COMPARISON OF DIFFERENT FRACTURE TOUGHNESS MEASURING METHODS OF IRRADIATED ALUMINIUM ALLOYS

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Ductile aluminium alloys and their weldments were tested under unirradiated and irradiated conditions. Results of K_c measurements on 1/2CT specimens, ASFE and S_c values obtained on smooth and notched tensile bars, Charpy impact energy and crack propagation energy values obtained on Navy specimens were compared to choose the best method. The ASFE (or critical value of Strain Energy Density) measurement seemed to be the best to evaluate the fracture toughness properties of this type aluminium alloys. The use of the instrumented impact testing on Charpy V specimens is also a good method to verify the acceptable level of fracture toughness of aluminium reactor materials.

INTRODUCTION

One of the most difficult tasks in the mechanical testing of materials is to evaluate the fracture toughness properties of relatively thin sections made of very ductile low alloyed alumina. In the testing of irradiation effects the size and number of the specimens are limited too.

The literature suggests several methods for testing ductile, low and middle strength aluminium alloys. Most are suitable for comparing earlier results, but not for being used as design criteria.

The following testing methods were applied to measure the toughness properties of the unirradiated and irradiated alumina alloys and the results were compared:

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- Instrumented Charpy test conducted on V notched standard size specimens.
- Navy energy measurement conducted on 30 and 60 mm high Navy specimens.
- The usual tensile properties, notch-yield ratio, and Absorbed Specific Fracture Energy (ASFE) were determined on smooth and notched tensile bars.
- The critical value of Strain Energy Density (S_c) and K_c were calculated from the above mentioned measurements.

INVESTIGATIONS

Applied materials. The chemical and mechanical properties of the foregoing alloys and their weldments are shown in Table 1.

TABLE 1. Chemical composition and mechanical properties of the tested alloys

Material	Chemical composition				Mechanical properties	
	Mg [%]	Si [%]	Mn [%]	Ti [%]	Yield stress [N/mm2]	Ultimate stress [N/mm^2]
5009	2.50	0.04	0.05	0.04	107	199
6005	0.6	0.86	0.03	0.03	101	119
weldment of 5009	4.7	0.05	0.14	0.09	91	188
weldment of 6005	0.1	5.3	0.01	0.09	99	121

Part of the specimens was irradiated in a 5 MW pool type LWR research reactor at 65 °C. The surface of the specimens was directly cooled by the reactor water flow which ensured the fixed temperature of irradiation. The fast neutron irradiation dose was $3\text{-}5*10^{19}$ n/cm^2 E>1 MeV.

Instrumented Charpy tests. A 300 J capacity standard Charpy machine equipped with load and deflection trancducers was used. The transient curves were transported in digitalized form without electronic filtering into a microcomputer. After mathematical filtering and dynamic calibration the dynamic yield stress and the rate of the energy used for crack initiation and propagation were evaluated. (See Fig. 1.)

Navy energy measurements. The Navy specimens are shown in Fig. 2. The energy represented by the area of the second part of the load-displacement curve (after F_{max}) specified for fractured surface is called Navy energy. That means the Navy energy is the specific surface energy of the crack propagation (1). The measurements were made with 0.5 mm/min crosshead velocity on an electronic tensile machine.

ASFE measurements. The process of the fracture can be divided into two parts: crack initiation and propagation. The deformation energy required for crack initiation in a unit of volume of material is called Absorbed Specific Fracture Energy (ASFE). This can be imagined by considering the specific value of the absorbed energy in an infinitely small element at the tip of a crack or around the fracture surface of a tensile specimen (see Fig. 3). Several interesting papers discussed the developing of the theory, measurement methods and application of ASFE (Gillemot (2), Czoboly et al. (3), Gillemot et al (4)).

Measurement of the energy in an infinitely small element is not possible, but can be approximated in practice with sufficient accuracy by calculating the fracture energy measured over the entire fracture cross section of an unnotched tensile specimen. For this purpose round bar tensile specimens are most suitable as crack initiation is followed immediately by unstable fracture. In this case the energy absorbed between crack initiation and the total fracture is small in comparison with that absorbed during plastic deformation. It follows that ASFE (denoted W_c) can be calculated:

$$W_c = \int_0^{\varepsilon_f} R' d\varepsilon \qquad (1)$$

The same measurement can also be performed on notched tensile specimens. The ASFE value calculated in this way represents an average value denoted W_m. This value is not a true characterization of the material as the plastic deformation energy is absorbed in a small notch tip zone and it is averaged over the entire fracture area of the specimen. These average values obtained on differently notched specimens and plotted as a function of the notch factor K_t indicate notch sensitivity. Additional information on ASFE measurements is given in (5).

Obtaining of Critical Strain Energy Density. According to Sih (6,7,8) a crack starts to propagate when the minimum value of the strain energy density function reaches the critical value, i.e:

$$(dW/dV)_c = S_c/r_c \tag{2}$$

where r_c characterizes the maximum of the selfsimilarity zone. K_c can be calculated from the value of S_c in the following way (6):

$$S_c = \frac{(1+\nu)(1-2\nu)}{2\pi E} K_{1c}^2 \tag{3}$$

The critical value of the selfsimilarity fracture zone size depends on the plastic constraint factor. The plastic constraint factor $\beta = \sigma_{yc}/\sigma_y$. Ivanova et al. (9,10) have shown that:

$$r_c = \left[\frac{\beta(K_{I*}^R)_{max}}{\sigma_y}\right]^2 \frac{1}{2\pi} \tag{4}$$

where K_{I*}^R controls the maximum value of the released energy and it is practically constant for aluminium.

The critical value of the dW/dV quantity at r^{max} can be characterized as:

$$\frac{dW}{dV} = \int_0^{\varepsilon_{ij}} \sigma_{ij}\, d\varepsilon_{ij} + f(\Delta T) \tag{5}$$

In case of uniaxial tensile specimens made from ductile material formula (1) can be combined with (5) by neglecting the generated heat:

$$(dW/dV)_{max} = W_c. \tag{6}$$

From the results of measurements on smooth and notched tensile bars the plastic constraint factor can be estimated and finally S_c can be calculated from ASFE by formula (2).

K_c calculation from notch-yield ratio. The ALCOA Research Laboratories developed an empirical method to calculate K_c values from the so-called notch-yield ratio. The notch-yield ratio is the rate of the ultimate strength of the notched specimens and the yield strength of the smooth tensile specimens. The diagram applied for calculation is shown in Fig. 4.

Tensile measurements. 6 mm diam. round smooth and notched tensile bars were tested on a 10 ton electronic tensile machine with a crosshead speed of 1 mm/min. The testing temperature varied between 0 and 150 °C. The ASFE values, tensile properties, K_{1c} from notch-yield ratio and S_c values were calculated from the results.

K_c measurements. Some attempts were made to conduct direct K_{1c} or J_{1c} measurements on 1/2CT specimens. The testing method was in accordance with the ASTM E-399 standard. Because of the small size of the specimens no valid K_{1c} or J_{1c} values could be obtained.

EVALUATION AND CONCLUSIONS

The fracture toughness properties calculated by the foregoing methods are given in Table 2. It is clearly demonstrated that the tendencies of the changing of different fracture parameters as function of the material quality and irradiation level are similar.

Fig. 5 shows that the results obtained on 1/2 CT specimens and calculated from S_c values (obtained from ASFE measurements) are correlating significantly. The K_c values calculated by the ALCOA diagram differ very much (see Table 2).

In order to give more evidence of the validity of the S_c values calculated from ASFE we took into consideration that the S_c mainly belongs to the crack initiation and the Navy energy is the energy of the crack propagation. The Charpy energy includes both. The rate of the Charpy initiation and propagation energy was calculated from the load deflection diagram and was plotted as the function of the rate of the S_c and Navy energy (Fig. 6). The effect of the strain rate is negligible in this type aluminium alloys, and it renders this comparison possible. The correlation is markedly significant.

TABLE 2. Fracture toughness values obtained by the different methods

Material	Testing temp. [C]	Irrad. $*10^{19}$ [n/cm^2]	Notch-yield ratio	W [MJ/m^3]	$K_c^{(1)}$ [**]	$K_c^{(2)}$ [**]	$K_c^{(3)}$ [**]	S_c [N/m]	Navy energy [KJ/m^2]	KV [J]
5009	20	0	1.66	218	58.3	33.8	32.8	10.8	296	94
	100	0	1.73	318	61.9	47.0	41.2	20.9	-	101
	150	0	1.99	541	77.0	31.5	37.5	9.4	-	105
	20	4.7	2.81	338	-	58.6	47.5	32.5	330	140
	150	4.7	2.00	354	77.1	30.1	-	8.6	-	142
6005	20	0	2.48	185	-	61.3	64.1	35.5	150	62
	20	3	3.32	244	-	33.9	37.2	10.9	270	77
Weld metal of 5009	20	0	3.0	171	-	27.0	27.3	6.9	292	78
	100	0	1.94	140	73.6	30.1	-	8.6	-	85
	150	0	1.98	170	76.5	29.5	44.0	8.2	-	86
	20	5.7	1.91	159	74.6	28.9	25.2	7.9	330	67
	100	5.7	2.51	200	-	46.7	32.7	19.6	-	72
Weld metal of 6005	20	0	3.0	150	-	37.9	24.6	13.7	90	95
	20	3	1.5	81	38.5	9.7	6.1	0.9	40	16

[**] = [MPam$^{0.5}$]
(1) Calculated by ALCOA (1) diagram
(2) Calculated from S_c by method of Ivanova (9)
(3) Measured on 1/2 CT specimens

A polynomial was also fitted as follows in order to verify the connection among S_c, Navy and Charpy results:

$$a*S_c + b*\text{Navy} = KV \tag{7}$$

This gives a significant correlation again as it is shown in Fig. 7.

These results verify that the S_c values calculated from ASFE are characterizing exactly the toughness properties of the tested aluminium alloys. Instrumented Charpy test is another succesful method used for testing the irradiation effects on aluminium alloys and their weldments.

SYMBOLS USED

a = constant

b = constant

E = Young's modulus (N/mm^2)

J_c = critical value of J integral (J/cm^2)

K_c = fracture toughness ($MPam^{0.5}$)

KV = impact energy on Charpy V specimen (J/cm^2)

K_t = notch factor

R' = true stress (N/mm^2)

r = size of selfsimiliraty zone (mm)

r_c = critical size of selfsimiliraty zone (mm)

S_c = critical value of Strain Energy Density (N/cm)

T = temperature (K)

V = volume (cm^3)

W = deformation energy (J)

W_c = Absorbed Specific Fracture Energy (J/cm^3)

W_c = average Absorbed Specific Fracture Energy (J/cm^3)

β = plastic constraint factor

ε = true strain

σ = stress (N/mm^2)

σ_y = tension yield stress (N/mm^2)

σ_{yc} = local tension yield stress (N/mm^2)

ν = Poisson's ratio

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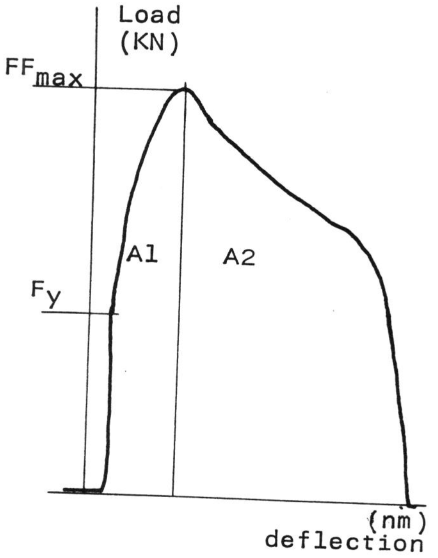

Figure 1. Evaluation of instrumented Charpy curve.

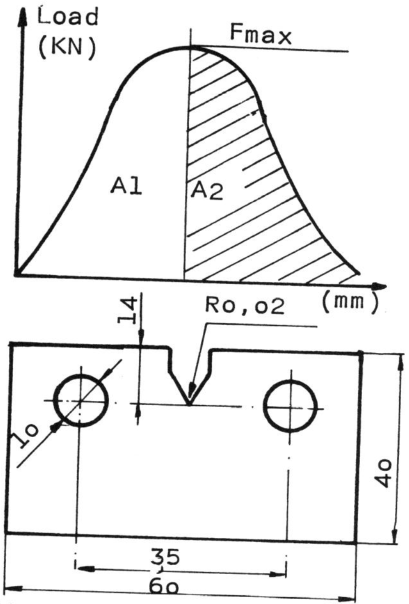

Figure 2. Navy specimen and evaluation.

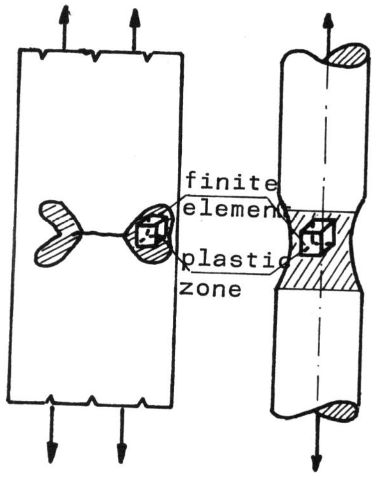

Figure 3. Theoretical definition of ASFE.

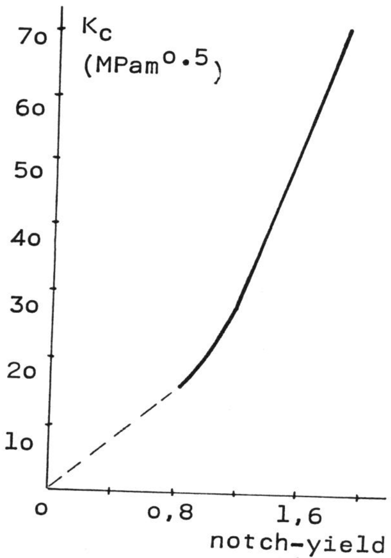

Figure 4. K_c calculation from notch-yield ratio.(1).

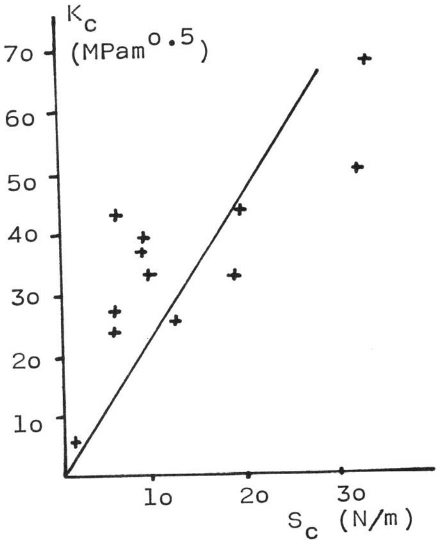

Figure 5. Correlation between measured K_c and S_c

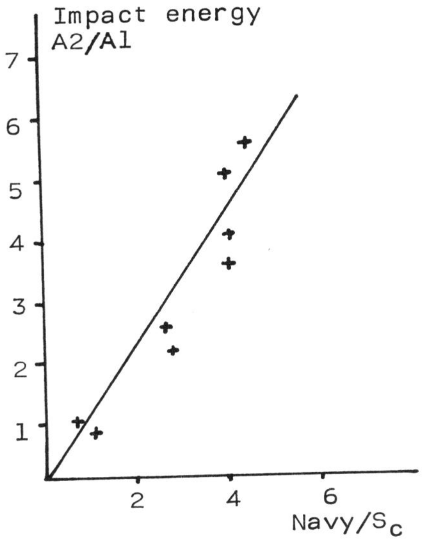

Figure 6. Correlation between impact, Navy energy and and S_c.

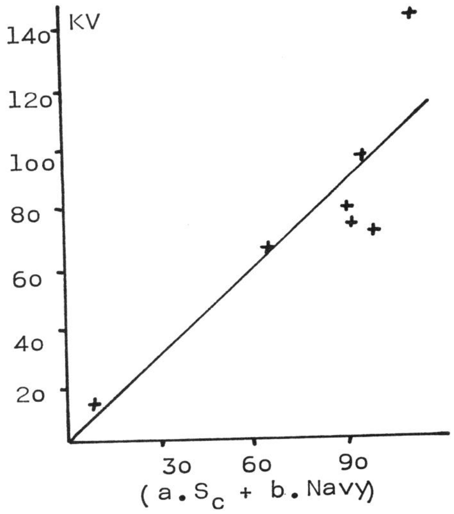

Figure 7. Correlation 2 between impact, Navy energy and S_c.