Usefulness of Precracked Charpy Specimens for Fracture Toughness Screening Tests of Titanium Alloys

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Although the K_{Ic} value of a material is a very useful measure of fracture toughness, its valid experimental determination can be a complex and expensive procedure, not at present suited to routine alloy screening or quality control purposes. To explore the feasibility of estimating K_{Ic} in titanium alloys using techniques that are more convenient to perform, impact and slow-bend tests were made on either V-notched or fatigue-precracked Charpy specimens, and the resulting energy values were compared with the corresponding approximate K_{Ic} values. Of the various tests studied, results from five titanium-based alloys, two steels, and two aluminum alloys showed that precracked specimens broken in slow-bend hold the most promise of giving energy values that can be related to K_{Ic}. The best correlation came from specimens having mostly flat fractures, but in the higher-toughness cases, where shear lips of an appreciable size were formed, just as reasonable a relationship between energy and K_{Ic} was observed when flat-fracture energies were used.

THE value of K_{Ic}, the critical plane strain stress-intensity factor, is an important measure of toughness. It is a material constant, it can be used in design to calculate a critical crack size for a given applied stress, and it can be determined experimentally using suitably designed laboratory specimens and tests.

Unfortunately, the basic experimental procedure for the measurement of valid K_{Ic} values, while quite well-established, remains somewhat complex, requiring careful attention to specimen design, fabrication, and testing, and calling for exacting techniques for analysis of the results.[1-4] These time-consuming and expensive requirements detract from the practical value of the test, and there are many cases where it would be desirable to have a simpler method for evaluating fracture toughness, even if only an estimate of K_{Ic} were obtained.

In the past, a Charpy impact test was commonly used to measure the toughness of a material, and it continues to be popular for both low- and high-strength materials. The test is simple to conduct, the specimen is readily fabricated, and the material requirements are modest. The primary disadvantages of the test are the difficulty of using energy values in design in a quantitative fashion, and the fact that the energy is not a material constant.

It would be useful if the Charpy impact and the plane strain tests could be combined so that we could take advantage of the experimental simplicity of the former to gain a measure of the K_{Ic} value afforded by the latter. At present there is no theoretical treatment that directly relates the energy absorbed in a V-notched Charpy impact test to the K_{Ic} value of a material, but correlations between the two properties have been observed in the past,[5-8] and comparisons have also been made between K_{Ic} or K_c and the energy absorbed in impact or slow-bend tests on precracked Charpy specimens.[5,9,10]

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Manuscript submitted December 9, 1970.

The aim of the present work was to examine the possibility of developing a correlation between Charpy energy and K_{Ic} for titanium alloys. Impact and slow-bend tests were run on V-notched and fatigue-precracked Charpy specimens from various alloys and the results were compared with the corresponding approximate K_{Ic} values obtained from three-point slow-bend testing. It can be concluded that for routine screening purposes the slow-bend test on precracked specimens can provide a practical, economical screening test for titanium alloys. The fracture toughness figures obtained in this way cannot be considered valid using established ASTM criteria but they would be adequate for many purposes. If such a screening system were to be employed, tests that adhere more rigorously to plane strain testing techniques would be needed only where the screening tests indicated marginal values.

EXPERIMENTAL PROCEDURE

The materials used in the investigation included four commercial titanium alloys, one experimental titanium alloy (Ti-5-5),[11] two steels, and two aluminum alloys, Table I. The Ti-6-2-4-6 and Ti-6-6-2 alloys were received as aircraft engine compressor disk forgings, the Ti-6-4, Ti-5-5, and β III alloys as extrusions, and the steels and aluminum alloys as plates. Several forgings, extrusions, or plates were used for each of the alloys, each product having experienced its own individual processing treatment, and the test specimens into which they were machined covered a wide range of tensile and toughness properties. None of the processing treatments were made specifically for the present program; the materials came from several sources and in most cases were already processed and heat-treated when received.

Standard V-notched Charpy specimens were prepared from the various alloys and broken in impact or slow-bend. A 240 ft-lb. machine was used for the impact specimens of the Ti-6-2-4-6 alloy, and a 24 ft-lb. machine for the Ti-6-4 alloy and the 4340 steel. A Physmet SB-750 tester was used for all the slow-bend tests, with a crosshead speed of 0.1 in. per min, and

Table I. Nominal Alloy Compositions

			Titanium Alloys				
	Al	V	Sn	Zr	Mo	Fe	Ti
Ti-6-2-4-6	6		2	4	6		bal.
Ti-6-6-2	6	6	2				bal.
Ti-6-4	6	4					bal.
Ti-5-5	5	5.5				1.0	bal.
β III			4.5	6	11.5		bal.
			Steels				
	C	Mn	Si	Cr	Ni	Mo	Fe
4340	0.40	0.85	0.2	0.75	1.8	0.25	bal
D6AC	0.46	0.75	0.2	1.0	0.55	1.0	bal.
			Aluminum Alloys				
	Zn	Mg	Cu	Cr	Li	Mn	Cd	Al
2020-T6			4.5		1.1	0.5	0.2	bal.
7075-T73	5.6	2.5	1.6	0.3				bal.

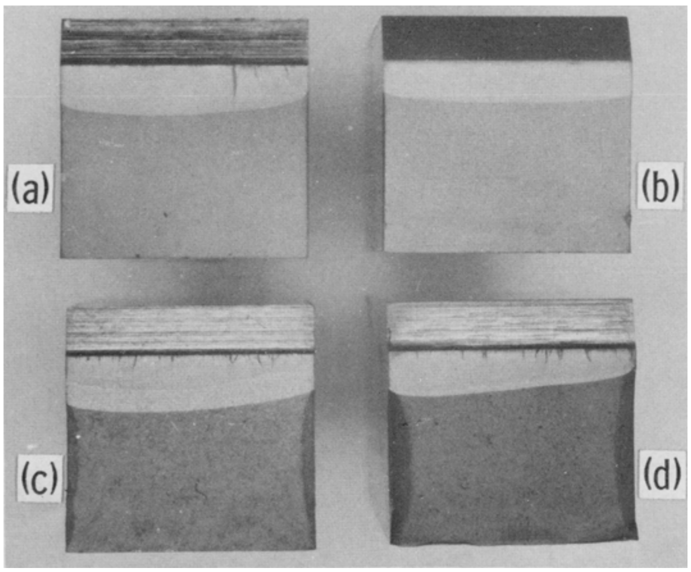

Fig. 1—Fracture faces of precracked Charpy specimens broken in slow-bend. (*a*) Ti-6-2-4-6; (*b*) Ti-6-6-2; (*c*) Ti-6-4; (*d*) D6AC.

load-deflection curves were recorded along with the energy values. Impact and slow-bend tests were also made on precracked Charpy specimens, prepared from V-notched specimens using a Physmet fatigue pre-cracking machine to introduce cracks approximately 0.060 in. deep at the roots of the notches.

The energy, W, absorbed in fracturing each of the specimens was converted to a W/A value, where A is either the area of cross-section under the notch for the V-notched specimens or the initial uncracked cross-sectional area for the precracked specimens.

In some cases, both full-size and 0.2 or 0.3 in. thick precracked Charpy specimens were prepared and tested in slow-bend. Apart from thickness, the subsize specimens were identical in every respect to the full-size ones and were tested under the same conditions.

The load-deflection curves for the slow-bend tests on precracked specimens of the titanium alloys and the 4340 steel allowed the determination of approximate K_{Ic} values for the materials, using methods based on ASTM recommendations for three-point specimens.[1,3,4] Compact tension K_{Ic} specimens were prepared from the D6AC steel and the aluminum alloys and were tested using techniques that were valid in every respect regarding current requirements for K_{Ic} measurements.[1,3,4]

RESULTS

Whether tested in impact or slow-bend, the fracture faces of Charpy specimens of a high-strength material usually have a macroscopically flat region bordered by slant shear lips. In the ultrahigh-strength aircraft materials the strength levels and toughness values are such that the shear lips account for only a small area of the fracture face, Fig. 1. For present purposes we will assume that the fracture is completely flat. We can also assume that in the materials we are dealing with, at the strength levels and test temperatures of interest, the flat fracture is formed under plane strain conditions.[12] If we make the further assumption that the energy absorbed per unit area of fracture can be related to the fracture toughness, G_{Ic}, then we can write:

$$G_{Ic} = \tfrac{1}{2}(W/A)$$

The factor of one-half used in this expression takes into account the two fracture faces formed on breaking the test specimen.

K_{Ic} is related to G_{Ic} as follows:

$$K_{Ic}^2 = \frac{EG_{Ic}}{(1-\nu^2)}$$

where E is the elastic modulus and ν is the Poisson ratio.

Hence:

$$K_{Ic}^2 = \frac{EG_{Ic}}{(1-\nu^2)} = \frac{E}{2(1-\nu^2)}\cdot(W/A)$$

Although the assumption of equivalence between K_{Ic} and W/A can be questioned, K_{Ic} being an instability parameter and W/A an integrated energy, it is made merely to provide a guide for plotting the experimental results. If there is some kind of direct relationship of this nature between Charpy energy and K_{Ic} it should be evident on plotting K_{Ic}^2/E vs W/A, and the plots in Figs. 2 to 5 are made on this basis. The values of K_{Ic} used are those obtained from the load-deflection curves for the slow-bend tests on precracked specimens. The straight line in each plot, the predicted line, is drawn by assuming $K_{Ic}^2 = E(W/A)/2(1-\nu^2)$, using a value of 0.3 for ν.

The results show that only in the case of the precracked specimens broken in slow-bend is there a reasonable correlation between K_{Ic}^2/E and W/A, Fig. 5. The experimental points for the V-notched and precracked impact, Figs. 2 and 3, and the V-notched slow-bend tests, Fig. 4, lie well away from the predicted line and there is no obvious correlation between K_{Ic}^2/E and energy.

In Fig. 5 the experimental points tend to follow the predicted line even though several alloys and a range of strength levels are involved. Deviation from the line occurs only at the higher W/A and K_{Ic} levels, where the specimens have shear lips of appreciable size and the W/A value includes a marked contribution from the energy absorbed in shear lip formation.

Also included in Fig. 5 are points for the two tough-

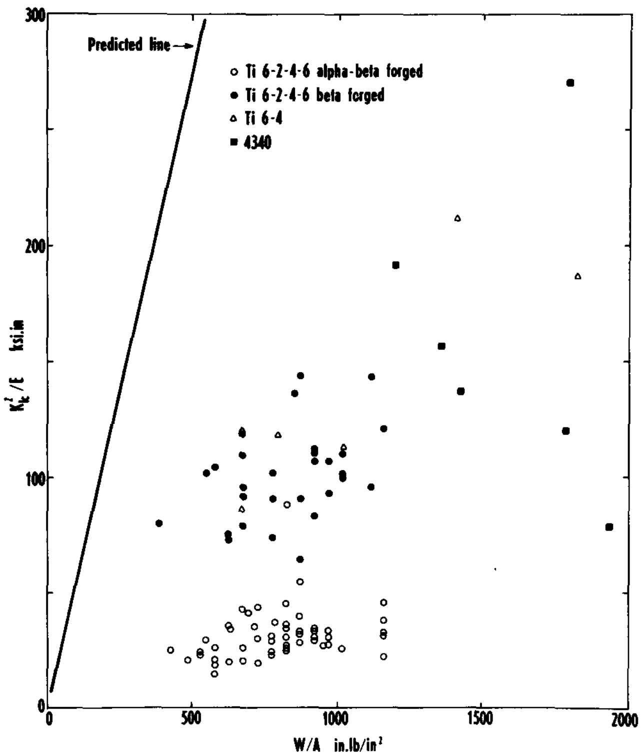

Fig. 2—K_{Ic}^2/E vs W/A for V-notched specimens tested in impact.

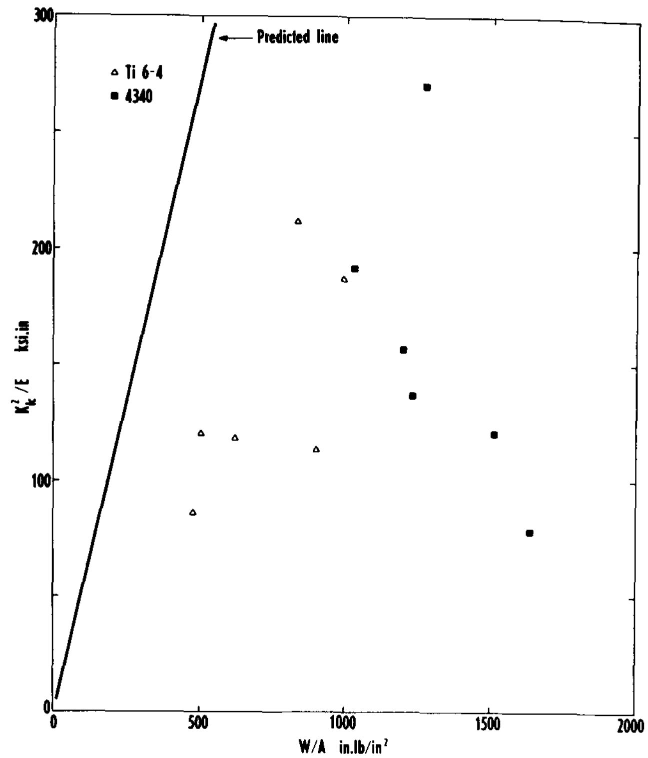

Fig. 4—K_{Ic}^2/E vs W/A for V-notched specimens tested in slow-bend. Each point represents the average values of three tests for W/A and three tests for K_{Ic}.

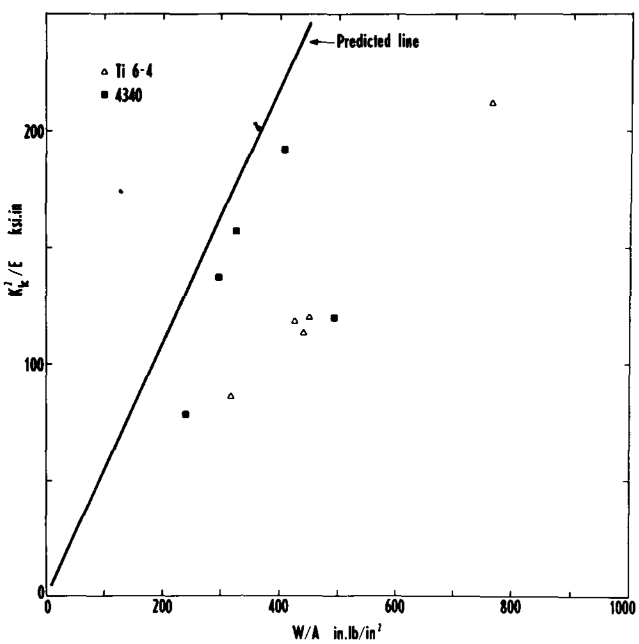

Fig. 3—K_{Ic}^2/E vs W/A for precracked specimens tested in impact. Each point represents the average values of three tests for W/A and three tests for K_{Ic}.

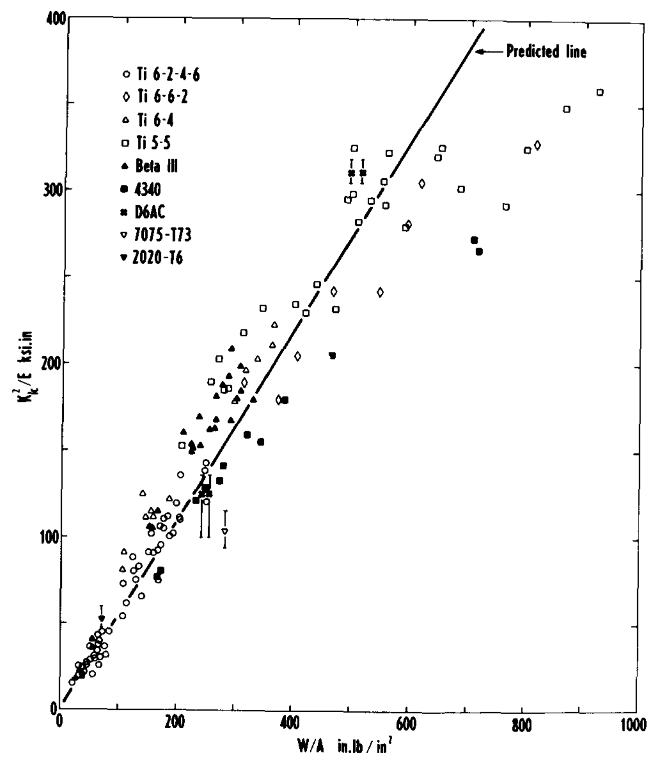

Fig. 5—K_{Ic}^2/E vs W/A for precracked specimens tested in slow-bend.

ness levels of the D6AC steel and the two aluminum alloys. The W/A values in this case came from tests on standard-size precracked Charpy specimens while the K_{Ic} values were obtained using compact tension specimens. The ranges covered by the valid K_{Ic} values are indicated on the plot. The K_{Ic} value used for the lower toughness condition of the D6AC steel is the average of twenty tests, and that for the higher toughness level is the average of two tests. The K_{Ic} values for the two aluminum alloys each represent the average of nine tests. The closeness of these particular experimental points to the predicted line indicates that it is possible to obtain excellent agreement between W/A and K_{Ic} when the Charpy specimen has small shear lips and valid values of K_{Ic} are used.

In Fig. 6 the K_{Ic} values given by the load-deflection

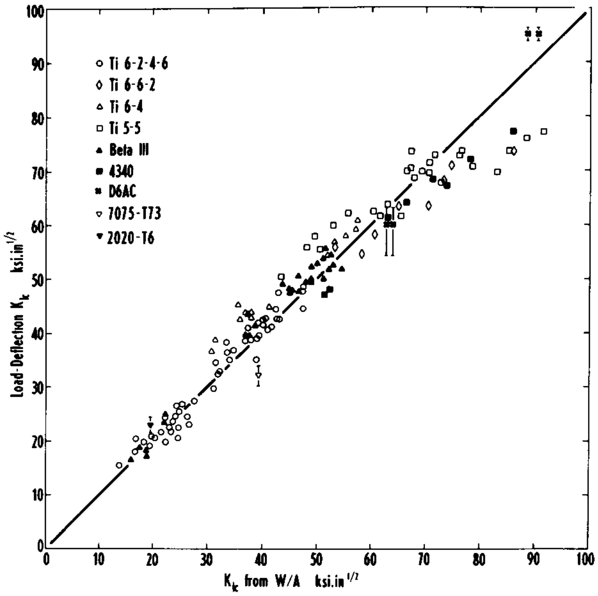

Fig. 6—K_{Ic} determined from slow-bend load-deflection curves vs K_{Ic} calculated from W/A values for precracked specimens tested in slow-bend.

curves are compared with the corresponding values derived from W/A. The W/A figures came from the slow-bend tests on precracked specimens and are used in the relation $K_{Ic}^2 = E(W/A)/2(1 - \nu^2)$ to give K_{Ic}. For this purpose ν is assumed to be 0.3, and values of $E = 29 \times 10^6$ psi are used for the steels, $E = 10.5 \times 10^6$ psi for the aluminum alloys, and $E = 16.5 \times 10^6$ psi for the titanium alloys. The latter value of $E = 16.5$ is only approximate, for the value of E for titanium alloys can vary quite markedly, being dependent on composition and heat treatment, and the exact values for the present alloys are not known.

The results of Fig. 6 follow the same trend as that shown in Fig. 5. The experimental points lie close to the 45 deg line over much of the range—indicating good agreement between the values determined by the two methods—and deviate to the right of the line at the higher toughness levels. The plot also includes points representing the average valid K_{Ic} values for the D6AC steel and the aluminum alloys, together with the corresponding ranges, and it can be seen that the values derived from the Charpy W/A results agree well with those obtained using the ASTM recommended practice.

DISCUSSION

Impact Results

The standard impact test on V-notched specimens is a simple one to run on a routine level, but Fig. 2 shows that it is difficult to relate the results to K_{Ic} in the case of the alloys studied in the present program. A possible explanation for the lack of a correlation in the case of the Ti-6-2-4-6 alloy comes from the knowledge that the microstructure of the alloy consisted of a mixture of the α and β phases, and that the relative amounts and morphologies of the individual phases varied markedly with prior thermal and mechanical history. Relative to the effect of the strain rate of slow-bend, the fast strain rate of the impact test may alter the properties of one phase more than those of the other; thus the different microstructures may have

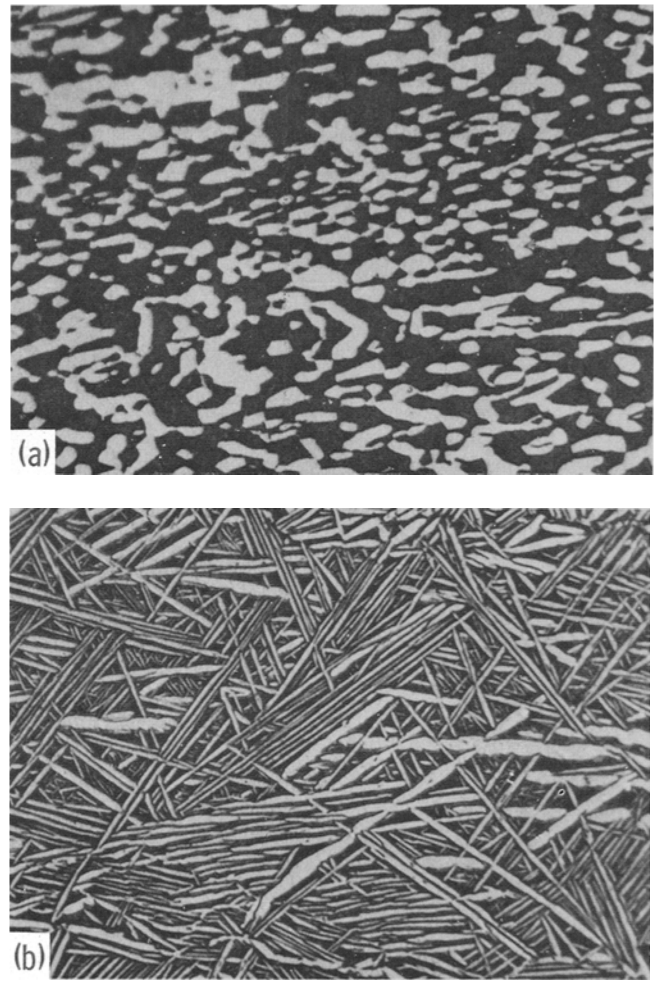

Fig. 7—Examples of microstructures observed in Ti-6-2-4-6 alloy. (*a*) α-β forged; (*b*) β forged. Magnification 825 times.

been strain rate sensitive to different degrees, leading to scatter in the results when comparing impact with slow-bend.

Fig. 2 may be reflecting this kind of behavior, for the Ti-6-2-4-6 experimental points can be divided roughly into two groups: the lower group, representing α-β processed material, having microstructures similar to that of Fig. 7(*a*), and the upper group, representing β-processed material, having microstructures like that of Fig. 7(*b*). In a case like this it is quite possible that a much better correlation between impact energy and K_{Ic} would be obtained if the latter were determined at the same strain rate as that experienced in the impact test.

Slow-Bend Results

In Fig. 5 the experimental data for the precracked slow-bend specimens follow the predicted line quite closely. This predicted line represents a relationship between W/A and K_{Ic} that was derived by assuming that all the energy absorbed in the precracked specimen is used to propagate the crack, and that the extension resistance remains constant as the crack progresses through the material. It is known that these assumptions are not necessarily valid—particularly the one concerning constant crack extension resistance[2,3,13-15]—but, nevertheless, the experimental results suggest that precracked specimens tested in slow-bend may form the basis of an acceptable screening test for the high-strength alloys studied.

The values of K_{Ic} used in the present comparison of K_{Ic} and W/A were determined from the slow-bend load-deflection curves and would not be considered valid by present ASTM standards. Although the specimen size is close to minimum requirements, the fatigue crack depth and the way it was introduced would not be acceptable. In addition, the design of the slow-bend machine did not allow the use of a compliance gage in the specimen notch and this would lead to some loss of sensitivity in detecting first crack growth.

In spite of these drawbacks, the results from the D6AC steel and the aluminum alloys in Fig. 6 show that the load-deflection curves of the slow-bend tests give K_{Ic} values that are quite close to the valid ones. Although this agreement does not necessarily mean that the slow-bend K_{Ic} values for all the alloys are correct, the overall general agreement of the experimental data with the predicted line in Fig. 5 suggests that our K_{Ic} values are reasonable. Probably the high strength levels of the alloys used in the present work were sufficient to allow good approximations of K_{Ic} to be obtained using the Charpy-size specimens.

Flat-Fracture Energy

In Figs. 5 and 6 the experimental points deviate from the straight line at the higher W/A and K_{Ic} levels. In the high toughness range the broken test specimens have shear lips that are of appreciable size, and, particularly in the case of the 4340 steel, there is a plastic hinge formed opposite the notch. The plastic flow associated with the shear lips and hinge accounts for a proportion of the energy absorbed by the specimen and the W/A values tend to be too high relative to the K_{Ic} levels.

In cases like this it is possible to obtain an estimate of the energy associated with flat fracture by testing a second specimen having a different thickness—a half-size one, for example—and employing a method related to that of Hartbower and Orner.[16] Using two specimens of different thicknesses, Fig. 8, the areas of flat fracture on each are measured using a planimeter on photographs taken at a known magnification. If $(W/A)_F$ is designated as the energy per unit area of flat fracture, and $(W/A)_S$ as the energy per unit area of non-flat fracture, whether it is shear lip or hinge, then for the thick specimen:

$$W = (W/A)_F \cdot A_F + (W/A)_S \cdot A_S$$

where W is the total energy needed to break the precracked specimen, A_F is the measured area of flat fracture, and A_S is the remaining area of fracture.

Similarly, for the thin specimen:

$$W' = (W/A)_F \cdot A'_F + (W/A)_S \cdot A'_S$$

Solving the simultaneous equations for $(W/A)_F$ gives:

$$(W/A)_F = \frac{W \cdot A'_S - W' \cdot A_S}{A_F \cdot A'_S - A'_F \cdot A'_S}$$

If we make the assumption that the fatigue crack is the same depth in both specimens, and that the shear lip size and shape is also independent of thickness, the above expression becomes that used by Hartbower and Orner:[16,17]

$$(W/A)_F = \frac{W - W'}{A_F - A'_F} = \frac{W - W'}{A - A'}$$

where A and A' are the net cross-sectional areas of the two specimens. In practice, slight variations in the size and shape of both the fatigue crack and the shear lips do exist, so this simpler form was not used in the present work.

The method for determining $(W/A)_F$ must give only an approximate value, of course, but the results suggest it may be useful. Fig. 9 compares the K_{Ic} values obtained from the Charpy load-deflection curves or the compact tension specimens with the K_{Ic} values derived from $(W/A)_F$. The experimental data came from the Ti-6-4 alloy and the two steels, and each point on the plot is the result of testing three standard-size specimens and three subsize ones. The use of flat-fracture energy rather than measured energy does not make much difference in the case of the Ti-6-4 or the D6AC, for the specimens had fracture faces that were almost completely flat; however, when $(W/A)_F$ values are used for the 4340 steel the points lie close to the line up to K_{Ic} values of about 90, a level at which the corresponding measured (W/A) values lie well to the right of the line, Fig. 5.

Other techniques for eliminating shear lip contribu-

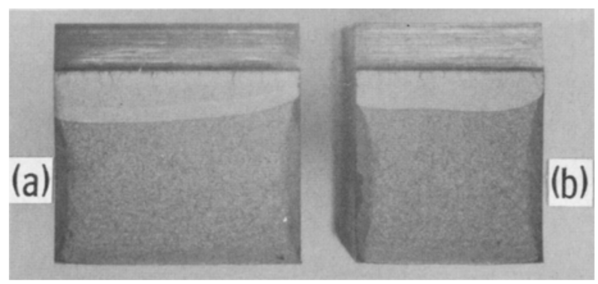

Fig. 8—D6AC steel. Fracture faces of precracked Charpy specimens broken in slow-bend. (*a*) Standard-size, 0.394 in. thick; (*b*) 0.3 in. thick.

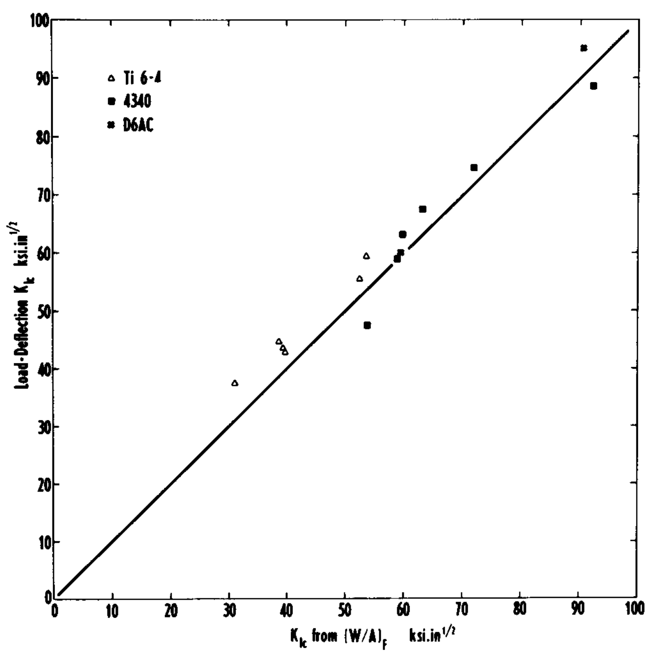

Fig. 9—K_{Ic} determined from slow-bend load-deflection curves vs K_{Ic} calculated from $(W/A)_F$ values for precracked specimens tested in slow-bend.

tions have been used in the past.[6,13,16,18-22] One method involves the introduction of a carburized or nitrided brittle boundary layer into the specimen to suppress the formation of shear lips,[2,16,18-20] another method uses side grooves to force the crack to follow a flat fracture path,[6,13,21,22] and in at least one instance surface embrittlement has been combined with the use of specimens of different thicknesses.[16] These methods have the disadvantage of making a change in the stress field in front of the crack (side grooves)[3,23] or of changing the material itself (nitriding). The specimen difference technique was used in the present work because it does not involve any such changes to the specimen.

The results of Fig. 9 emphasize the usefulness of slow-bend tests on precracked Charpy specimens. They cannot be used for determining valid K_{Ic} values, but the correlation apparent between K_{Ic} and (W/A) or $(W/A)_F$, combined with the simplicity of the test and its economical use of material, make its consideration for alloy development or screening purposes worthwhile. Although it would be necessary to run extensive correlation studies for various materials before one could be sure that the Charpy energy could be used to estimate K_{Ic} with any degree of confidence, the technique may be applicable where it is not feasible to employ valid testing methods.

In deriving the relationship between W/A and K_{Ic}^2/E, used as a basis for plotting the experimental results, it was assumed that the crack extension resistance remains constant as the crack propagates through the specimen and that the fracture is formed under plane strain conditions. The observed correlation between energy and K_{Ic}^2/E in itself suggests that these must be reasonable assumptions to make for the precracked slow-bend specimens of the materials studied, but there is additional evidence from Pellini and Judy[15] that such a relationship between W/A and K_{Ic} would not be unexpected.

Pellini and Judy classify materials according to the shape of their fracture extension resistance curves (R curves), which indicate the rate at which the resistance to fracture increases as the crack moves away from the initial crack tip. The shape of the R curve for a particular material is linked to the rate at which the transition occurs from the initial plane strain fracture mode to the final plane stress or mixed mode that is characteristic of the material and section thickness. High-strength steels, such as D6AC and 4340, and titanium alloys, other than the lowest-strength ones, apparently have R curves that rise at only a moderate rate with increasing crack length; consequently, slant fracture is not developed to any great extent in the Charpy specimen—particularly in the precracked Charpy specimen—and the fracture is essentially of the plane strain type.

In effect, the fracture path in the Charpy specimen is too short to allow the full development of a plane stress fracture mode, and the specimen represents a pseudo-plane-strain configuration. Hence the measured energy approximates that for plane strain fracture, and it correlates well with K_{Ic}. On this basis, it can be inferred that precracked Charpy specimens should prove useful for estimating K_{Ic} in other materials where the fracture extension resistance either does not increase, or increases only slowly as the crack grows and the stress state changes.

SUMMARY

To examine the feasibility of using simple experimental testing techniques to estimate K_{Ic} in high-strength titanium alloys, impact and slow-bend tests were made on either V-notched or fatigue-precracked Charpy specimens.

No simple correlation between K_{Ic} and impact energy was evident for the alloys studied, but promising results came from slow-bend tests on precracked specimens, where the measured energies gave good indications of the K_{Ic} levels for specimens having fracture faces that were mostly flat. In the materials of higher toughness, where the shear lips were of an appreciable size, just as reasonable a relationship between energy and K_{Ic} could be obtained if flat-fracture energies were used.

ACKNOWLEDGMENTS

We are indebted to Mr. M. M. Cook and Mr. N. L. Harruff for their diligent assistance in the testing phase of the program, and we would like to thank Mr. P. L. Hendricks, Mr. A. M. Adair, Mr. C. L. Harmsworth, Dr. M. Greenfield (Air Force Materials Laboratory) and Mr. R. Sprague (Pratt and Whitney) for providing test material. Discussion with Mr. I. Perlmutter, AFML, is also appreciated.

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