DISCUSSION

S. T. Rolfe[1] *and S. R. Novak*[2] *(written discussion)*—In view of the growing use of fracture mechanics data by engineers, the authors' paper on the influence of specimen size on K_{Ic} values is most timely. They show that K_{Ic} values which were determined in accordance with the ASTM Proposed Test Method for Plane Strain Fracture Toughness of Metallic Materials[3] can vary moderately (15 percent) within the specimen size and geometrical limitations imposed by the test method. They further state that these variations would be increased by a relaxation of the current size requirements. We agree with this statement and thus agree with the authors that the use of *subsize* specimens with the ASTM Committee E-24 Test Method does not constitute a useful screening procedure.

However, with the development of fracture mechanics to the point where it is a working tool that can be of significant value to engineers, and the concomitant development of very high-strength steels with good toughness, the engineer is faced with a serious dilemma. On the one hand, he has a powerful tool that can help him in research, material specification, alloy development, analysis of subcritical crack growth, and most importantly, in structural analysis of members that may have cracks in them. Conversely, the metallurgist continually is developing new materials with crack toughness that cannot be measured by the currently specified test method because of the specimen-size requirements. The engineer is then faced with one of several choices. He can choose not to use fracture mechanics. Under the rigid requirements that currently exist for K_{Ic} testing, such a choice would appear to be proper for very tough materials where valid K_{Ic} values cannot be obtained in reasonably sized specimens. Thus he is forced to use other methods of determining fracture behavior that may be significantly less accurate. Furthermore, these less accurate methods cannot relate the critical flaw size/design stress parameters so important to designers. Because of the

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[3] "Proposed Method of Test for Plane-Strain Fracture Toughness of Metallic Materials," *1969 Book of ASTM Standards*, Part 31.

tremendous potential of fracture mechanics, this choice should be avoided, if possible. A second choice (at least until a nonlinear or plastic fracture-mechanics analysis becomes available) is to use an approximation to K_{Ic} that is useful for engineering purposes.

The authors do not recommend the use of *subsize* specimens, even for engineering purposes, and we would agree with this statement. However, by using *subthickness* specimens, consistent approximations to K_{Ic} have been obtained within ± 15 percent for several high-strength steels. Recent test results[4] also have shown this same behavior for aluminum. Specifically, by following the ASTM Test Method in all aspects except the limitation on thickness, the engineer can obtain an engineering approximation to K_{Ic} (designated as K_{IE}) that can be used in the same manner as K_{Ic} values. Obviously, considerable research is necessary before a K_{IE} test method can be established in the same manner that the test method for K_{Ic} was established; however, research in progress indicates that using the current K_{Ic} test method with *subthickness* (not subsize) specimens, within the limitations described below, will provide a good approximation to K_{Ic}. Because specimen thickness is usually the limiting requirement (the a and W dimensions of a test specimen cut from a plate usually can be made quite large, but the B dimension is fixed by the original thickness of plate), the use of *subthickness* specimens is a realistic solution to the problem of specimen-size limitations.

To substantiate the fact that subthickness slow-bend specimens may give a good approximation to the K_{Ic} values obtained from full-thickness K_{Ic} specimens, slow-bend K_{Ic} tests of several high-strength steels were conducted. In these tests, the a and W dimensions of the specimens were kept large enough to satisfy the ASTM Test Method. However, the B dimension was varied so that the results from subthickness specimens could be compared with results obtained from standard-size specimens.

Preliminary results for an 18Ni maraging steel (192 ksi yield strength) are presented in Fig. 21. These results show that by keeping the a and W dimensions sufficiently large, that is, $W > 5.0\,(K_{Ic}/\sigma_y)^2$ and $a > 2.5\,(K_{Ic}/\sigma_y)^2$, test specimens where B is less than the currently specified minimum thickness ($B = 2.5\,(K_{Ic}/\sigma_y)^2$) can be used to approximate K_{Ic} within ± 15 percent. Similar subthickness specimen tests of other high-strength steels with strengths from 150 to 250 ksi are in progress, and preliminary results substantiate this behavior.

The data of Fig. 21 also show substantial stable crack propagation above $K_{I5\%}$ (to $K_{I\max}$) for this alloy. In addition, the data show the dependence of $K_{I\max}$ on thickness, B, while $K_{I5\%}$ (K_{IE}) appears to be relatively invariant.

[4] Kaufman, J. G., "Thickness Effects on Aluminum Alloys," presented at ASTM Committee E-24 Meeting, 23 Sept. 1969.

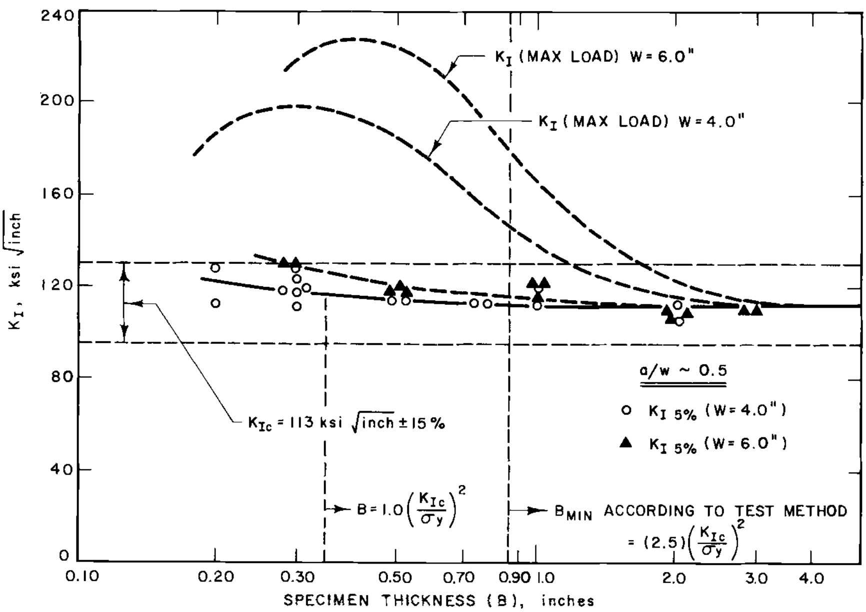

FIG. 21—*Effect of specimen thickness on* K_I *at 5 percent secant intercept and at maximum load for an 18Ni (190 grade) marging steel in three-point bending.*

The significant feature of this engineering approximation to K_{Ic} is that by making a and W sufficiently large *in a bend specimen with a steep stress gradient*, the plastic zone size ahead of the crack tip is sufficiently small so that an elastic analysis can be used. Although the plastic zone size also is controlled by the B dimension, the only current technique for determining the thickness limitation is experimental, and results of *subthickness* specimens indicate that specimens having $B < 2.5\,(K_{Ic}/\sigma_y)^2$ still yield satisfactory results. In fact, using *subthickness* test specimens and making $B \cong 1.0\,(K_{Ic}/\sigma_y)^2$ gives a close approximation to K_{Ic}.

Analysis of the authors' data also substantiated the fact that subthickness specimens should give satisfactory results. For the 4340 steel tempered at 750 F (σ_y = 213 ksi), the average K_{Ic} value is approximately 70 ksi $\sqrt{\text{in.}}$ Using this value, the minimum thickness, crack length, and specimen depth in accordance with the ASTM Recommended Test Method should be 0.27, 0.27, and 0.54 in., respectively. Using the proposed K_{IE} procedure for engineering approximations, the minimum specimen dimensions should be approximately 0.11, 0.27, and 0.54, respectively. Note that by using only subthickness specimens, the a and W dimensions still satisfy the recommended test method for K_{Ic}.

Analysis of the authors' data presented in Figs. 8, 9, and 10 of their paper shows K_{Ic} values of 64, 69, and 73 ksi $\sqrt{in.}$, respectively, at $B = 0.27$ in. At $B = 0.11$ in. the K_{IE} values are 63, 70, and 77 ksi $\sqrt{in.}$, respectively. This variation between K_{Ic} and K_{IE} is well within the 15 percent variation that the authors observed for the valid K_{Ic} test results on specimens tempered at 750 F. Thus, it would appear that *subthickness* specimens can be used to get an engineering approximation to K_{Ic}. For the 4340 steel tempered at 925 F ($\sigma_y = 182$ ksi), the K_{Ic} value is approximately 107 ksi $\sqrt{in.}$ On this basis, a K_{IE} test specimen should have B, a, and W dimensions of 0.34, 0.85, and 1.70 in., respectively. Those test specimens that do satisfy the K_{IE} size requirement will have a K_{IE} of approximately 105 ksi $\sqrt{in.}$, Fig. 13.

In Figs. 15 and 16, the authors analyze Srawley's test results[5] for a maraging steel heat treated to various yield strengths to further show that *subsize* specimens give misleading results. However, because the subsize specimens were proportioned in all three dimensions (W, a, and B), only the results on material tempered from 800 to 1000 F would meet the *subthickness* specimen-size requirements. These values obviously agreed with the K_{Ic} values obtained from the large-size specimens, because even the small-size specimens satisfied the ASTM Test Method.

In conclusion, the authors are to be complimented on a very timely paper describing the effects of specimen size on determination of K_{Ic} values. We would agree with their conclusion that *subsize* specimens should not be used for screening purposes, but we would suggest that *subthickness* specimens can be used to obtain engineering approximations to K_{Ic}, namely, K_{IE} values.

J. G. Kaufman[6] (*written discussion*)—This investigation was carried out with the usual thoroughness of the authors, and we are fully in agreement with their conclusions that (*a*) relaxation of present requirements for K_{Ic} testing are unwarranted and (*b*) the results from undersized specimens are of little or no value for screening purposes. The data presented in Figs. 8, 9, and 10 amply demonstrate that values of K_Q calculated from thin specimens may be either higher or lower than K_{Ic}, dependent upon the interrelation of the thickness, the toughness, and the absolute crack extension. Data from undersized specimens are best considered only as guides for the selection of more appropriate sizes of specimen.

[5] Srawley, J. E., "Plane Strain Fracture Toughness Tests on Two-Inch Thick Maraging Steel Plate at Various-Strength Levels," *Proceedings of the Second International Conference on Fracture*, Brighton, Sussex, England, 1969 (to be published).

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A popular misconception regarding data from specimens which are undersized with regard to thickness is that, although they may not be valid K_{Ic} values, they are useful as "K_c" values to indicate the "thin-section" toughness of the material. This is not the case. Disregarding the questions which have arisen in recent years about the meaning and constancy of K_c values, the plane strain fracture-toughness test as presently defined tells nothing about the thin-section instability as it was embodied in the K_c approach. The values are not quantitative measures of the thin-section toughness in any terms understood at this time, although there may be some possibility of interpretation of the load-deformation curves from such tests in terms of resistance curves, after the fashion proposed by Heyer and McCabe.[7] I would be interested in the authors'comments on this point.

J. M. Krafft[8] *(written discussion)*—This excellent paper provides much needed: (1) systematic studies of the effect of specimen dimensions on the measure of K_{Ic}, and (2) comparisons of plastic flow properties with fracture behaviors. I would like to cast a vote on the alternatives suggested in the conclusions.

We need not be too concerned that the measure of K_{Ic} is not invariant if a_0 and W depart from required size and ratio. We are usually testing plate or sheet product with adequate area available to make a_0 and W what we would. And indeed, as the authors note, the whole concept of linear elastic analysis breaks down if the planar dimensions are inadequate. However the thickness is usually limited, yet K_{Ic} values are of great value. The systematic trends in K_Q with thickness for three specimen widths, Figs. 8 through 11, appear to be explicable in terms of the effects of these variables on the shape of the crack growth resistance curve which is sampled at different levels by the 5 percent secant. Authors' Conclusion 3 would solve this dilemma through control of the shape of the resistance curve by continuing to require relatively thick sections. I prefer the alternative, noted in Conclusion 2, of abandoning the secant intercept in favor of "basing K_{Ic} on a fixed (and preferably vanishingly small) increment of crack extension." Our own experience indicates that if only the thickness requirement is reduced, this should require no change in the present instrumentation, down to thicknesses of about 1.0 $(K_{Ic}/\sigma_{YS})^2$. Such a change would vastly enhance the applicability of the K_{Ic} test, and thus be worth the extra care of crack growth detection.

With respect to the attempted correlations with tensile properties, the physical event which George Hahn and I attempt to predict is the onset of

[7] Heyer, R. H. and McCabe, D. E., "Plane-Strain Fracture Toughness Testing Using a Crack-Line-Loaded Specimen," presentation at the *National Symposium of Fracture Mechanics*, Lehigh University, Bethlehem, Pa., 25 Aug. 1969.

[8] Head, Fracture Mechanics Consultant Staff, Naval Research Laboratory, Washington,

crack growth, which would be the K_{Ic} instability for a very large specimen. As with decreased thickness noted above, increased toughness, as with higher tempering temperature, tends to accentuate the value of K_Q. This could account in part for the failure of the n values of Fig. 18 to rise as fast as K_{Ic}. It argues further for replacement of the secant intercept method with a more sensitive measure of the onset of crack extension.

Among materials poorly characterized by parabolic strain hardening and a constant strain hardening exponent, n, is 4340 quenched and tempered above 600 F, as authors note from Ref *10* of the paper. In such cases we find it useful to replot true stress σ strain ϵ curves in an inverted differential form, $d\sigma/d\epsilon/\sigma$ versus $1/\epsilon$. Here parabolic hardening is indicated by a straight line through the origin of slope n. Whatever the curve, the intercept with the line $d\sigma/d\epsilon/\sigma = 1.0$ defines the strain for uniaxial tensile instability. With these steels, the curve tends to flare out so as to gradually descend below the 1.0 level before dropping toward the origin. This oblique intersection makes actual intercept sensitive to small variations in curve shape, although it can be rather accurately defined in this way without exercise of undue "imagination." Perhaps these refinements in measures of K_{Ic} and of instability strain would improve prospects of estimating K_{Ic} from plastic flow properties.

M. H. Jones and W. F. Brown, Jr. (authors' closure)—We are pleased that Mr. Kaufman agrees it would be unwise to relax the present size requirements for K_{Ic} testing. It is our opinion that these requirements as they stand now are barely sufficient to permit the use of an elastic mechanics as the basis for a quantitative method of fracture testing. In fact, we always have believed the present requirements should be doubled. As Mr. Kaufman correctly states, the value of K_{Ic} tells us nothing about thin-section fracture instability as was originally embodied in the K_c approach. It is, of course, possible that crack growth resistance curves obtained from under-thickness specimens might be useful in characterizing an alloy's resistance to mixed mode fracture. This is the approach being followed by Heyer and McCabe,[7] and measurements of this kind should be encouraged. However, it is not yet clear what feature or features of the K versus a curves should receive attention for a standardized measure of fracture resistance, nor has the influence of crack length in these tests been sufficiently well explored.

Both Messrs. Rolfe and Novak and Mr. Krafft call attention to the problem of evaluation of very tough materials where the thickness needed for practical applications is not sufficient to meet the ASTM Committee E-24 size requirements. They propose to circumvent this problem by reducing the thickness requirement. This suggestion has been made before, and we are quite opposed to it. The size requirements as given in the ASTM Committee E-24 Proposed Method of Test for Plane Strain Fracture Toughness of Metallic Materials were designed to ensure that conditions of small scale yielding will be sufficiently approximated in the specimen that a useful engineering estimate of K_{Ic} can be obtained. Any relaxation of these requirements can reduce the accuracy of this estimate and may lead to serious error in judging the toughness of a given alloy.

Unfortunately the method suggested by Messrs. Rolfe and Novak for determining a less precise engineering estimate (K_{IE}) of K_{Ic} can result in K_{IE} values substantially in excess of the true K_{Ic} value. They propose to define K_{IE} in the same way as K_{Ic} except to relax the thickness requirement to $B > (K_{Ic}/\sigma_y)^2$, which really should be stated as $B > (K_{IE}/\sigma_y)^2$ since the true value of K_{Ic} will not be known. Presumably, also they would abolish the present W/B limits. Difficulties can arise when the crack length is in excess of that necessary for a valid K_{Ic} determination. Under these circumstances, as pointed out in our paper, the measured K_Q value will tend to increase with decreasing thickness. The magnitude of this effect will depend on the amount of excess crack length and the change in shape of the crack growth resistance curve with thickness. This change in turn will depend on the material characteristics. In the case of the 18Ni maraging steel, Fig. 21, tested by Rolfe and Novak, and for the 750 F tempered 4340 tested by the authors, the elevation of K_Q with decreasing thickness is moderate and where $K_Q = K_{IE}$ overestimates of K_{Ic} would not exceed the 15 percent variation between K_{Ic} and K_{IE} mentioned by the discussers.

However, in some cases we will not be as fortunate in finding so nice a balance between the effects of crack length and thickness. For example, cracked bend tests on 6Al-6V-2Sn-Ti, Fig. 22, show steeply rising values of K_Q as the thickness is reduced below that required for a valid K_{Ic} test. These specimens had crack lengths of about 0.5 in. (approximately six times the

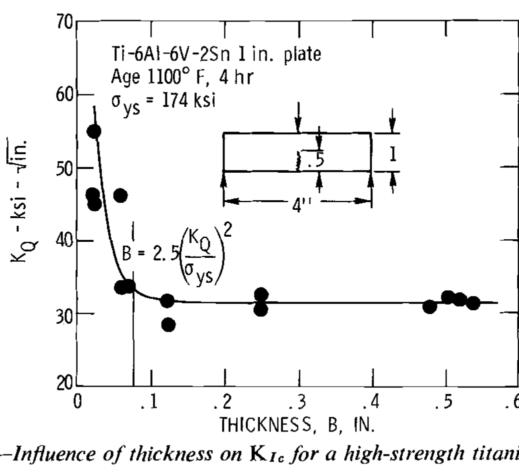

FIG. 22—*Influence of thickness on* K_{Ic} *for a high-strength titanium alloy.*

required value) and a/W ratios of about 0.5. These tests were conducted in accordance with the present ASTM Committee E-24 Test Method and are valid with the exception of those at the two smallest thicknesses, which passed the test for excess plasticity but failed to meet the thickness requirement. Note that for this alloy specimens meeting the proposed thickness requirement of $B > (K_{Ic}/\sigma_y)^2$ can overestimate K_{Ic} by 50 percent. Restating the requirement as $B > (K_{IE}/\sigma_y)^2$ could still result in accepting estimates of K_{Ic} which are over 30 percent too high. It might be argued that this titanium alloy shows an unusually large effect and perhaps it does; however, there is no way of knowing in advance of how to adjust the crack length so that a subthickness specimen will give the "right" estimate of K_{Ic}.

The suggestion by Mr. Krafft that K_{Ic} be based on some very small fixed increment of crack extension is not in our opinion a workable solution to the problems introduced by using subthickness specimens. Furthermore, it is completely incompatible with the present method of test which employs a clip gage to sense crack mouth displacement. This displacement is sensitive to *both* crack extension and plastic flow. It might be possible to develop a new method of test based on some fixed increment of crack extension, but this would require a means to sort out plastic flow effects. In any event a "vanishingly small" amount of crack extension is not what we would want because this is essentially impossible to define by measurement. Further, it should be noted that below a certain unknown limit a given increment of crack extension may have little significance to the gross fracture characteristic of the sample.

We show poor correlation of K_{Ic} with tensile properties in Fig. 18. Mr. Krafft suggests that by basing K_{Ic} on a more sensitive measure of crack growth the correlation with n values might be improved. All the K_{Ic} results shown in Fig. 18 represent 1-in.-thick specimens, and at 600 and 750 F temper these are respectively about eight and four times the present thickness requirement. We are not sure what the "K_{Ic} instability" would be in still larger specimens; however, we assume that it might approach the "K_{Ic}" values calculated on the basis of acoustic indications from the 1-in.-thick specimens. Acoustic monitoring was used on all 4340 steel specimens although the results were not given in our paper. We designate the K_I value corresponding to the appearance of definite crack sounds as K_{Ia}. The range of K_{Ia} values obtained at each tempering temperature for the 4340 steel specimens is given in Table 3. These values are lower than the K_{Ic} values shown in Fig. 18, but still show a strong dependence on tempering temperature in the range where n is quite insensitive to tempering temperature. We do not consider these results support an argument for replacing the secant intercept with a more sensitive measure of the onset of crack extension. We agree with Mr. Krafft that the tensile instability strain for 4340 steel tempered above 600 F is difficult to measure. However, we do not believe any clever constructions will get

TABLE 3—*Results from acoustic monitoring*[a] *of 1-in.-thick 4340 steel specimens.*

Tempering Temperature, deg F	Range of K_{Ia}[b] Values, ksi $\sqrt{in.}$
600	38 to 41
750	53 to 59
850	70 to 80
925	75 to 86

[a] Jones, M. H. and Brown, W. F., Jr., "Acoustic Detection of Crack Initiation in Sharply Notched Specimens," *Materials Research & Standards*, Vol. 4, No. 3, 1964, pp. 120–129.

[b] K_{Ia} was calculated on the basis of the load at which the first definite crack sound was detected.

around the fundamental difficulty which is absence of a well-defined maximum in the load-extension curve. It does seem reasonable to search for correlations between flow and fracture properties, and Mr. Krafft has done pioneering work on this problem. However, we question whether refinements in measurement of K_{Ic} and tensile instability strains will result in improved correlations.

In conclusion, we want to emphasize that we are aware of the problems faced by those who wish to measure the fracture toughness of the new high-strength steels. However, in a sense they are quite fortunate because when the thickness of the material required for structural application is insufficient for a K_{Ic} test, plane strain catastrophic failure in service is extremely unlikely. Under these circumstances the engineer needs new methods of test that will yield a thickness dependent measure of fracture toughness. Unfortunately, the development of a mixed mode fracture criterion has turned out to be a much more difficult task than originally anticipated. However, there is no reason to believe that a rating of material based on K_{Ic} values will be the same as a rating based on values derived from a mixed mode fracture test. Therefore, we believe that attempts to estimate K_{Ic} by some empirical method are of dubious value when plane strain failure is not a practical consideration for anticipated structural applications. It is not clear to us that the engineer is then faced with a true dilemma when he wishes to evaluate the fracture characteristics of these new alloys. In other words, we do not believe that K_{Ic} constitutes all of fracture mechanics and that no other satisfactory choices are available.

Where valid K_{Ic} values cannot be measured, we would favor the application of another standardized fracture test for alloy development work. This might be either the center cracked or sharp edge-notch test described in ASTM Designation E 338–68 or the conventional Charpy V-notch impact test.

Messrs. Rolfe and Novak made good use of the standard Charpy V-notch test in their work on the development of the exceptionally tough 5Ni steels.[9] On the other hand, if plane strain failure is a consideration in anticipated service applications, then K_{Ic} should be determined as accurately as possible and any estimates should err on the low side.

[9] Manganello, S. J. et al, "Development of a High Toughness Alloy Plate Steel with a Minimum Yield Strength of 140 ksi," *The Welding Journal.*