112, and H32 herein after referred as T-O, T-H112 and T-H32. The specimen geometries for tensile, fatigue crack growth rate (FCGR), Charpy impact, and bend testing are shown in Fig. 1(a-d). The dumb-bell shape tensile specimen has a gauge length, width, and thickness of 30 mm, 15 mm, and 2 mm respectively, which complies with ISO 6892-3. The compact tension specimen for test of FCGR, as shown in Fig. 1b, complies with ASTM E647 and ISO 12108, and the specimen has an initial ratio of crack length (a) to width (W) of 0.35. The V-notch specimen for Charpy impact testing, shown in Fig.1c, complies with ISO 148-1. The specimen geometry for three-point bend test, shown in Fig. 1d, complies with ISO 7438. Both the tensile and bend tests were conducted in liquid nitrogen in a displacement control on a 100 kN capacity electro-mechanical test machine (MTS model-SANS CMT5105S). The local deformation during tensile testing was monitored with a cryogenic-grade Epsilon extensometer with a gauge length of 25 mm. The mechanical tests at

low temperatures were conducted with a homemade cryostat and the 77 K environment was obtained by immersing the test jig and specimen into liquid nitrogen in the cryostat. The Charpy impact test was conducted with an impact testing machine (model: MTS SANS XJ-300A) with an alternative hammer of 150 J energy. The Charpy impact test at 77 K was conducted with specimens immersed in liquid nitrogen for more than 15 min that were then transferred to the test machine within 5 s to keep the temperature, whereas the test at 150 K was conducted with specimens placed in 150 K environmental cryostat for more than 5 h and then were transferred to the test machine within 5 s. The fatigue crack propagation behaviour was investigated with a 120 kN capacity, servo-hydraulic dynamic test machine (Instron Model 8850). The crack mouth opening displacement (CMOD) was recorded with a cryogenic-grade Epsilon clip-on extensometer. The 77 K environment was obtained as that for both tensile and bend tests. The test was conducted with a constant-load controlled mode and with a stress ratio (R) of 0.1, i.e., a stress intensity factor K-increasing method, and the tests were conducted at a frequency of 20 Hz and 10 Hz at room temperature and 77 K respectively.
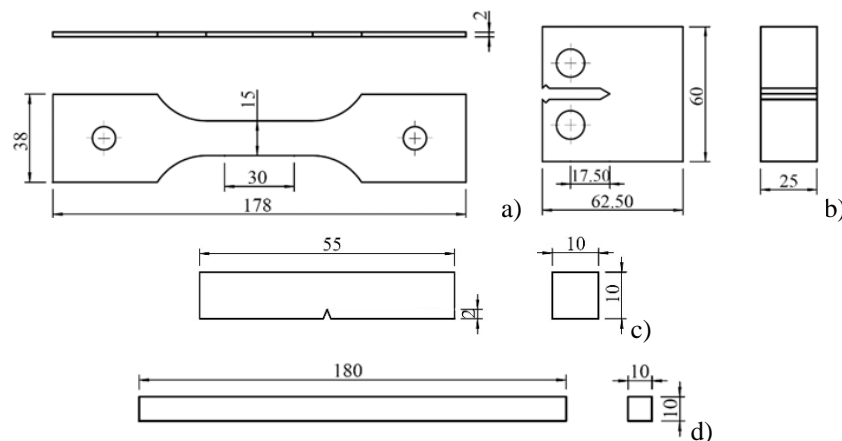

Figure 1. Specimen geometries for a) tensile, b) FCGR, c) Charpy impact, and d) bend testing.

3. Results and Discussion

3.1 Tensile properties

The cryogenic tensile properties of the AA5083 in different tempers are summarized in Table 1. It is found that the average 0.2% proof stress ($R_{p0.2}$) of the T-O, the T-H112, and the T-H32 at 77 K is 177.4 MPa, 175.4 MPa and 176.0 MPa, respectively. The Young's moduli of the T-O, T-H112 and T-H32 all demonstrate relatively large scatter but the average values are of a similar level. The average ultimate tensile strength (R_m) of the T-O, T-H112, and T-H32 at 77 K is 421.0 MPa, 417.0 MPa, and 419.8 MPa, respectively, whereas the average elongation at failure (A) of the T-O, T-H112, and T-H32 at 77 K are all around 45%. These results indicate that T-O, T-H112 and T-H32 fractured with a ductile behaviour in liquid nitrogen. Typical engineering stress-strain curve of AA5083 tested at 77 K is shown in Fig. 2, which confirms that the AA5083 undergoes a large plastic deformation before final fracture. Based on results of tensile properties including the 0.2% proof stress, ultimate tensile strength, and elongation at failure, the effect of O, H112, and H32 temper on cryogenic tensile strength and ductility at 77 K is slight.

Table 1 Tensile properties of T-O, T-H112, and T-H32 at 77 K

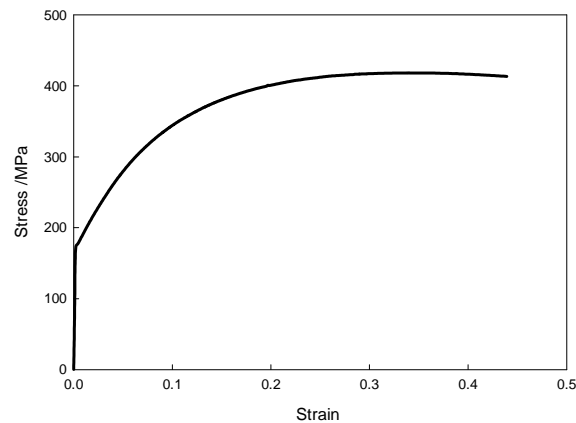| No.	$R_{p0.2}$ /MPa	R_m /MPa	E /GPa	A /%
T-O				
#-1	177	420	85	47
#-2	177	420	78	47
#-3	175	420	80	48
#-4	178	420	88	46
#-5	180	425	81	44
	177.4±1.82	421.0±2.24	82.4±4.04	46.4±1.52
T-H112				
#-1	174	415	75	43
#-2	176	420	72	47
#-3	176	415	88	45
#-4	178	420	89	48
#-5	173	415	89	47
	175.4±1.95	417.0±2.74	82.6±8.38	46.0±2.00
T-H32				
#-1	179	420	82	49
#-2	175	420	85	40
#-3	177	420	80	48
#-4	174	420	75	46
#-5	175	419	86	41
	176.0±2.0	419.8±0.45	81.6±4.39	44.8±4.09

Figure 2. Tensile stress-engineering strain curve of T-O at 77 K.

3.2 Bend properties

   The bend properties of T-O, T-H112, and T-H32 tested at 77 K are listed in Table 2. The average bend moduli of T-O, T-H112, and T-H32 are 76.0 GPa, 71.8 GPa, and 71.8 GPa. Considering the bend testing uncertainty, it is found that the temper has a negligible effect on the cryogenic bend modulus of AA5083. The average cryogenic bend strength of T-H32 is

larger than that of T-O and T-H112, whereas T-O exhibits a slightly larger value than that of T-H112. A typical bending stress-strain curve of the AA5083 at 77 K is shown in Figure 3, which indicates a typical ductile behaviour. Moreover, serrated stress-strain behaviour was observed, as shown in Fig. 3.

Table 2 Bend properties of T-O, T-H112, and T-H32 at 77 K

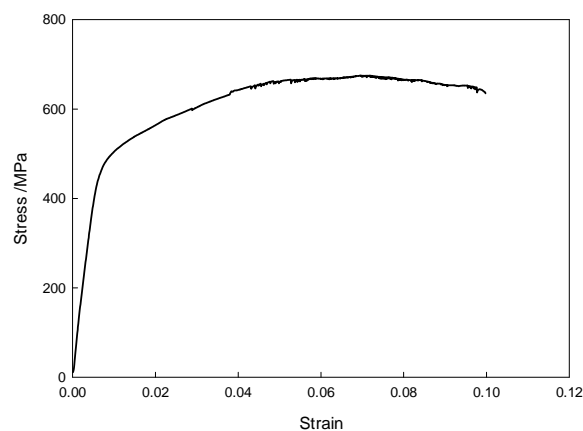| No.	Bend strength /MPa	Bend Modulus /GPa
T-O		
#-1	695	81
#-2	650	79
#-3	675	77
#-4	685	71
#-5	645	72
	670±21.8	76.0±4.36
T-H112		
#-1	650	72
#-2	650	74
#-3	640	69
#-4	645	71
#-5	660	73
	649±7.42	71.8±1.92
T-H32		
#-1	715	70
#-2	705	73
#-3	700	72
#-4	705	72
#-5	700	72
	705±6.12	71.8±1.10

Figure 3. Bending stress-strain curve of T-O at 77 K.

3.3 Charpy impact properties

The Charpy impact energy can be described as notch toughness of a material, which is qualitative and comparative in nature. The Charpy impact energy of T-O, T-H112, and T-H32 test at 150 K and 77 K is listed in Table 3. At 150 K, T-O has Charpy impact energy of 24.7 J, which is the same as that of T-H112, whereas T-H32 demonstrates a slightly larger value, i.e., 26.7 J. When temperature decreased to 77 K, the average Charpy impact energy of all three tempers are around 21±1 J. Moreover, it is found that T-O, T-H112, and T-H32 exhibit significant reduction in Charpy impact energy when temperature decreases from 150 K to 77 K. It has been reported that the *J*-integral fracture toughness of T-O at 111 K demonstrated a slightly high value than that at 77 K, but it was dependent on specimen orientation [5]. The Charpy impact energy provides qualitative fracture toughness and the tendency with temperature change is consistent with that obtained by the *J*-integral test.

Table 3 Charpy impact energy of T-O, T-H112, and T-H32 at 150 and 77 K

No.	Temperature /K	Impact Energy /J
T-O		
#-1	150	25
#-2	150	25
#-3	150	24
		24.7±0.58
#-1	77	22
#-2	77	22
#-3	77	22
#-4	77	22
#-5	77	22
		22.0±0
T-H112		
#-1	150	25
#-2	150	24
#-3	150	25
		24.7±0.58
#-1	77	22
#-2	77	20
#-3	77	20
#-4	77	21
#-5	77	21
		20.8±0.84
T-H32		
#-1	150	26
#-2	150	27
#-3	150	27
		26.7±0.58
#-1	77	21

#-2	77	21
#-3	77	21
#-4	77	22
#-5	77	21
		21.2±0.45

3.4 Fatigue crack propagation behaviour

The fatigue crack growth rate (*da/dN*) as a function of stress intensity factor range (*ΔK*) of AA5083 in different tempers has been determined both at room and liquid nitrogen temperatures. Figure 4 provides the fatigue crack propagation behaviour of T-O, T-H112, and T-H32 tested both at room temperature and 77 K. As shown in Figure 4, the fatigue crack growth of AA5083 for all tempers occurs more slowly at low temperature than that at room temperature if small to moderate *ΔK*-values (10~23 MPa.m$^{1/2}$) are applicable, whereas faster crack growth was observed for larger *ΔK*-values with K_{max} close to plane stress fracture toughness K_c. This kind of behavior holds for most metallic materials and the crack growth rate was lower at small and moderate *ΔK*-values (i.e., the threshold (region I) and Paris (region II) region) has mainly been ascribed to the reduced cyclic plasticity at the crack tip at low temperature [6]. Tobler and his co-worker have attributed this to the presence of moisture in ambient air, which played a critical role in significant increase of the fatigue crack growth rate at room temperature compared to cryogenic temperature [5]. They also found that the fatigue crack growth rates of T-O at 111 K were nearly equivalent to those at 4 K. These findings indicated that moisture in air plays a crucial role in fatigue crack growth rate of AA5083, rather than the temperature effects per se. The increased fatigue crack growth behaviour for large *ΔK*-values at low temperature can be attributed to the reduced ductility of AA5083.

When investigating the effect of temper on fatigue crack propagation behaviour of AA5083 at 77 K, it is found that the FCGRs of T-H32 were higher than those of T-O, whereas T-H112 demonstrated the lowest FCGR.
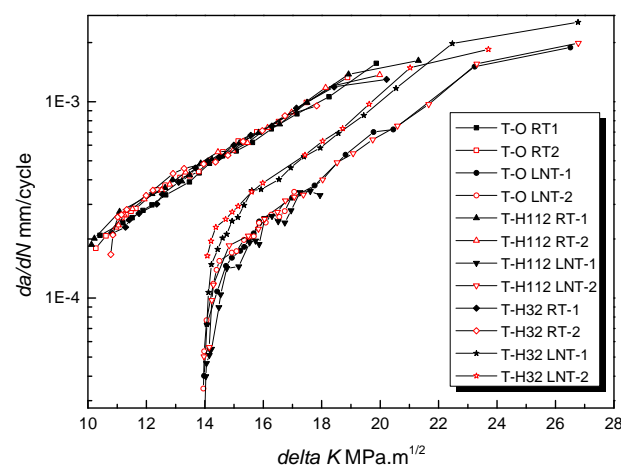

Figure 4. FCGRs for T-O, T-H112, and T-H32 at room temperature and 77 K.

4. Conclusion

In the present work, the mechanical properties of AA5083 in temper O, H112, and H32 were investigated both at room and low temperatures. It was found that the tensile properties including 0.2% proof stress, ultimate tensile stress and elongation at failure at 77 K depended slightly on the temper. For the bend properties at 77 K, it was observed that the temper H32 resulted in the highest bend strength whereas the temper H112 resulted in the lowest one. T-O exhibited the same Charpy impact energy value as T-H112 and both were slightly lower than that of T-H32 at 150 K. The Charpy impact energy of T-O, T-H112, and T-H32 was close at 77 K and all were lower than those at 150 K. The fatigue crack propagation of AA5083 in all three tempers occurred more slowly at low temperature than that at room temperature in the small to moderate ΔK-values range, whereas in the large ΔK-values range, the reverse condition was observed. Moreover, the FCGR of AA5083 at 77 K significantly depended on the temper condition.

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