DISCUSSION

J. E. CHARD.[1]—When Ray Decker and I were asked to prepare a paper on the role of fracture toughness testing in alloy development, we contacted a number of individuals in various research laboratories and they were most cooperative in replying to a questionnaire which we prepared. However, after putting this information together and drawing some general conclusions, we felt that the resultant summary did not justify presenting a technical paper but that the findings could be better presented as a short contribution to the discussion at the symposium.

In every case history of alloy development for which we obtained details, there was a realization from the beginning that some form of test was required to give an index of fracture toughness performance to supplement the conventional tension test data. However, there appeared to be an almost universal tendency to employ some relatively simple test at least during the earlier stages of development, the more sophisticated fracture toughness tests for determination of K_c value being employed only in the later stages. We feel that this is a very realistic approach from the point of view of keeping the expenditure in man-hours to a minimum.

In the initial stages of evaluating the potentials of a new and promising alloy system, comparatively simple tests provide sufficient discrimination to enable the best compositions to be selected for further work. To carry out K_c determinations at this stage would obviously be wasteful and unnecessary.

In the development of PH 14-8 Mo stainless steel, D. C. Perry of Armco Steel Corp. found the Allison instrumented bend test most useful until, as development progressed, the steel became so tough that this test was no longer definitive, at which stage a precracked sheet Charpy test was employed. Fatigue-cracked center-notched specimens for K_c determination were employed only in the later stages.

In the development of high-strength titanium alloys, E. F. Erbin of Titanium Metals Corporation of America used the NASA edge-notched specimen for screening and investigating variables and the fatigue-cracked center-notched specimen for K_c determinations.

In the development of improved low-alloy steels for heavy forgings, S. Yukawa of General Electric Co., found that the Charpy V-notch fracture appearance transition temperature was a useful index of effect of metallurgical parameters; at a later stage, slow bend tests having a fatigue-cracked or a nitrided notch were employed and, as a final stage, notched disk specimens were used for spin-bursting tests.

G. K. Bhat of Mellon Institute employed the fatigue-cracked center-notched sheet specimen and a round notched tension specimen at all stages in the development of MX-2 (a low-alloy cobalt modified 4135 ultrahigh-strength steel), and Rocoloy 270, (a low-alloy cobalt-silicon modified 4340 ultrahigh-strength steel). A biaxial cup test was

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also employed for sheet. Small 3.5-in. diameter deep drawn (seamless) spin-closed pressure vessels, 18 in. long, were also used for study of crack growth at specified stress levels, crack tolerance, and biaxial stress enhancement. For investigating $\frac{1}{2}$- to $\frac{3}{4}$-in. thick plates, a three-point loaded notched slow bend test was found useful. The part-through-thickness surface-notched tension test was also used. Fatigue-cracked notches were employed throughout.

W. F. Brown, Jr., of NASA has found the machined, edge-notched specimen very satisfactory for studies involving the optimization of composition, and for the investigation of melting, processing, and heat-treatment variables.

At Inco, in the development of improved zerolled stainless sheet alloys by trace-element control, the machined, edge-notched sheet specimen was used throughout and proved a satisfactory means of evaluation. In the development of maraging steels, a round notched tension specimen (0.300 in. in major diameter, 0.212 in. in minor diameter, with a root radius of 0.0006 in.) was found to be a simple and effective test. There were considerable advantages in time-saving and economy in working with round bar stock in the early stages; and the ratio of notched to smooth tensile strength was found to be a useful index in evaluating the effect of compositional and processing variables. At a later stage, sheet was rolled from the more promising alloys and evaluated using the machined, edge-notched tension test. For the lower-strength compositions (below about 200-ksi yield strength) the standard Charpy V-notch impact test appears to be a satisfactory means of evaluation. The work of Puzak and Pellini has established that the Charpy V-notch impact energy is quite reliable in predicting edge drop-weight tear energy and explosive tear energy.

To sum up the situation as we see it, relatively simple and inexpensive test methods are adequate for indicating fracture toughness characteristics during the early stages of alloy development. For the final evaluation of sheet alloys, the fatigue-cracked center-notched sheet specimen is well established. However, some general agreement on the best way of measuring slow crack growth and on the relative merits of compliance gages and electrical resistance methods would be helpful. The situation for evaluation of heavier plate material is far less satisfactory at the present time. Much active development is proceeding on a variety of tests such as those utilizing notched plate tension specimens having a single notch on one edge only; notched slow bend tests; and the part-through-thickness surface-cracked plate specimens. However, there appears as yet to be no universal acceptance of any one of these tests and some question as to the relative merits of acoustical and electrical methods for following the progress of the crack. It is believed that the present symposium should serve a most useful purpose in clarifying this situation.

J. S. PASCOVER, M. HILL, AND S. J. MATAS (authors).—The authors wish to thank Mr. Chard for his interesting discussion to our paper. It is, of course, gratifying to see confirmation of our testing philosophy by so many independent organizations as was indicated in Mr. Chard's questionnaire.