FRACTURE TOUGHNESS EVALUATION OF A MEDIUM STRENGTH Al-Mg ALLOY

J.D.da COSTA,* C.M.BRANCO** and J.C.RADON***

COD and specific absorbed energy data was obtained in the Al-Mg alloy 5083 in the temperature range -200°C to + 180°C. The J resistance curve and J_c values were also obtained at room temperature. The specimens were 3-point bend specimens with 12 mm plate thickness.

The fracture toughness results were analysed and compared as a function of specimen size, specimen orientation in the plate material and temperature. Maximum load COD values were obtained and discussed using the BS 5762 specification. Provided certain details are taken into account both COD and J should be used to characterize the fracture toughness behaviour of this material.

INTRODUCTION

Aluminium alloys are quite extensively used in structural applications where high values of the strength /density ratio are required. Besides this fact, the alloys of series such as 5000 combine generally high corrosion resistance, good weldability and only slight variations of toughness with the temperature in a very wide temperature range down to very low values (up to -200°C).

The 5000 series aluminium alloys (Al-Mg alloys) are particularly attractive for cryogenic applications in the storage and transportation of liquid gases at very low temperatures. Other structural uses of these alloys include ship hulls, welded chassis frames for transport vehicles, military vehicles and bridges and also an extensive number of components in the aircraft industry. In this group the 5083 Al-Mg alloy is one of the more widely used alloys.

---

* Department of Mechanical Engineering, University of Coimbra, Portugal
** Materials Research Center, University of Minho, Portugal
*** Department of Mechanical Engineering, Imperial College, London, U.K.

The 5000 series aluminium alloys are medium strength aluminium alloys. Their mechanical strength is usually lower than the 2000 or 7000 alloys but exhibit higher toughness values and no ductile to brittle transition with the temperature. Moreover, these alloys are not strain rate sensitive in the range 10^{-5} mm/sec. to 1mm/ sec. both at room and very low temperatures.

Hence 5000 series aluminium alloys are particularly suited when wide temperature ranges and loading rates occur.

As far as fracture toughness is concerned the 5000 series Al-Mg alloys do not show unstable fracture even at very low temperatures. Ductile fracture with extensive shear lip formation is the most common failure mechanism. K_{1c} data can not be obtained usually in these alloys and therefore fracture toughness has to be evaluated using elastic-plastic fracture mechanics parameters such as COD and J integral.

In comparison with the 2000 or 7000 series alloys, used in the aircraft and aerospace field, much less information is available in the literature on fracture toughness and fatigue of the 5000 series alloys. One of the few examples is a comprehencive fracture testing programme on these alloys published in the USA by ASTM in 1975 (1). One of the more important papers presents fracture toughness data obtained by Kaufman (2) in R curve type testing mainly carried out in large thick plate CCT and CT specimens of 5083 plate and 5183 welds with thickness values in the range 1/2 to 9 ins. Most of the results were obtained at room temperature,-260^{o}F(-162^{o}C) and -320^{o}F(-195^{o}C). Kaufman (2) has evaluated critical fracture toughness K_c based on the ASTM Method E 399-74 (3) while Argy et al (4) have obtained K_c values in 5083 plate material from the crack growth resistance curves. Equivalent K_{1c} values were also obtained in (4) using the J integral technique developed at that time,(1975) and known now as the single specimen test method (see ASTM E 813-81).

In the work discussed so far it is most likely that both the estimates of K_c and K_{1c} in a ductile material such as the 5083 alloy are not valid when applying current fracture toughness specifications for COD and J integral determination. Hence it would be appropriate to characterize the fracture toughness behaviour of this material in a very wide temperature range and using COD and J integral. This would be used to test the applicability of EPFM testing methods in ductile aluminium alloys and compare those with the traditional energy based methods. For the reasons mentioned above the SMP of AGARD have decided to sponsor both in Portugal and UK a research project dealing mainly with the development of more accurate damage tolerance assessment methods applicable in structural components made of ductile Al-alloys such as 5083 (5). This project started in 1983 and as a preliminary study the fracture toughness behaviour of 5083 was evaluated in order to define the appropriate limits for fatigue crack propagation and also to characterize the static failure modes.

In this paper maximum load COD values and specific absorbed energy in slow bend were obtained and compared in the temperature range -200°C to + 180°C. Two different orientations were selected (LS and LT) and fracture toughness was compared. Finally the J resistance curve was obtained at room temperature only and from this data tentative J_c values were obtained.

EXPERIMENTAL

The Al-Mg alloy 5083 was tested in the as received normalized condition (0 state) without any strain hardening or cold worked treatment. The material was supplied in plates of 12 mm thickness. Chemical composition of the alloy is indicated in Table 1. Tensile data was obtained in cylindrical specimens 8x40 DIN 50125 both in longitudinal (rolling) and transverse directions. The results are given in Table 2. It is seen that the material has a true stress-strain curve with a change in slope (two values of strain hardening exponent and coefficient) in the equation $\sigma=K\varepsilon^n$. This behaviour is typical of aluminium alloys.

TABLE 1 - Chemical composition of 5083 Al-Mg alloy

Mg	Mn	Fe	Cu	Ni	Ti	Si	Zn	Sn	Pb
4.5	0.55	0.37	0.12	0.5	0.05	0.1	0.1	<0.05	<0.05

TABLE 2 - Mechanical properties of Al-Mg alloy 5083-0

		Longitudinal direction		Transverse direction	
Hardness (HRF)		78.0		72.0	
σ_{ys} (MPa)		179.7		159.0	
σ_{UTS} (MPa)		320.8		314.1	
ε_r (%)		18.2		24.0	
K_1	n_1	369.9	0.129	379.4	0.156
K_2	n_2	609.8	0.253	616.6	0.276
Correlation Coefficients		0.997	0.9996	0.996	0.9998

Tensile data indicates that there is more ductility and less strength in the transverse direction. Comparison of true stress - true strain curves also shows that the curve for longitudinal direction is above the one for the transverse direction (Table 2).

Since values of Young's modulus, E, are required at the temperatures of the 3PB COD tests, for calculation of COD this parameter was experimentally obtained in bending. Strain gauge readings were taken in a calibrated bar exposed to the temperature of interest. Fig.1 shows the variation of Young's modulus with the temperature in the range - 100°C to + 100°C. The value of E decreases when the temperature is increased giving a 15% variation in this temperature interval.

COD tests were carried out in 3PB specimens prepared according to the BS 5762 (6). Two types of specimens were used: the preferred size 12x24 mm and the subsidiary test piece (12x12 mm). The first size was used in the directions LT and TL and the subsidiary size in the directions LS and TS. Preliminary results carried out at three scattered temperatures have shown that the orientations giving higher toughness were the LS and LT. Hence the remainder of the test programme was carried out in these two directions only.

Slow bend tests were performed on CVN specimens based on the ASTM E 812-81 method(7). As the COD tests, these tests were carried out in the LS and LT directions with square specimens 10 mm thickness. In one series of tests the specimens were provided with blunt notches with average of 0.2 mm tip radius as defined in ASTM E 812-81. In second series of tests the specimens were fatigue precracked till the crack reached half the specimen width.

J tests were carried out at room temperature according to ASTM E 813-81 (8). Specimens were 12x12 and 12x x24 for the LS an LT orientations also. The two different techniques refered in the specification were used: multiple specimen technique and single specimen with unloading.

All the precracking of specimens was carried out at room temperature in a specially built fatigue test rig (9). The maximum level of K attained in the precracking was 8 MPa $\sqrt{m}$, in accordance with the specifications refered above.

Three point bend tests up to fracture were carried out in a hydraulic universal testing machine fitted with an appropriate set of rollers and clip-gauge and vertical displacement extensometers. In the tests below room temperature and above -120°C cooling of the specimens was done by immersion in a mixture of alcohol and liquid nitrogen contained in a thermoinsulated chamber. For temperatures below -120°C cooling was done by local immersion of the specimens during the tests in liquid nitrogen only. The same chamber was used for heating the specimens in oil in the tests above room temperature where the oil was heated by an electric resistance. In every test, temperature was controlled with an accuracy of ± 0.5°C using chromel-alumel thermocouples placed near the crack tip.

In the J tests slow crack growth was measured on the specimen fracture surface with a stereomicroscope, after some crack growth by fatigue carried out immediately after the first loading for the J determination.

RESULTS AND DISCUSSION

Specific absorbed energy vs. temperature

Figure 2 is the plot specific absorbed energy in slow bend against temperature in the temperature range -200°C to + 200°C. Only the results of fatigue crack specimens are included in this plot since data obtained in the tests with the specimens provided with blunt notches gave consistently values of energy 50% above the fatigue cracked specimens (9,10). Hence specific absorbed energy values in this material should be obtained in specimens with fatigue cracks otherwise unsafe toughness values could be assumed if the blunt notch specimen data is used.

In Fig.2 the specific absorbed energy is the energy per unit area of the specimen cross section taken from the area below the load deflection curve of the specimen. It is seen that the LS direction is tougher than LT direction giving energy values on average 50% higher. Specific absorbed energy increases when the temperature drops below 0°C, reaches a maximum near - 100°C and keeps approximately constant for lower temperatures. For temperatures above room temperature specific absorbed energy increases again with the temperature. This is explained by the fact that ductility decreases from 25% at 25°C up to 60% at 200°C (11).

The results in Fig.2 show that the best service temperature range for this material is from -200 to-60°C where higher values of toughness are obtained.

Minimum toughness occurs at room temperature and the values are 130 kJ/m^2 for the LS orientation and 90 kJ/m^2 for the LT orientation. Hence extremely good toughness behaviour was obtained in this material at low temperatures. Other results available in the literature for this alloy were obtained by Kaufman (12) who reported higher value of 218 $k\ J/m^2$ but for a plate thickness of 1.6 mm. This result seems to be in agreement with the present results for 12 mm plate thickness.

COD vs. temperature

For the LT and LS orientations maximum load COD values, δ_m, were obtained using the equation from BS 5762 (6)

$$\delta_m = \frac{K^2(1-\upsilon^2)}{2\sigma_{ys}E} + \frac{V_p}{1+\frac{1}{r}\frac{(a+z)}{(W-a)}} \qquad (1)$$

where K is the value corresponding to the maximum load attained in the test, V_p is the plastic displacement for the maximum load also, and r is the rotational factor, which was taken as 0.4 as required in the specification.

The bulk of the COD results was obtained in the

LT and LS orientations. In the LS orientation all the specimens were of subsidiary type (12x12 mm) while in LT both specimens (12x24 mm) and (12x12 mm) were tested. Fig.3 shows a typical plot load against clip-gauge displacement obtained at - 60°C. The plastic portion of the displacement is indicated and the curve shows considerable ductile behaviour. In all the specimens failure occured with extensive plasticity and shear lip formation, and after maximum load.

The influence of specimen width is shown in Fig.4. COD values are lower in the square 12 mm specimens. Hence it seems that COD is size dependent reaching lower values when more constraint occurs in the specimen as in the case of the 12x12 mm cross section.

The influence of specimen orientation and temperature is illustrated in Fig.5. Only the results of the square subsidiary specimens were taken since these gave lower toughness (Fig.4). These plots are similar to the specific absorbed energy ones (Fig.2) showing higher values of COD in the range 0 to - 100°C followed by a slight decrease from - 100°C to - 200°C. Minimum values are reached about room temperature (Fig.5) and are kept constant till + 150°C. It is likely that for temperatures above + 150°C a slight increase of COD could occur as noticed in the specific absorbed energy results (Fig.2).

The LS orientation is tougher than LT orientation confirming the trend of the specific absorbed energy results (Fig.2). In the LS orientation COD values range from 0.35 to 0.20 mm, while for LT direction a smaller variation was obtained (0.20 to 0.14 mm). These results clearly indicate that 5083 Al alloy is considerably tough in a very wide temperature range.

Despite some scatter in the results (Figs.4 and 5) it may be stated that COD is a valid fracture toughness parameter for this alloy. Scatter can be reduced by two factors: a) more careful control of the ratio a/W during precracking and b) more accurate values of the rotational factor r. Fractographic observations carried out in some specimens (10) have shown that r can not be assumed constant but depends on the ratio a/W. While this influence is not significant in steels, as pointed out in the BS 5762 specification, it is important in the Al-alloys and hence more detailed observations are required in order to assume an accurate value of r. Less scatter was observed in the results obtained with subsidiary test pieces due to more uniform crack fronts and consequently values of r less dependent of the ratio crack length/specimen width.

J results at room temperature

Figure 6 shows a typical plot load against central deflection obtained in a 3-point bend test. Considerable ductile behaviour was obtained with deformation past maximum load.

The J values were obtained with the equation (ASTM E 813-81)

$$J = \frac{A}{2B(W-a)} \tag{2}$$

where A is the area under the load displacement curve up to the point of loading.

The J resistance curve is plotted in Fig.7 both for the LT and LS orientation. Although the results are not enough to obtain a valid J_c value, provisional values yet subjected to confirmation by further tests, can be assumed as J_c = 6.5 kJ/m^2, for the LT direction, and 4.5 kJ/m^2 for the LS orientation. The equivalent values of K_c are 21.7 MPa$\sqrt{m}$ and 18 MPa$\sqrt{m}$ respectively, which are below the expected values of toughness for a ductile aluminium alloy.

Comparison of these results with results available in the literature show indeed that the obtained values of J_c are in the lower limit of toughness of other series of aluminium alloys (2000, 6000 and 7000 series), and are below the values quoted in (4) for the same alloy, temperature and thickness range. However it should be pointed out that the J_c tests performed by Argy (4) did not follow the ASTM specification and hence some difference of results could be expected. Further tests are in progress to evaluate the influence of testing technique in these results.

Despite the fact that the J resistance curve for LT direction is above the LS one, and hence in contradiction with the COD data plotted in Fig. 5, this could be explained by the bigger width of the specimens used in the tests carried out in the LT direction (Fig.7). It is likely that similarly to the COD results, there is a width influence on the J results, and hence further tests are in progress with square 12x12 mm specimens to clarify this point.

CONCLUSIONS

1- In 12 mm thick specimens of medium strength 5083 Al-Mg alloy it was found that both COD and specific absorbed energy in slow bend increased when the temperature decreased in the range 0°to - 200°C. High values of toughness were obtained at low temperatures thus confirming the ability of this alloy to withstand impact loads at low temperature.

2- COD values at maximum load, in 5083 Al-Mg alloy are dependent on specimen width increasing with the width. Hence for COD determination with BS 5762 specification it is recommended to use the square subsidiary test piece since lower toughness values are obtained.

3- Some scatter observed in the COD tests and also the dependence of COD in specimen width requires a more accurate determination of the rotational factor, instead of relying on the value 0.4 quoted in the BS 5762 specification.

4- In the determination of specific absorbed energy in slow bend the specimens should have fatigue cracks instead of blunt notches, otherwise unrealistic high toughness values will be obtained.

5- COD values at maximum load in 5083 are higher in the LS direction compared with LT direction. The same trend was observed in the specific absorbed energy results. Both parameters describe adequately the fracture toughness behaviour of this material.

6- The obtained J_c results are below the values reported in the literature for the same alloy and temperature. Further tests are in progress to clarify this point.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support awarded by the SMP of AGARD under the program Additional support to Portugal and Turkey. This work is included in the P17 Project (Ref. ASP 13),"Development of damage tolerance assessment methods".

REFERENCES

(1)- ASTM,"Properties of materials for liquefied natural gas tankage", STP 579, U.S.A., 1975

(2)- Kaufman, J.G. and R.A.Kelsey,"Fracture toughness and fatigue properties of 5083-0 plate and 5183 welds for liquefied natural gas applications", Ibid, pp. 138-158

(3)- ASTM,"Test for plane strain fracture toughness of metallic materials", E 399-74, USA, 1974

(4)- Argy,G,Paris.P.C. and Shaw,F.,"Fatigue crack growth and fracture toughness of 5083-0 aluminium alloy", Ibid,pp.96-131

(5)- AGARD,SMP,Project P17 proposal,"Development of damage tolerance assessment methods", NATO, Paris, 1983.

(6)- BSI, "Methods for crack opening displacement testing",BS 5762, UK, 1979

(7)- ASTM,"Standard test method for crack strength of slow-bend precracked Charpy specimens of high strength metallic materials", E 812-81, USA, 1981

(8)- ASTM,"Standard test for J_{1c} - a measure of fracture toughness", E 813-85, U.S.A., 1985

(9)- Costa,J.D.,"Fracture toughness evaluation in Al-Mg alloy 5083", in portuguese, MSc thesis, University of Coimbra,Portugal,1985

(10)-Costa,J.D. and Branco,C.M.,"Fracture toughness in Al-alloys", in portuguese, Proc. Conf.Materiais 85, Lisbon, Portugal,1985, pp. 17-34.

(11)-Aluminium Federation,"The properties of aluminium and its alloys", Birmingham, UK, 1983

(12)-Kaufman, J.G. and Holt, M., "Fracture Characteristics of aluminium alloys", Alcoa Res. Lab.,Tech. Paper Nº18, 1965

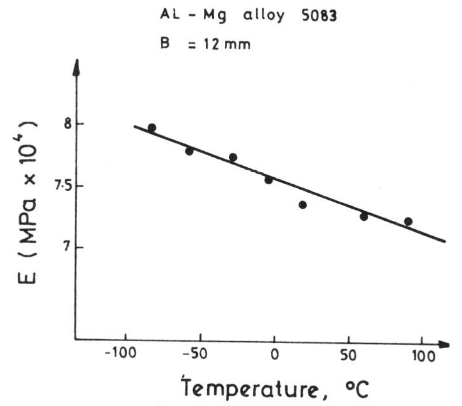


Fig.1-Variation of Young's modulus with the temperature.

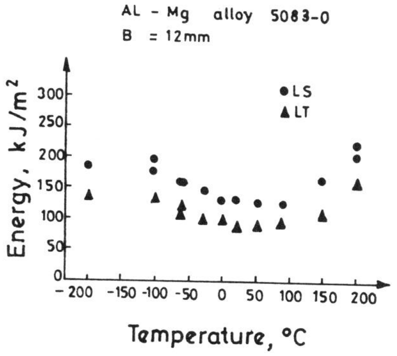


Fig.2-Specific absorbed energy against temperature.

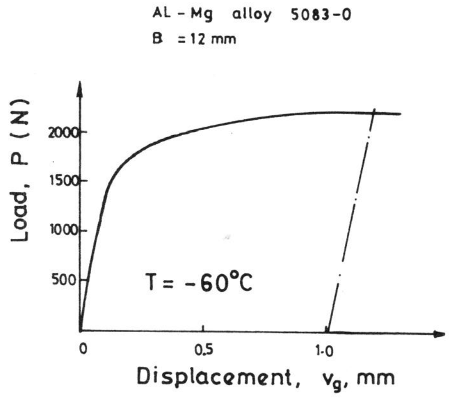


Fig.3-Typical plot load-clip gauge displacement

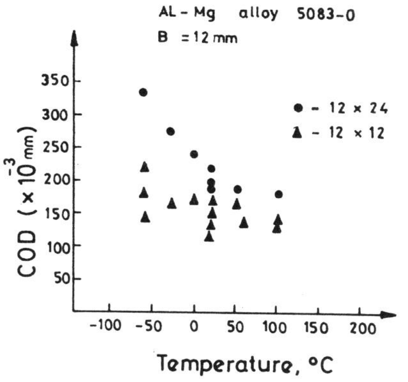


Fig.4-Influence of specimen width on the COD values.

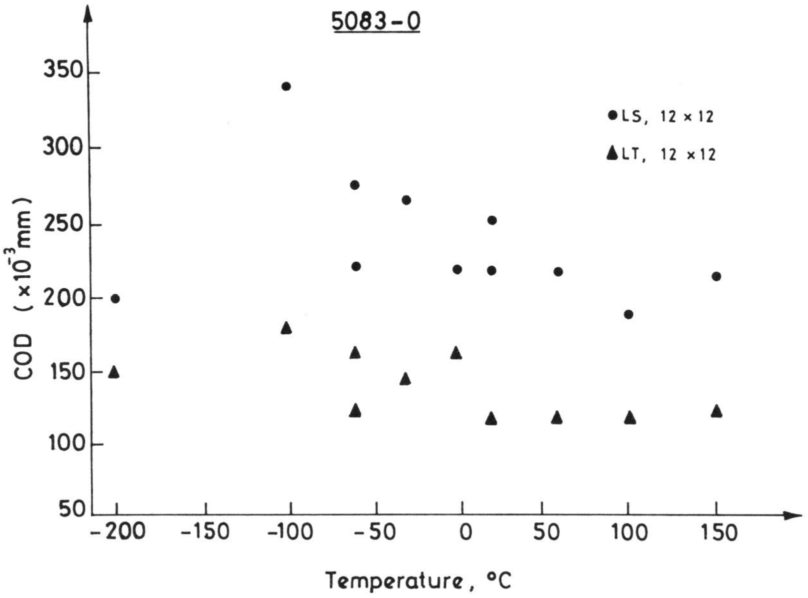
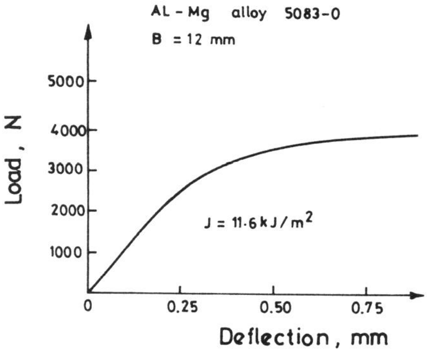


Fig.5-COD results against temperature.Al-Mg alloy 5083. Square 12x12 mm specimens



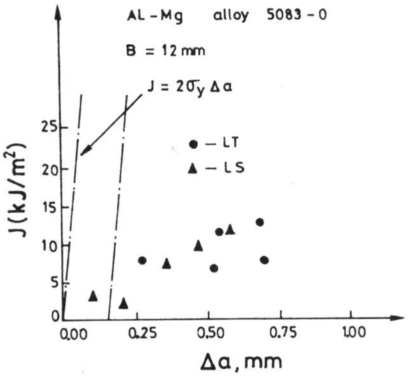


Fig.6-Typical plot load vs. displacement

Fig.7-J vs. Δa curve at room temperature.