

DISCUSSION

J. G. Kaufman¹ and R. J. Bucci¹ (written discussion)—The authors have presented some valuable data on the properties of aluminum alloy 5083-0 and 5183-0. Of particular value are the crack resistance curves obtained under static and dynamic loading, providing confirmation that the dynamic toughness of this material is equal to or greater than its static toughness. There are several points in the paper which seem to justify some additional discussion.

The first concerns the authors description of a fatigue test of a specimen with a welded-on bracket. They report that the test showed unexpected behavior in that the specimen failed suddenly before the crack penetrated the thickness and at a net-section stress estimated to be below or very near the yield strength on the basis of strain gage measurements in the plane of the crack near the specimen edges. Examination of the configuration of the specimen illustrates that, with the bracket welded on opposite the notch, this behavior would be expected regardless of what type or thickness of material had been used. It would appear very unlikely for the crack to grow around the relatively thick welded-on bracket and so penetrate the other side before it grew sufficiently far across the net section of the principal tension member to fail by net-section yielding. While the referenced strain gage measurements indicate that the failure stress was below yield, simple calculations of the remaining net-section stress based upon Fig. 15 of the paper and the gross stress data provided show that the actual net-section stress was well above the yield strength, probably in excess of 30 ksi. This conclusion was confirmed by a more detailed finite element analysis of the specimen configuration. The strain gage measurements do not appear consistent with the other information, perhaps because of their location or measurement capacity.

On another point, we, like the authors, agree that considerable conservatism is justified in making stress and crack size calculations for such a critical application. Yet in their discussion of leak-before-break thicknesses, the authors appear to compound their conservatism unnecessarily, first, by the use of very cautious expressions for the limiting thickness and second, by the application of relatively low values of estimated K_{Ic} for calculation of the limiting thickness. For example, they use the Rolfe and

¹Engineering Properties and Testing Division, Aluminum Company of America, Alcoa Technical Center, Alcoa Center, Pa. 15069.

Novak criterion for plane strain specimen thickness² which was developed, not for establishing structural fracture conditions, but for the selection of minimum requirements on specimen thickness useful for obtaining approximate values of the K_{Ic} in tests of certain steels. It was never the intention of Rolfe and Novak to imply that steel structures or any others would fail under plane-strain conditions when their thicknesses were so small. A criterion attributed to Irwin is also used, but without reference and without description of all of the terms (for example, what is α and c_0 and what is the significance of the value of $\alpha = 1.25$). With regard to the values of K_{Ic} used, no one can argue that 45 ksi $\sqrt{\text{in.}}$ is a conservative figure at -260°F , but it should be pointed out that the authors data as well as those referenced from Kaufman would conservatively suggest a value of at least 5 ksi $\sqrt{\text{in.}}$ higher; and, this small difference has the effect of putting the calculated value well over 4 in., even by the most conservative equations.

With regard to fatigue crack growth rates, the authors seem to suggest that the wide range in the values obtained from the published literature to be a reflection of the variability and lack of predicability of the material characteristics. It would seem that the variability of data obtained, such as presented in Fig. 12, could be better understood through consideration of variations in environment, specimen configuration and orientation, and test frequency, in addition to the stress ratio. Especially important is the environment (moisture content) which, as the authors show, may shift the growth rate by a factor of 2. Previously published works on high strength aluminum alloys³ have shown that for frequencies on the order of 1 Hz, the moisture content must be controlled at levels lower than several parts per million to ensure removal of moisture effects from fatigue crack propagation behavior. In addition, the transition from wet to dry crack propagation rates is known to be dependent upon frequency, stress intensity level, and prior history.

G. Argy, P. C. Paris, and F. Shaw (authors' closure)—We appreciate the interest shown in our paper by the discussers, and we welcome the opportunity to reemphasize and clarify some of the points that we originally tried to make.

The discussers have commented on the test of the specimen with a welded-on bracket (see Fig. 15 of this paper). They question whether the net section stress in the plane of the flaw was, in fact, below the material yield strength at the time of failure and state that they estimate the net section stress at failure to have probably been in excess of 30 ksi.

Such an estimate would indeed be correct if the load carrying capability

²Rolfe, S. T. and Novak, S. R. in *Review of Developments in Plane Strain Fracture Toughness Testing, ASTM STP 463*, American Society for Testing and Materials, 1970, pp. 92-101.

³Wei, R. P., *Journal of Engineering Fracture Mechanics*, Vol. 1, No. 4, 1970, p. 633.

of the welded-on bracket were completely ignored. In reality, while the load carried by the bracket cannot be determined without a complete stress analysis of the specimen, which the authors have not done, it appears obvious that some load transfer to the bracket will occur, resulting in a decrease in nominal stress in going from the front face of the specimen to the back face. Strain gage measurements on the front face of the specimen near the edges showed a stress of 25.6 ksi at the time of failure, as compared to a material yield strength of 24 ksi. The assumption that stress decreased through the specimen thickness due to some load transfer to the bracket, rather than remaining constant across the thickness and thereby reducing the "average" stress over the net section, prompted the authors' statement that failure occurred "at a net section stress estimated to be below or very near yield."

Since the net section stress averaged over the entire section was only an estimate, the authors recognize that it may be subject to debate. It is felt that the importance of this test lies not in the determination of the value of the net section stress at failure, but rather in its function as a caution to designers that in the presence of nonpenetrating flaw, "fast fracture" can occur at stress near yield in nominal thicknesses, which would not be expected to result in plane strain conditions if the effective material thickness were increased locally through design details such as welded-on brackets.

The discussers state that "the authors appear to compound their conservatism unnecessarily" with respect to the leak before break criterion. Now, with LNG vessels for ships, it would seem to be prudent to assure conservatism thoroughly, short of very extensive testing of all details of both structure and material. We feel that the conservatism in our calculations may indeed be compounded, but it simply represents a reasonable level required to be conservative in each of the steps required in predicting structural behavior from material properties.

First, in the original leak before break criterion suggested by Irwin,⁴ one should work stress, σ_w , equal to the yield strength, σ_{yp} , for full conservatism. With this conservatism, the leak before break criterion becomes ($\alpha = 1$)

$$t \leq \frac{1}{2\pi} \left(\frac{K}{\sigma_{yp}} \right)^2$$

This older criterion accounts for some bending, residual stresses, and other uncertainties through letting the working stresses cause some yield-

⁴Irwin, G. R., "Structural Aspects of Brittle Fracture," *Applied Materials Research*, Vol. 3, No. 2, 1964.

ing. The K_c number for the material should be inserted for the *proper crack length* (since K_c is acknowledged to vary with crack length). Thus for $a = 2$ to 4 in. (typical thickness), one would look at the *smaller* K_c test reported and estimate a safe value of about $70 \text{ ksi}\sqrt{\text{in}}$. This leads to

$$t \leq \frac{1}{2\pi} \left(\frac{70}{22} \right)^2 = 1.6 \text{ in.}$$

We concede that this might be too conservative.

Next, we note that this material has some rather strange fracture behavior patterns. Figure 18 shows one of the $w = 15.75$ in., $t = 2$ in. R -curve tests exhibiting an entirely flat fracture surface, although normally under such conditions aluminum alloys should give full slant fracture surfaces. An explanation might be severe tunneling of the crack with progressive fracturing. In this case, for a straight through crack such as assumed for leak before break, pop-in might lead to severe tunneling, that is, substantial lengthening of the crack. As early as 1960, Krafft, Irwin, and coworkers at the Naval Research Laboratory⁵ reported substantial pop-in in aluminum alloys at

$$t = 1.0 \left(\frac{K_{Ic}}{\sigma_{yp}} \right)^2$$

This is equally well reflected by the Rolfe and Novak criterion for obtaining substantial plane strain, which is identical. Perhaps we should have said their criterion is an upper limit on thickness to avoid plane strain, but this also implies avoiding catastrophic failure in this leak before break context.

Next, the discussers question the K_{Ic} value used in this and other criteria. With the "strange" material behavior exhibited by Fig. 18, we believe caution should be exercised. We chose $K_{Ic} = 45 \text{ ksi}\sqrt{\text{in}}$ to be a reasonable value in the circumstances. However, if the pop-in tunneling view is taken, we might suspect pop-in as a potential mode of crack growth with the first onset of cracking. Figure 19 shows some new J -test results on this same 5083-0 material. Note that the onset of crack extension occurs at $J = 90 \text{ lb/in.}$ or $K = 30 \text{ ksi}\sqrt{\text{in}}$. These same values have been reproduced within 5 percent in two other similar tests.⁶ If this value were used to assure conservatism, the result would be

$$t = 1.0 \left(\frac{30}{22} \right)^2 = 1.8 \text{ in.}$$

⁵Krafft, J., Sullivan, A., and Boyle, R., "Effect of Dimensions on Fast Fracture and Stability of Notched Sheets," presented at Crack Propagation Symposium, Cranfield, England, 1961.

⁶Paris, P. and Hermann, L., "Improved Compliance Techniques for Observing Crack Growth with Respect to the J -Integral," accepted for presentation at the Ninth National Symposium on Fracture Mechanics, American Society for Testing and Materials, 1975.

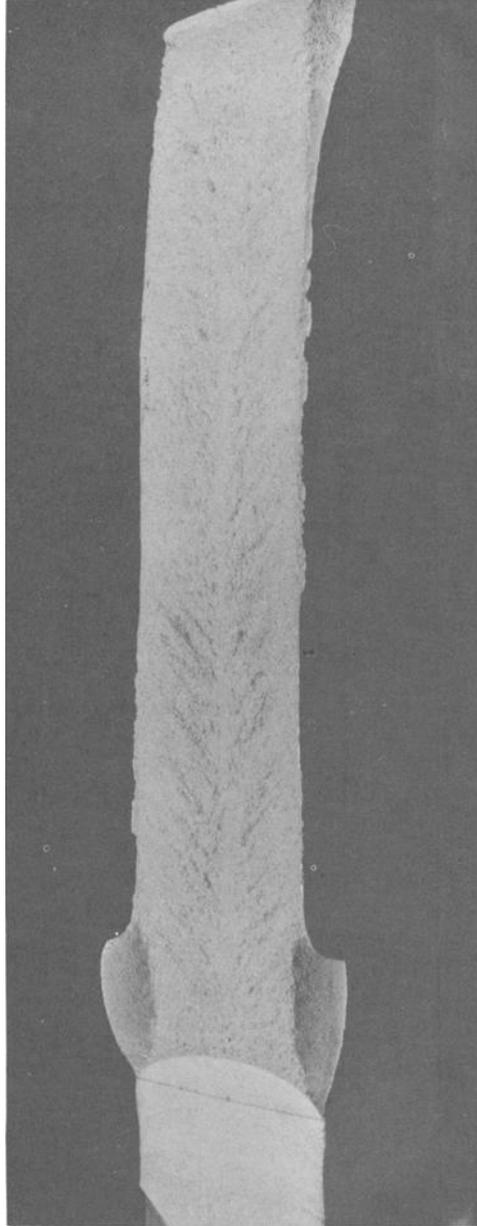


FIG. 18—*Flat fracture surface for 2-in.-thick R-curve test.*

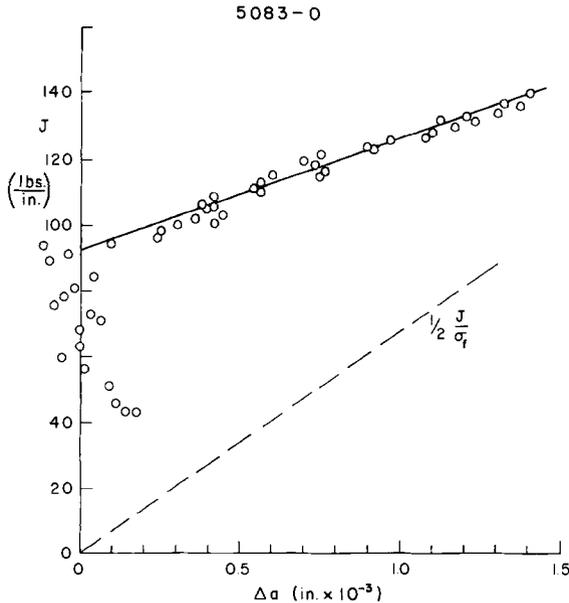


FIG. 19—Detailed J-test results for T-type at room temperature.

Indeed, we do believe these views are a bit too conservative, and we are sure that at least 2-in.-thick vessels are undoubtedly safe by leak before break phenomena. We believe that some crack growth may occur without danger of complete fracture. However, for thicker vessels, the doubts remain and we would still urge caution.

The discussers still question our use of $\alpha = 1.25$ in the newer Irwin⁷ leak before break criterion using half σ_{yp} as the working stress. We feel that, in such a case, setting $\alpha = 1.25$ is justified, since any bending or residual stresses could cause cracks longer than twice the thickness prior to breakthrough, and setting $\alpha = 1.25$ accounts for a modest influence of such factors in open areas of a vessel (away from supports, etc.). As noted, if bending is obviously present, this factor should be increased. Moreover, in this particular analysis, the discussers note the sensitivity to upward changes in K_{Ic} , but we hasten to point out the same sensitivity applies in the other direction, in which case the K for initiating growth of 30 as noted from Fig. 19 causes some apprehension.

Finally, the discussers point out correctly that the fatigue crack growth data show variability which can undoubtedly be explained by differences in load ratio, environment, and test frequency. We agree, but hasten again to point out that, if so, this behavior shows an unusually high

⁷Irwin, G. R., "Linear Fracture Mechanics, Fracture Transition, and Fracture Control," *Journal of Engineering Fracture Mechanics*, Vol. 1, No. 2, 1968.

sensitivity of 5083-0 to these conditions which is quite unexpected for a low strength aluminum alloy. Again, such unexpected behavior should provide a note of caution.

In summary, we would agree with the discussers that they may be correct in their optimism about 5083-0. However, we remain reluctant to apply simplified safety criteria without assured conservatism where exacting and extensive structural behavior data are lacking.