LISTINGS ARE GIVEN BELOW for two programs. The first program is an interactive unloading compliance data acquisition similar to that described in Joyce and Gudas (1979). This program is written in Microsoft Quick BASIC Version 4.5 and uses a National Instruments IEEE 488 interface to communicate with a Keithley Model 199 (now Model 2000) digital multimeter scanner. The device-specific part of the program is limited and can easily be changed to accommodate other hardware. The second program is a data initialization program to calculate a "shifted" *J-R* curve and a J_{Ic} result in accordance with E 1737 and to qualify the results—except for crack straightness requirements. This program accepts the output of the first program as input.

The first program uses conventional inch and pound units, but it could use any set of consistent units, i.e., Newtons and metres. The use of typical metric units (kN and mm) would require changes to be made in this program. There are three outputs of the data acquisition program. First, a *.DAT file contains the raw data measured during the test. This data file is complete, containing all data taken on unloadings and between unloadings, and it can be used to "rerun" the test with modified equations, specimen dimensions, or material parameters, if desired, at a later date.

The data acquisition program can be converted easily to a replay program that will read data from a file rather than the digital multimeter and carry out all calculations exactly as done in the data acquisition program. The second output file is a *.JRA file that contains 15 columns of data with one row corresponding to each unloading taken during the test. Columns are identified as follows:

1. Unloading number.
2. Number of data on the unloading.
3. Crack opening displacement.
4. Crack opening stiffness.
5. Crack opening stiffness calculation correlation.
6. Load line displacement.
7. Load line stiffness.
8. Load line stiffness calculation correlation.
9. Load.
10. Load-crack opening displacement area.
11. Load-load line displacement.
12. Crack length.
13. Crack extension.
14. *J*-integral.
15. Plastic *J* component.

The third output file is a *.JRM file, which has the same format as the above *.JRA file except that it is in units of mm, kN, and kJ/m^2, as desired by the JIC-CALC.BAS program.

The data acquisition program below is intended for use with a screw-type testing machine. It relies on a machine operator to generate the unloadings by following the screen and pen plotter outputs of the program. Occasional, partial unloadings are harder to generate on a standard servohydraulic test machine and generally require additional equipment. An internal D/A card can be used for this purpose, or a commercial product like an MTS Microprofiler can be purchased for this purpose.

When the computer is in control of the unloading process, completely automated testing can be accomplished that eliminates the possible errors that test operators can sometimes produce. On the other hand, unless the test result is well known before the test is begun, more data must generally be taken to assure that good results are achieved. In general, the present author does not recommend fully automated tests, but if tests are fully automated they can, for instance, be run very slowly to study environmental effect, etc., but this is outside of the scope of E 1737.

A1 Unloading Compliance Data Acquisition Program

```
' $INCLUDE: 'QBDECL4.BAS'
' $DYNAMIC
        DECLARE SUB PLOTSETUP2 ()
        DECLARE SUB JCALC ()
        DECLARE SUB CODCALC ()
        DECLARE SUB ROTATE ()
        DECLARE SUB SLOPE ()
        DECLARE SUB CRKLEN ()
        DECLARE SUB SCANSUBK ()

        COMMON SHARED A0!, A2!, A9!, B1!, B2!, B3!, E1!, H!, H2!, I8!, J1!, J2!, J3!, J7!
        COMMON SHARED N%, P2!, U1!, W1!, Q1!, Q2!, Q3!, Q4!, X1!, X2!, Y1!, Y2!, R1!, E5!, G!
        COMMON SHARED XI!, YI!, G!(), O!(), DPLMAX#, A1!, SIGY!, D2#
        COMMON SHARED X$, Y$, T$
        COMMON SHARED D#(), B#(), DVM%, ISET%

        DIM D#(2), XB#(3), G!(10), O!(10)
        DIM B#(1 TO 3, 1 TO 3)

        CONST TRUE = 1
        CONST FALSE = 0
'
'  COMMANDS LIKE IBCLR, IBWRT, IBRD, ETC. ARE CALLS TO THE NATIONAL INSTRUMENTS
'  IEEE488 INTERFACE THAT COMMUNICATES WITH THE KEITHLEY DVM AND SCANNER.
'  THE INTERFACE CARD USED HERE IS THE MODEL PCIIA AND THE SOFTWARE TO DRIVE
'  IT FROM QuickBASIC 4.5 IS AVAILABLE FROM NATIONAL INSTRUMENTS
'
'  IEEE488 INTERFACE AND Keithley Model 2000 (Model 199) initialization here
'
        BDNAME$ = "Dev5"
        CALL IBFIND(BDNAME$, DVM%)          ' SET UP KEITHLEY AS DEVICE 5
        CALL IBCLR(DVM%)                    ' CLEAR THE KEITHLEY
        WRT$ = "F0 R3 Z0 P0 S1 W50 G1 Q20 X" ' INITIALIZATION STRING
        CALL IBWRT(DVM%, WRT$)                     ' SEND INITIALIZATION STRING
'
        KEY 1, "STOP"
        ON KEY(1) GOSUB STOPIT
        KEY(1) ON

        CLS
'
'   SETUP OF TRANSDUCERS
'   PUT COD GAGE SIGNAL INTO CHANNEL 1 OF KEITHLEY Model 2000 Scanner
'   PUT LOAD SIGNAL INTO CHANNEL 2 OF KEITHLEY Model 2000 Scanner
'
'
        OPEN "LPT1" FOR OUTPUT AS #2 'Set Up Printer
'
'       OPEN "COM2:2400,E,7,1,CD5000,CS5000,DS5000" FOR OUTPUT AS #3 ' PLOTTER COM PORT
        OPEN "COM2" FOR OUTPUT AS #3 ' PLOTTER COM PORT
'
PRINT "BACK FROM COM2 CALL"
        PRINT "JPLAY Computer Interactive Data Acquisition Program "
        PRINT "1995 Version Using QuickBASIC 4.5"
        PRINT #2, "JPLAY Computer Interactive Data Acquisition Program "
        PRINT #2, " 1995 Version Using QuickBASIC 4.5"

'  INITIALIZE FLAGS
'
        F1! = 0
'
'   Here we introduce the SETUP file
'
        PRINT
        PRINT
        PRINT "DO YOU WISH TO READ PARAMETERS FROM A SETUP FILE? (YES/NO)"
        INPUT X$
        IF X$ = "STOP" THEN 6250
        IF X$ <> "YES" THEN CLS : GOTO 1200
        PRINT "THE SETUP FILE I.D. IS? ";
        INPUT SET$
        OPEN SET$ FOR INPUT AS #8
'
'      Input here from an existing SETUP file
'
        INPUT #8, G!(1), O!(1), G!(2), O!(2), E1!, U1!, SIGY!, W1!, B1!, B2!
        INPUT #8, X1!, X2!, Y1!, Y2!, XI!, YI!
        INPUT #8, T$
        INPUT #8, X$
```

```
        INPUT #8, Y$
        INPUT #8, B$
        CLOSE #8
        GOTO MENU
'
'      Menu questions asked here
'
1200     GOTO QUESTS


MENU:    K7% = 1
        B3! = B1! - (B1! - B2!) ^ 2 / B1!
'
'      Print the menu
'
        CLS
        PRINT
        PRINT
        PRINT "1 - COD CALIBRATIONS (QUAN/VOLT) = "; G!(1); ", "; O!(1)
        PRINT "2 - LOAD CALIBRATIONS (QUAN/VOLT) = "; G!(2); ", "; O!(2)
        PRINT "3 - MATERIAL PROPERTIES E, NU, SIGY = "; E1!; ","; U1!; ","; SIGY!
        PRINT "4 - SPECIMEN WIDTH W = "; W1!
        PRINT "5 - SPECIMEN GROSS B AND NET Bn B, Bn = "; B1!; " , "; B2!
        PRINT "6 - SPECIMEN IDENTIFICATION = "; B$
        PRINT "7 - X AXIS MIN AND MAX = "; X1!; ", "; X2!
        PRINT "8 - Y AXIS MIN AND MAX = "; Y1!; ", "; Y2!
        PRINT "9 - X AXIS TIC INTERVAL = "; XI!
        PRINT "10 - Y AXIS TIC INTERVAL = "; YI!
        PRINT "11 - PLOT TITLE = "; T$
        PRINT "12 - X AXIS LABEL = "; X$
        PRINT "13 - Y AXIS LABEL = "; Y$
        PRINT
        PRINT
        IF F7% = 1 THEN F7% = 0: RETURN
        Z5% = 1
        PRINT "ENTER HERE THE NUMBER OF THE ITEM THAT YOU WISH TO"
        PRINT "CHANGE OR RETURN IF ALL IS CORRECT ";
        INPUT Z$
        IF Z$ = "STOP" OR Z$ = "999" THEN 6250
        IF Z$ = "" THEN 2350
        Z7% = VAL(Z$)
        IF Z7% = 999 THEN 6250
        ON Z7% GOTO 10, 20, 30, 40, 40, 60, 70, 80, 90, 100, 110, 120, 130
2350     IF F7% = 1 THEN RETURN
        PRINT "DO YOU WISH TO SAVE THESE PARAMETERS IN A SETUP FILE? (YES/NO)"
        INPUT QS$
        IF QS$ = "STOP" THEN 6250
        IF QS$ <> "YES" THEN 200
'
'    Print the SETUP File to Disk here
'
        PRINT "YOUR SETUP FILE I.D. IS: ";
        INPUT SET$
        OPEN SET$ FOR OUTPUT AS #8
        PRINT #8, G!(1); ","; O!(1); ","; G!(2); ","; O!(2); ",;^E'1!; ","; U1!; ","; SIGY!; ",";
        PRINT #8, W1!; ","; B1!; ","; B2!; ",";
        PRINT #8, X1!; ","; X2!; ","; Y1!; ","; Y2!; ","; XI!; ","; YI!
        PRINT #8, T$
        PRINT #8, X$
        PRINT #8, Y$
        PRINT #8, B$
        CLOSE #8
        GOTO 200
QUESTS:
60       PRINT
        PRINT "INPUT FOR THIS SPECIMEN AN I.D. STRING AS A DISK FILE HEADER "
        INPUT B$
        IF Z5% = 1 THEN GOTO MENU
40       PRINT
        PRINT "INPUT HERE THE SPECIMEN GEOMETRY: W, B, AND Bnet "
        INPUT W1!, B1!, B2!
        IF Z5% = 1 THEN GOTO MENU
30       PRINT
        PRINT "INPUT FOR THIS SPECIMEN THE MATERIAL CONSTANTS E, NU, AND YIELD STRESS "
        INPUT E1!, U1!, SIGY!
        IF Z5% = 1 THEN GOTO MENU
        PRINT
        PRINT #2, "  INPUT DATA FOR THIS SPECIMEN IS: "
        PRINT #2, "         W  = "; W1!
        PRINT #2, "         B  = "; B1!
        PRINT #2, "         BN = "; B2!
        PRINT #2, "         E  = "; E1!
        PRINT #2, "       SIGY = "; SIGY!
        PRINT #2, "       I.D. = "; B$
```

```
        PRINT #2,
        PRINT #2,
10      PRINT
        PRINT "INPUT FOR THE CLIP GAGE THE CALIBRATION SLOPE AND INTERCEPT "
        INPUT G!(1), O!(1)
        IF Z5% = 1 THEN GOTO MENU
20      PRINT
        PRINT "INPUT FOR THE LOAD CELL THE CALIBRATION SLOPE AND INTERCEPT "
        INPUT G!(2), O!(2)
        IF Z5% = 1 THEN GOTO MENU
        PRINT #2, "THE CALIBRATION FACTORS ARE"
        PRINT #2,
        PRINT #2, "CHANNEL NO.", "OUTPUT QUAN/VOLT", "INTERCEPT"
        FOR I% = 1 TO 2
                PRINT #2, " "; I%; " "; G(I%); " "; O(I%)
        NEXT I%
        PRINT #2,
        PRINT #2,
70      PRINT
        PRINT "INPUT THE MIN AND MAX X PLOTTER VALUES ";
        INPUT X1!, X2!
        IF Z5% = 1 THEN GOTO MENU
80      PRINT
        PRINT "INPUT THE MIN AND MAX Y PLOTTER VALUES ";
        INPUT Y1!, Y2!
90      PRINT
        PRINT "INPUT THE X TIC INTERVAL ";
        INPUT XI!
        IF Z5% = 1 THEN GOTO MENU
100     PRINT
        PRINT "INPUT THE Y TIC INTERVAL ";
        INPUT YI!
        IF Z5% = 1 THEN GOTO MENU
110     PRINT
        PRINT "INPUT THE PLOT TITLE ";
        INPUT T$
        IF Z5% = 1 THEN GOTO MENU
120     PRINT
        PRINT "INPUT THE X AXIS LABEL ";
        INPUT X$
        IF Z5% = 1 THEN GOTO MENU
130     PRINT
        PRINT "INPUT THE Y AXIS LABEL ";
        INPUT Y$
        GOTO MENU
200     CLS
        PRINT "INSERT A FILE I.D FOR YOUR OUTPUT DATA FILE <CR> "
        INPUT M$
        O$ = M$ + ".JRA"
        N$ = M$ + ".JRM"
        M$ = M$ + ".DAT"
        CLS
        PRINT
        PRINT "PLOTTING PLEASE BE PATIENT "
'
'    Call Plot Setup to Draw Axes and Titles
'
        CALL PLOTSETUP2
'
        PRINT #2,
        PRINT #2, "START OF CRACK LENGTH ESTIMATION ROUTINE HERE "
        PRINT #2,
        PRINT #2,
        PRINT
        PRINT "WE NEED HERE AN INITIAL SPECIMEN CRACK LENGTH ESTIMATE."
        PRINT "LOAD AND UNLOAD HERE AS OFTEN AS YOU LIKE - BUT DO NOT "
        PRINT "EXCEED THE LINEAR PORTION OF THE LOAD DISPLACEMENT CURVE "
        PRINT "FOR THIS SPECIMEN."
        PRINT
        PRINT "INSTALL YOUR SPECIMEN, TURN ON HYDRAULIC PRESSURE "
        PRINT
        PRINT "CHECK THAT THE LOAD PINS ARE CENTERED AND TYPE <ENTER> TO CONTINUE "
        INPUT QUES$
        PRINT
                PRINT "WHEN YOU ARE READY TO BEGIN THIS LOADING TYPE GO/RETURN"
                PRINT
                PRINT "TO STOP PRESS <s> or <S>"
                INPUT H$
        DO
                PRINT
                PRINT "TO START TAKING DATA TYPE <G> "
                PRINT
        DO
                IF INKEY$ = "G" THEN GOTO 380
```

```
        LOOP
380             FOR I% = 1 TO 3 ' INITIALIZE B# MATRIX
                     FOR J% = 1 TO 3
                          B#(I%, J%) = 0!
                      NEXT J%
                NEXT I%
                K% = 1
'  START DATA ACQUISITION LOOP HERE
                DO
                        CALL SCANSUBK
                        IF INKEY$ = "S" OR INKEY$ = "s" THEN GOTO DUN
'
                        D#(1) = D#(1) * G!(1) + O!(1) 'CALIBRATE
                        D#(2) = D#(2) * G!(2) + O!(2)
                        XB#(1) = 1 ' SET UP THE B MATRIX
                        XB#(2) = D#(1)
                        XB#(3) = D#(2)
                        FOR I% = 1 TO 3
                                 FOR J% = I% TO 3
                                  B#(I%, J%) = B#(I%, J%) + XB#(I%) * XB#(J%)
                                 NEXT J%
                        NEXT I%
                        K% = K% + 1
                        D1! = D#(1)
                        P1! = D#(2)
                LOOP
DUN:             CALL SLOPE ' GET SLOPE AS H!
                CALL CRKLEN ' GET CRACK LENGTH
                A1! = A2!
                PRINT "THE CRACK LENGTH FROM COMPLIANCE IS: "; A1!
                PRINT #2, A1!
                PRINT "NUMBER OF DATA POINTS TAKEN = "; K%
                PRINT #2, "NUMBER OF DATA POINTS TAKEN = "; K%
                PRINT #2,
                PRINT
                PRINT "DO YOU WANT TO REPEAT THIS STEP ";
                INPUT H$
                LOOP UNTIL H$ = "NO" OR H$ = "N"
        PRINT
        PRINT "BRING THE LOAD DOWN TO A STARTING VALUE - TYPE <S> TO CONTINUE "
        PRINT
        DO
                IF INKEY$ = "S" THEN 390
        LOOP
390      CLS
        PRINT
300      PRINT "DO YOU WISH TO INPUT AN AVERAGE A0 AND COMPLIANCE?";
                INPUT H$
        IF H$ = "YES" OR H$ = "Y" THEN
                PRINT "INPUT YOUR A0 AND COMPLIANCE HERE"
                INPUT A1!, C1!
                PRINT #2, "INPUT VALUES OF INITIAL A0 AND COMPLIANCE ARE: "; A1!, C1!
                H! = 1 / C1!
        END IF
        S0! = H! ' INITIALIZE FILES
        OPEN M$ FOR OUTPUT AS #8 ' OPEN OUTPUT DATA FILES
        OPEN N$ FOR OUTPUT AS #9
        OPEN O$ FOR OUTPUT AS #7
'
        F1% = 0 ' INITIALIZE VARIABLES
        L% = 1
        P1! = 0
        A2! = A1!
        D1# = 0
        D4# = 0
        K% = 1
        A0! = 0
        I1% = 0
        I8! = 0
        P2! = 0
        D2# = 0
        K1% = 0
        COUNT% = 0
        J7! = 0
        A9! = A1!
        B4! = W1! - A1!
        E5! = 2. + .522 * B4!/W1!
        G5! = 1. + .76 * B4!/W1!
        DMAX# = -.2
        KEY ON
'
        CLS
```

```
                                'START MAIN TEST LOOP HERE

        LOCATE 8, 20: PRINT " TO PAUSE TEST PRESS <p> OR <P> AND PUSH HOLD KEY (F10) '
        PRINT #2,
        PRINT #2, " J TEST BEGUN "
        LOCATE 10, 20: PRINT "WHEN READY TO START TYPE <S> "
        DO
                IF INKEY$ = "S" THEN GOTO 29
        LOOP

29       FOR I% = 1 TO 3
                FOR J% = 1 TO 3
                        B#(I%, J%) = 0
                NEXT J%
        NEXT I%
        CLS
        PRINT
        PRINT "J TEST STARTED"
        PRINT
        DO WHILE F1% <> 999 'BEGIN MAIN TEST LOOP
                IF F1% = 999 THEN 3520
                IF I1% = 0 THEN
                 START! = TIMER ' USE TIMER TO GET 1 SEC. DATA
                        DO
                        STP! = TIMER
                        LOOP WHILE (STP! - START!) < 1
                END IF
'
'        Read data from channels 1 and 2 with slow scan
                CALL SCANSUBK
'
'        CALIBRATE THE RESULTS
'
                FOR I% = 1 TO 2 ' Calibrate
                 D#(I%) = D#(I%) * G!(I%) + O!(I%)
                NEXT I%
2720     IF K% > 1 THEN 2750
                PRINT #3, "PA", Q1! * D#(1) + Q3!, Q2! * D#(2) + Q4!
                GOTO 2760
2750     PRINT #3, "PD"
                PRINT #3, "PA", D#(1) * Q1! + Q3!, Q2! * D#(2) + Q4!
        DH! = D#(1)
        PH! = D#(2)
2760     PRINT #8, K%; " "; I1%; " "; DH!; " "; PH!
                IF (INKEY$ = "P") OR (INKEY$ = "p") THEN
                 INPUT "PRESS RETURN TO RESTART DATA TAKING ", DUMMY$
                END IF
2830     P2! = D#(2)
                D2# = D#(1)
                IF D2# > DMAX# THEN DMAX# = D2# ' UNLOAD LIMIT
                IF K% < 20 THEN 3430 'BEGIN K LOOP
                DTEST# = D2# - DMAX#
                IF DTEST# < -.00005 THEN 2920 'CHECK FOR AN UNLOADING
                IF I1% = 0 THEN 3430
                IF D2# >> D9# THEN 2980
                GOTO 3330
2920     IF I1% = 0 THEN
                P9! = P2! ' START OF AN UNLOADING
                I1% = 1
'
'        Read data from channels 1 and 2 with slow scan
                CALL SCANSUBK
'
'        CALIBRATE THE RESULTS
'
                D9# = D#(1) * G!(1) + O!(1) ' CALIBRATED END OF UNLOADING
                DMAX# = D9#
                DPLMAX# = DMAX# - P9! / H!
        END IF
        GOTO 3330
2980     IF L% < 5 THEN 3290
                K1% = K1% + 1
                CALL SLOPE ' GET STIFFNESS
                H2! = H!
                CALL ROTATE ' ROTATION CORRECTION
                CALL CRKLEN ' CRACK LENGTH
                A3! = A2! - A1!
                A4! = A2!
                PRINT "A = "; A2!; " DELTA A = "; A3!; " K = "; K%; " L = "; L%
                CALL JCALC ' GET J QUANTITIES
                PRINT #2, "A = "; A2!; " DELTA A = "; A3!; "K = "; K%; " L = "; L%
                PRINT "PLASTIC AREA = "; I8!; " Jpl = "; J3!; " J = "; J1!
                PRINT #2, "PLASTIC AREA = "; I8!; " Jpl = "; J3!; " J = "; J1!
```

```
        FOR I% = 1 TO 3
        FOR J% = 1 TO 3
         B#(I%, J%) = 0!
        NEXT J%
        NEXT I%
'
' OUTPUT CALCULATED RESULTS
'
        D9! = D9#
        OUT$ = "### ### ##.#### #########.# #.##### ##.#### #########.# #.##### ######.## #####.# #####.# ###.### ###.###
        #####.## ######.##"
        PRINT #7, USING OUT$; K1%; L%; D9!; H!; R1!; D9!; H!; R1!; P9!; I8!; I8!; A2!; A3!; J1!; J3!
        PRINT #9, USING OUT$; K1%; L%; D9!*25.4; H!/5708.; R1!; D9!*25.4; H!/5708.; R1!; P9!*.00445; I8!*.113; I8!*.113;
        A2!*25.4; A3!*25.4; J1!*.1751; J3!*.1751

        IF A3! > 0 THEN
         PRINT USING "##.####";" DEL A = ", A3!;
         PRINT #2, USING "##.####";" DEL A = ", A3!;
         PRINT
         PRINT #2,
        ELSE
                IF A3! <^0 THEN
                 PRINT "NO CRACK EXTENSION TO THIS POINT."
                 PRINT #2, "NO CRACK EXTENSION TO THIS POINT."
                END IF
        END IF
        PRINT
        PRINT #2,
3290    IF L% < 3 THEN 3330 ' CLEAN UP TO RETURN TO TAKING DATA
        I1% = 0
        DMAX# = 0!
        L% = 0
        GOTO 3430
'
' TAKE DATA INTO SLOPE CALCULATION (I1% = 1)
'
3330    IF P2! > .98 * P9! THEN 3430
        XB#(1) = 1
        XB#(2) = D2#
        XB#(3) = P2!
        L% = L% + 1
        FOR I% = 1 TO 3
        FOR J% = I% TO 3
         B#(I%, J%) = B#(I%, J%) + XB#(I%) * XB#(J%)
        NEXT J%
        NEXT I%
3430    K% = K% + 1 'END OF K LOOP
        IF F1% = 999 THEN 3520
        IF I1% = 1 THEN 3490
'
' CALCULATE PLASTIC AREA IF NOT ON UNLOADING
'
        Dpl# = D2# - P2! / H!
        I8! = I8! + (Dpl# - D4#) * (P2! + P1!) / 2 ' ACCUMULATED PLASTIC AREA
        D4# = Dpl#
3490    P1! = P2!
        D1# = D2#
        IF (INKEY$ = "S") OR (INKEY$ = "s") THEN F1% = 999 ' STOP POINT
    LOOP ' END MAIN LOOP
'
' CLOSE UP FILES BEFORE GETTING OUT
'
3520    PRINT " 2 COLUMNS OF "; K%; " NUMBERS HAVE BEEN PUT INTO "; M$
    PRINT #2, " 2 COLUMNS OF "; K%; " NUMBERS HAVE BEEN PUT INTO "; M$
    PRINT #2, "DEL A J DATA ON "; K1%; " UNLOADINGS HAS BEEN PUT INTO "
    PRINT "DEL A J DATA ON "; K1%; " UNLOADINGS HAS BEEN PUT INTO "
    PRINT #2, "FILES "; O$;" AND ";N$
    PRINT "FILE "; O$;" AND "‧6250     PRINT "THAT'S ALL FOLKS"
    PRINT #2, "THAT'S ALL FOLKS"; Page$
    CLS
6300    PRINT
    PRINT
    PRINT "BRING THE LOAD TO ZERO AND REMOVE THE TEST PIECE "
    PRINT
    PRINT "INPUT <CR> TO CONTINUE ";
    INPUT QUES$
    PRINT
    PRINT "THAT'S ALL FOLKS"

' SHUT DOWN IEEE-488 CARD AND METER
    CALL IBCLR(DVM%)
    CALL IBONL(DVM%, (0))
    CLOSE
    END ' END OF MAIN
```

```
'
' COMPLIANCE COEFFICIENTS FOR LOAD LINE CT SPECIMEN
'
        DATA 1.000196,-4.06319,11.242,-106.043,464.335,-650.677

' STOPIT GOSUB - KEY 1

STOPIT:
        PRINT "DO YOU REALLY WISH TO STOP (Y/N) ";
        INPUT QUES$
        IF QUES$ <> "Y" THEN RETURN
        F1% = 999
        RETURN
'
' * * * SUBROUTINES START HERE * * * * * * *
'
        SUB CRKLEN ' CRACK LENGTH BY HUDAK RELATIONSHIP - C(T) SPECIMEN
        DIM JIM!(9), DA!(6)
        FOR I% = 1 TO 6
         READ JIM!(I%)
        NEXT I%
        C! = SQR(E1! * B3! / H!)
        C! = 1 / (C! + 1)
        DA!(1) = C!
        FOR I% = 2 TO 5
         DA!(I%) = DA!(I% - 1) * DA!(1)
        NEXT I%
        F! = JIM!(1)
        FOR I% = 1 TO 5
         F! = F! + JIM!(I% + 1) * DA!(I%)
        NEXT I%
        A2! = F! * W1!
        RESTORE
        END SUB ' END CRKLEN

        SUB JCALC ' GET J FOR C(T) SPECIMEN
        E4! = A2! / W1!
        F0! = (.886 + 4.64 * E4! - 13.32 * E4!   2 + 14.72 * E4!   3 - 5.6 * E4!   4) * (2 + E4!)
        F0! = F0! / (1 - E4!)   1.5
        K4! = P2! / SQR(B1! * B2! * W1!) * F0!
        J2! = K4! * K4! * (1 - U1! * U1!) / E1! ' ELASTIC J
        J3! = (J7! + E5! / B4! * (I8! - A0!) / B2!) * (1 - G5! / B4! * (A2! - A9!))
        J1! = J2! + J3! ' TOTAL J
        B4! = W1! - A2!
        E5! = 2 + .522 * B4! / W1!
        G5! = 1 + .76 * B4! / W1!
        A9! = A2!
        J7! = J3!
        A0! = I8!
        END SUB ' END JCALC

        SUB PLOTSETUP2 'PLOTTER SUBROUTINE FOR A HPGL PLOTTER
'
' THIS PROGRAM WILL DRIVE AN HPGL OR EMULATOR PLOTTER CONNECTED TO A COM
' PORT. THIS SETUP PROGRAM DRAWS AXES AND LABELS - DATA IS PLOTTED IN
' THE MAIN SECTION OF THE PROGRAM
'
        PRINT #3, "SP1;"
'        PRINT #3, "PU;"
        A3 = X1
        P2 = 2000
        P4 = 1500
        P3 = 14500
        P5 = 9200
        P6 = ((P3 - P2) / (X2 - X1)) * XI
        Z$ = CHR$(3)
        PRINT #3, "TL", 74.5
        PRINT #3, "PA", P2, P4
        PRINT #3, "SR .7, 1.5"
        FOR I = P2 TO P3 STEP P6
        PRINT #3, "PA", I, P4, "PD;"
        PRINT #3, "PA", I, P5, ";"
        PRINT #3, "PA", I, P4, "PU;"
        A3 = A3 * 1000
        A3 = CINT(A3)
        A3 = A3 / 1000
        A$ = STR$(A3)
        L7 = LEN(A$) + 1
        PRINT #3, "SR,.7,1.5"
        PRINT #3, "CP", -L7 / 2, -1
        PRINT #3, "LB"; A$; Z$
        A3 = A3 + XI
        NEXT I
        A3 = Y1
```

```
        P7 = ((P5 - P4) / (Y2 - Y1)) * YI
        Z$ = CHR$(3)
        PRINT #3, "TL", 83
        PRINT #3, "PA", P2, P4
        A$ = STR$(A3)
        FOR I = P4 TO P5 STEP P7
        PRINT #3, "PA", P2, I, "PD;"
        PRINT #3, "PA", P3, I, ";"
        PRINT #3, "PA", P2, I, "PU;"
        A$ = STR$(A3)
        L7 = LEN(A$)
        PRINT #3, "SR,.7,1.5"
        PRINT #3, "CP", -L7, 0
        PRINT #3, "LB"; A$; Z$
        A3 = A3 + YI
        NEXT I
        L6 = LEN(T$) / 2
        PRINT #3, "SP1"
        PRINT #3, "PA", (P2 + P3) / 2 - 120 * L6, P5 + 300
        PRINT #3, "SR 1.5,3"
        PRINT #3, "CP -L6,0.3"
        PRINT #3, "PD"
        PRINT #3, "LB"; T$; Z$
        PRINT #3, "SR"
        PRINT #3, "PU"
        L6 = LEN(X$) / 2
        PRINT #3, "SP1"
        PRINT #3, "SR 1,2"
        PRINT #3, "PA", (P2 + P3) / 2 - 80 * L6, 800
        PRINT #3, "CP -L6,-3"
        PRINT #3, "PD"
        PRINT #3, "LB"; X$; Z$
        PRINT #3, "PU"
        PRINT #3, "PA", P2, (P4 + P5) / 2
        L6 = LEN(Y$) / 2
        PRINT #3, "DI 0,1"
        PRINT #3, "SR 1,2"
        PRINT #3, "PA", 1200, (P4 + P5) / 2 - 80 * L6
        PRINT #3, "CP -L6,3"
        PRINT #3, "PD"
        PRINT #3, "LB"; Y$; Z$
        PRINT #3, "PU"
        PRINT #3, "DI 1,0"
        PRINT #3, "SR"
        Q1! = (P3 - P2) / (X2 - X1)
        Q2! = (P5 - P4) / (Y2 - Y1)
        Q3! = P2 - Q1! * X1
        Q4! = P4 - Q2! * Y1
        END SUB

        SUB ROTATE ' ROTATION CORRECTION
        R3! = .5 * (W1! + A2!)
        H3! = .5 * W1!
        DSPACE! = .1 ' 1/2 OF THE INITIAL CLIP GAGE OPENING
        T2! = (D2# / 2 + DSPACE!) / SQR(DSPACE!   2 + R3!   2)
        T2! = ATN(T2! / SQR(1 - T2!   2)) - ATN(DSPACE! / R3!)
        H! = (H3! / R3! * SIN(T2!) - COS(T2!)) * (DSPACE! / R3! * SIN(T2!) - COS(T2!)) * H2!
        END SUB ' END ROTATE
'
'*************************************************************************
SUB SLOPE ' SLOPE CALCULATION
'
        Qs1# = (B#(1, 1) * B#(2, 2) - B#(1, 2)   2) / (B#(1, 1) * (B#(1, 1) - 1))
        Qs2# = (B#(1, 1) * B#(3, 3) - B#(1, 3)   2) / (B#(1, 1) * (B#(1, 1) - 1))
        H! = (B#(1, 1) * B#(2, 3) - B#(1, 2) * B#(1, 3)) / (B#(1, 1) * B#(2, 2) - B#(1, 2)   2)
        IF H! < 0 THEN
         PRINT "POOR DATA SLOPE <0"
         H! = 333333.3
         R1! = 0
        ELSE
         R1! = H! * SQR(Qs1# / Qs2#)
         PRINT "SLOPE = "; H!; " COMPLIANCE = "; 1 / H!; "CORR. = "; R1!
         PRINT #2, "SLOPE = "; H!; " COMPLIANCE = "; 1 / H!; "CORR. = "; R1!
         N7% = B#(1, 1)
        END IF
END SUB ' END SLOPE
'
SUB SCANSUBK
'
        WRT$ = "I2 M08 N22 T5 X"         'TRIGGER STRING - 2 CHANNELS
        CALL IBWRT(DVM%, WRT$)                  ' SEND TRIGGER SIGNAL
        MASK% = &H5800
        CALL IBWAIT(DVM%, MASK%)         ' WAIT FOR SRQ, ERROR, OR TIMEOUT
        CALL IBRSP(DVM%, SPR%)                  ' DO A SERIAL POLL
```

```
'
        RD1$ = SPACE$(16)
        FOR ILOOP% = 1 TO 2
        CALL IBRD(DVM%, RD1$)
        D#(ILOOP%) = VAL(RD1$)              ' READ TWO CHANNELS OF DATA
        NEXT ILOOP%
'
END SUB                         ' END OF SCANSUBK
```

A2 Initialization Fit Program

```
' $DYNAMIC
        DECLARE SUB JQCALC ()
        DECLARE SUB SLOPE ()
        DECLARE SUB JFIT ()
        DECLARE SUB GAUSS ()

        COMMON SHARED B1!, B2!, E1!, Elp!, U1!, W1!, SPAN!, SFLOW!
        COMMON SHARED JQ!, AQ#, MQ#, BQ#, RQ#, JZ!(), AZ!(), XY!()
        COMMON SHARED JM!(), AM!(), X!(), Y!(), AN!(), XN!(), AX!(), JX!()
        COMMON SHARED NUMDAT%, NFIT%, SLOPEM!, AZMEAS!, AFMEAS!, RFIT!
        COMMON SHARED FF!(), RDAT%, DELAMIN!, DELALIM!, JLIMIT!, DELASEC!
        COMMON SHARED ASHFT!

        DIM XB#(3), JZ!(100), AZ!(100), JM!(100), AM!(100), XY!(17)
        DIM AX!(100), JX!(100), X!(100), Y!(100), AC!(100), FF!(100)
        DIM XN!(3), PM!(100)
        DIM AN!(1 TO 3, 1 TO 4)
'
'        INITIALIZATION FIT VERSION DECEMBER 1994 - WITH BLUNTING LINE SLOPE
'
'        PROGRAM TO EVALUATE A SHIFTED J-R CURVE AND A Jic ACCORDING TO ASTM E1737
'
        CONST TRUE = 1
        CONST FALSE = 0
        DIAM! = 2!
        W1! = 2!
        Page$ = CHR$(12)
        CLS
'
'        THIS VERSION IS FOR THE C(T), DC(T), and SE(B) SPECIMENS ONLY ******************
'
        OPEN "LPT1" FOR OUTPUT AS #2 'PRINTER
        PRINT "INITIALIZED J-R CURVE AND Jic EVALUATION "
        PRINT "****** METRIC VERSION - WATCH THE UNITS ******* "
        PRINT #2, "INITIALIZED J-R CURVE AND Jic EVALUATION"
        PRINT #2,
        PRINT #2, "JOYCE/ASTM MANUAL VERSION OF DECEMBER 1994"
        PRINT #2,
        PRINT
'
'   Here we introduce the SETUP file
'
        PRINT
        PRINT "DO YOU WISH TO READ PARAMETERS FROM A REPLAY SETUP FILE? (YES/NO)"
        INPUT QUES$
        IF QUES$ <> "YES" THEN CLS : GOTO 5
        PRINT "THE SETUP FILE I.D. IS? ";
        INPUT SET$
        OPEN SET$ FOR INPUT AS #6
'
'     Input here from an existing SETUP file
'
        INPUT #6, E1!, U1!, SIGY!, SIGUTS!, W1!, B1!, B2!, SPAN!
        INPUT #6, AZMEAS!, AFMEAS!, SLOPEM!
        INPUT #6, PQUES$
        INPUT #6, B$
        INPUT #6, SPEC$
        CLOSE #6
        SFLOW! = (SIGY! + SIGUTS!) / 2
        JLIMIT! = SFLOW! * (W1! - AZMEAS!) / 15!
        GOTO MENU
'
'      Menu questions asked here
'
5        GOTO QUESTS
'
MENU:
       Elp! = E1! / (1 - U1! * U1!)
'
'      Print the menu
```

```
        CLS
        PRINT
        PRINT "1 - MATERIAL PROPERTIES E (GPa), NU = "; E1!; ","; U1!
        PRINT "2 - MATERIAL PROPERTIES SIGY, SIGUTS(MPa) = "; SIGY!; ", "; SIGUTS!
        IF SPEC$ = "CT" OR SPEC$ = "DCT" THEN PRINT "3 - SPECIMEN WIDTH W (mm)
  = "; W1!
        IF SPEC$ = "SEB" THEN PRINT "3 - SPECIMEN WIDTH W and SPAN (mm) = "; W1!; ", "; SPAN!
        PRINT "4 - SPECIMEN GROSS B AND NET Bn B, Bn (mm) = "; B1!; " , "; B2!
        PRINT "5 - SPECIMEN IDENTIFICATION = "; B$
        PRINT "6 - SPECIMEN MEASURED AZ AND AF (mm) = "; AZMEAS!; ", "; AFMEAS!
        PRINT "7 - SPECIMEN TYPE (CT, DCT, OR SEB)               = "; SPEC$
        PRINT "8 - CONSTRUCTION LINE SLOPE (M)          = "; SLOPEM!
        PRINT
        PRINT
        IF F7% = 1 THEN F7% = 0: RETURN
        Z5% = 1
        PRINT "ENTER HERE THE NUMBER OF THE ITEM THAT YOU WISH TO"
        PRINT "CHANGE OR RETURN IF ALL IS CORRECT ";
        INPUT Z$
        IF Z$ = "" THEN 10
        Z7% = VAL(Z$)
        ON Z7% GOTO 30, 31, 40, 40, 60, 34, 44, 50
10 IF F7% = 1 THEN RETURN
        PRINT "DO YOU WISH TO SAVE THESE PARAMETERS IN A SETUP FILE? (YES / NO)"
        INPUT QS$
        IF QS$ <> "YES" THEN 200
'
' Print the SETUP File to Disk here
'
        PRINT "YOUR SETUP FILE I.D. IS: ";
        INPUT SET$
        OPEN SET$ FOR OUTPUT AS #6
        PRINT #6, E1!; ","; U1!; ","; SIGY!; ","; SIGUTS!; ",";
        PRINT #6, W1!; ","; B1!; ","; B2!; ","; SPAN!
        PRINT #6, AZMEAS!; ","; AFMEAS!; ","; SLOPEM!
        PRINT #6, PQUES$
        PRINT #6, B$
        PRINT #6, SPEC$
        CLOSE #6
        GOTO 200

QUESTS:
60 PRINT
        PRINT "INPUT FOR THIS SPECIMEN AN I.D. STRING AS A DISK FILE HEADER "
        INPUT B$
        IF Z5% = 1 THEN GOTO MENU
40 PRINT
        PRINT "INPUT HERE THE SPECIMEN GEOMETRY: W, B, AND Bnet (mm) "
        INPUT W1!, B1!, B2!
        IF Z5% = 1 THEN GOTO MENU
30 PRINT
        PRINT "INPUT FOR THIS SPECIMEN THE MATERIAL CONSTANTS E (GPa), NU "
        INPUT E1!, U1!
        IF Z5% = 1 GOTO MENU
31 PRINT
        PRINT "INPUT THE MATERIAL YIELD STRESS AND UTS (MPa) ";
        INPUT SIGY!, SIGUTS!
        SFLOW! = (SIGY! + SIGUTS!) / 2!
        IF Z5% = 1 THEN GOTO MENU
34 PRINT "INPUT MEASURED INITIAL AND FINAL CRACK LENGTHS (mm) "
        INPUT AZMEAS!, AFMEAS!
        IF Z5% = 1 THEN GOTO MENU
44 PRINT "INPUT THE SPECIMEN TYPE (CT, DCT, OR SEB) ";
        INPUT SPEC$
        SPAN! = 203.2
        IF SPEC$ = "SEB" THEN INPUT "INPUT BEND SPAN (mm) ", SPAN!
        IF Z5% = 1 THEN GOTO MENU
50 PRINT "INPUT THE DESIRED CONSTRUCTION LINE SLOPE (USUALLY 2.0) ";
        INPUT SLOPEM!
        GOTO MENU
200 PRINT
        PRINT #2, " INPUT DATA FOR THIS SPECIMEN IS: "
        PRINT #2,
        IF SPEC$ = "CT" OR SPEC$ = "DCT" THEN PRINT #2, " W (mm) = "; W1!
        IF SPEC$ = "SEB" THEN PRINT #2, " W (mm) = "; W1!; " SPAN (mm) = "; SPAN!
        PRINT #2, " B (mm) = "; B1!; " Bn (mm) = "; B2!
        PRINT #2, " AZMEAS (MPa) = "; AZMEAS!; " AFMEAS (MPa) = "; AFMEAS!
        PRINT #2, " E (GPa) = "; E1!; " U1 = "; U1!
        PRINT #2, " SIGY (MPa) = "; SIGY!; " SIGUTS (MPa) = "; SIGUTS!
        PRINT #2, " I.D. = "; B$; " SPECIMEN TYPE = "; SPEC$
        PRINT #2, " M = "; SLOPEM!
        PRINT #2,
```

```
        INPUT "INPUT THE DATA FILE I.D. FOR THIS SPECIMEN (WITHOUT THE *.JRM): ", DT$
        DTN$ = DT$ + ".JRM"                ' READS METRIC SPECIMEN RESULTS FILE
'
' Calculate PmLim in kN
'
        IF SPEC$ = "CT" OR SPEC$ = "DCT" THEN PMLIM! = .4 * B1! * (W1! - AZMEAS!)   2 * SFLOW! / (2! * W1! + AZMEAS!) /
        IF SPEC$ = "SEB" THEN PMLIM! = .5 * B1! * (W1! - AZMEAS!)   2 * SFLOW! / SPAN! / 1000!
        JLIMIT! = SFLOW! * (W1! - AZMEAS!) / 15!
'
' Input data must be in kN and mm, J in kJ/m 2
'
        I% = 1 'DATA COUNTER
        OPEN DTN$ FOR INPUT AS #1
        AMIN! = 500!
        DO UNTIL EOF(1)
                FOR K% = 1 TO 15
                        INPUT #1, XY!(K%)
                NEXT K%
' FIND Amin
                AM!(I%) = XY!(12)
                IF AM!(I%) < AMIN! THEN AMIN! = AM!(I%)
                JM!(I%) = XY!(14)
                PM!(I%) = XY!(7)
        I% = I% + 1
        LOOP
        NUMDAT% = I% - 1
        CLOSE #1
'
' REDUCE THE DATA SET FOR THE INITIALIZATION FIT
'
        J% = 0
        FOR I% = 1 TO NUMDAT%
                IF PM!(I%) > PMLIM! AND AM!(I%) < AMIN! + 2.5 THEN
                        J% = J% + 1
                        JX!(J%) = JM!(I%)
                        AX!(J%) = AM!(I%)
                END IF
        NEXT I%
        PRINT #2,
        PRINT
'
' CALL THE INITIALIZATION FIT SUBROUTINE
'
        RDAT% = J%
        CALL JFIT
        ASHFT! = XN!(1)
        PRINT #2,
        PRINT #2, USING "& ###.## & ### "; " ASHFT! = "; ASHFT!; " USING "; RDAT%; " POINTS"
        PRINT USING "& ###.## & ### "; " ASHFT! = "; ASHFT!; " USING "; RDAT%; " POINTS"
'
' NOW GET JQ!, DELAMIN, AND DELALIM
'
        DELAMIN! = -100
        DELALIM! = 500
'
        CALL JQCALC
'
'
' THIS ENDS THE INITIALIZATION FIT
'
' CHECK FOR DATA EXCLUDED BY DELAMIN, DELALIM, OR JLIMIT RESTRICTIONS
'
        J% = 1
        FOR I% = 1 TO NUMDAT%
                IF AM!(I%) - ASHFT! < DELAMIN! THEN GOTO 300
                IF AM!(I%) - ASHFT! > DELALIM! THEN GOTO 300
                IF JM!(I%) > JLIMIT! THEN GOTO 300
                IF AM!(I%) - ASHFT! < JM!(I%) / (SLOPEM! * SFLOW!) + .15 THEN GOTO 300
                IF AM!(I%) - ASHFT! > JM!(I%) / (SLOPEM! * SFLOW!) + 1.5 THEN GOTO 300
                J% = J% + 1
300 NEXT I%
         IF J% = NFIT% + 1 THEN 320
                PRINT #2, "DATA FOUND THAT MUST BE EXCLUDED - RE-SOLVE FOR JQ"
'
                CALL JQCALC
320 :
'
' CHECK ASHFT! AGAINST AMEAS! - INITIAL CRACK LENGTH ACCURACY
'
        FI% = 0
        IF (ABS(ASHFT! - AZMEAS!)) > .01 * W1! THEN
                PRINT
                PRINT #2,
                PRINT "DATA SET FAILS CRACK LENGTH ACCURACY REQUIREMENT "
```

```
                PRINT #2, "DATA SET FAILS CRACK LENGTH ACCURACY REQUIREMENT "
                PRINT #2, USING "& ###.## & ###.##"; " AZMEAS = "; AZMEAS!; " ASHFT! = "; ASHFT!
                PRINT USING "& ###.## & ###.##"; " AZMEAS! = "; AZMEAS!; " ASHFT! = "; ASHFT!
        FI% = 1
        END IF
'
' CHECK QUALITY OF INITIALIZATION FIT
'
        IF RFIT! < .96 OR RDAT% < 8 THEN
                PRINT "INITIALIZATION FIT FAILED STANDARD REQUIREMENTS "
                PRINT USING "& #.### & ##."; " CORRELATION = "; RFIT!; " RDAT = "; RDAT%
                PRINT #2, "INITIALIZATION FIT FAILED STANDARD REQUIREMENTS "
                PRINT #2, USING "& #.### & ##."; " CORRELATION = "; RFIT!; " RDAT = "; RDAT%
                FI% = 1
                END IF
'
' CHECK E1737 Jic QUALIFICATION REQUIREMENTS
'
        FJ% = 0
        IF NFIT% > 4 THEN GOTO COUNTOK
                PRINT "DATA COUNT IN INCLUSION REGION IS NOT ADEQUATE, N = "; NFIT%
                PRINT #2, "DATA COUNT IN INCLUSION REGION IS NOT ADEQUATE, N = "; NFIT%
                FJ% = 1
COUNTOK:
' CHECK JQ FIT POWER COEFFICIENT
'
        IF MQ# < 1! THEN GOTO POWEROK
                PRINT USING "& #.###"; "C2 COEFFICIENT IS UNACCEPTABLE - C2 = "; MQ#
                PRINT #2, USING "& #.###"; "C2 COEFFICIENT IS UNACCEPTABLE - C2 = "; MQ#
                FJ% = 1
POWEROK:
' CHECK SLOPE REQUIREMENT
        JTEST! = MQ# * BQ# * AQ#   (MQ# - 1)
        IF JTEST! < SFLOW! THEN GOTO SLOPEOK
                PRINT "DATA FIT FAILS SLOPE REQUIREMENT "
                PRINT #2, "DATA FIT FAILS SLOPE REQUIREMENT "
                FJ% = 1
SLOPEOK:
' CHECK DATA CLUSTERING REQUIREMENT
                FOR I% = 1 TO NFIT%
                        IF (AZ!(I%) - AQ#) > (DELALIM! - AQ#) / 3 THEN GOTO CLUSTOK
                NEXT I%
                PRINT AZ!(1) - AQ#, (DELALIM! - AQ#) / 3
                PRINT "DATA FAILS - NO DATA IN REGION B "
                PRINT #2, "DATA FAILS - NO DATA IN REGION B "
                FJ% = 1
CLUSTOK:
'
' CHECK EARLY DATA COUNT REQUIREMENT
        J% = 0
        FOR I% = 1 TO NUMDAT%
                IF JM!(I%) < .4 * JQ! THEN GOTO 700
                IF AM(I%) - ASHFT! > AQ# THEN GOTO 700
                J% = J% + 1
700 NEXT I%
        IF J% > 3 THEN GOTO ECOUNTOK
        FJ% = 1
        PRINT "DATA SET FAILS EARLY DATA COUNT REQUIREMENT - COUNT = "; J%
        PRINT #2, "DATA SET FAILS EARLY DATA COUNT REQUIREMENT - COUNT = "; J%
ECOUNTOK:
'
' CHECK SPECIMEN SIZE REQUIREMENTS
        REQSIZE! = 25 * JQ! / SFLOW!
        IF (W1! - AZMEAS!) > REQSIZE! AND B1! > REQSIZE! THEN GOTO SIZEOK
        PRINT USING "& ###.##"; "SPECIMEN FAILS SIZE REQUIREMENTS, 25*JQ/SFLOW = "; REQSIZE!
        PRINT #2, USING "& ###.##"; "SPECIMEN FAILS SIZE REQUIREMENTS, 25*JQ/SFLOW = "; REQSIZE!
        FJ% = 1
SIZEOK:
'
        IF FJ% > 0 THEN GOTO JRTEST
                PRINT
                PRINT #2,
                PRINT "DATA SET PASSES ALL Jic QUALIFICATION REQUIREMENTS "
                PRINT #2, "DATA SET PASSES ALL Jic QUALIFICATION REQUIREMENTS "
                PRINT
                PRINT #2,
                PRINT #2, USING "& ####.#"; " Jic = "; JQ!; " kJ/m 2"
                PRINT USING "&####.#"; " Jic = "; JQ!; " kJ/m 2"
'
JRTEST:
'
' CHECK J-R CURVE QUALIFICATION REQUIREMENTS
'
        FR% = 0
```

```
' CHECK NUMBER OF J-R CURVE DATA
'
        J% = 0
        FOR I% = 1 TO NUMDAT%
                IF AM!(I%) - ASHFT! < AMIN! - ASHFT! THEN GOTO 800
                IF AM!(I%) - ASHFT! > DELALIM! THEN GOTO 800
                IF JM!(I%) > JLIMIT! THEN GOTO 800
                J% = J% + 1
                AC!(J%) = AM!(I%) - ASHFT!
800 NEXT I%
        IF J% > 10 THEN GOTO NUMDATOK
        PRINT "J-R CURVE DATA COUNT INADEQUATE - COUNT = "; J%
        PRINT #2, "J-R CURVE DATA COUNT INADEQUATE - COUNT = "; J%
        FR% = 1
NUMDATOK:
' CHECK SECANT LINE REQUIREMENT
'
        DELASEC! = ((3 * BQ#) / (4 * SFLOW!))   (1 / (1 - MQ#))
        JB% = 0
        JA% = 0
        FOR I% = 1 TO J%
                IF AC!(I%) < DELASEC! THEN
                        JB% = JB% + 1
                        ELSE JA% = JA% + 1
                END IF
        NEXT I%
        IF JA% < 2 OR JB% < 8 THEN
                PRINT "J-R CURVE DATA FAILS SECANT SPACING REQUIREMENT "
                PRINT #2, "J-R CURVE DATA FAILS SECANT SPACING REQUIREMENT "
                FR% = 1
        END IF
SECANTOK:

        PRINT
        PRINT #2,
        PRINT USING "& ###.##"; "THE FINAL ESTIMATED CRACK LENGTH IS: "; AM!(NUMDAT%); " mm"
        PRINT #2, USING "& ###.##"; "THE FINAL ESTIMATED CRACK LENGTH IS: "; AM!(NUMDAT%); " mm"
        PRINT
        PRINT #2,
        PRINT USING "& ##.##"; "THE ESTIMATED FINAL CRACK EXTENSION IS: "; AM!(NUMDAT%) - ASHFT!; " mm"
        PRINT USING "& ##.##"; "THE MEASURED FINAL CRACK EXTENSION IS: "; AFMEAS! - AZMEAS!; " mm"
        PRINT
        PRINT #2, USING "& ##.##"; "THE ESTIMATED FINAL CRACK EXTENSION IS: "; AM!(NUMDAT%) - ASHFT!; " mm"
        PRINT #2, USING "& ##.##"; "THE MEASURED FINAL CRACK EXTENSION IS: "; AFMEAS! - AZMEAS!; " mm"

        PRINT #2,
        FDIFF! = ((AFMEAS! - AZMEAS!) - (AM!(NUMDAT%) - ASHFT!)) / (AFMEAS! - AZMEAS!) * 100
        PRINT USING "& ##.#"; "THE PERCENT ERROR IN THE FINAL CRACK EXTENSION PREDICTION IS: "; FDIFF!; " %"
        PRINT #2, USING "& ##.#"; "THE PERCENT ERROR IN THE FINAL CRACK EXTENSION PREDICTION IS: "; FDIFF!; " %"
        IF ABS(FDIFF!) > 15 THEN
                PRINT "THIS FINAL CRACK EXTENSION ACCURACY IS NOT SATISFACTORY!! "
                PRINT #2, "THIS FINAL CRACK EXTENSION ACCURACY IS NOT SATISFACTORY!! "
                FR% = 1
        END IF
'
' TEST J-R CURVE FLAG
        IF FR% = 0 AND FI% = 0 THEN GOTO JROK
                PRINT "THE J-R CURVE HAS NOT PASSED ALL REQUIREMENTS "
'
JROK:
        PRINT
        PRINT #2,
        PRINT "THIS J-R CURVE PASSES ALL J-R CURVE QUALIFICATION REQUIREMENTS"
        PRINT "FOR THE REGION ENCLOSED BY JLIMIT AND DELALIM."
        PRINT #2, "THIS J-R CURVE PASSES ALL J-R CURVE QUALIFICATION REQUIREMENT "
        PRINT #2, " FOR THE REGION ENCLOSED BY:"
        PRINT #2, USING "& ####.# "; " JLIMIT = "; JLIMIT!; " kJ/m 2"
        PRINT #2, USING "& ##.###"; " DELALIM = "; DELALIM!; " mm"
'
'
PRINTOUT:
'
' PRINT OUT A MODIFIED *.JRI FILE WITH CHANGES ONLY IN THE DEL A COLUMN
        ET$ = DT$ + ".JRI"
        OPEN ET$ FOR OUTPUT AS #1
        OPEN DTN$ FOR INPUT AS #7
        I% = 1
        DO UNTIL EOF(7)
        FOR K% = 1 TO 15
                INPUT #7, XY!(K%)
        NEXT K%
' PRINT OUT IN *.JRA FORMAT (15 COLUMNS)
        PRINT #1, XY!(1); " "; XY!(2); " "; XY!(3); " "; XY!(4); " "; XY!(5); " "; XY!(6); " "; XY!(7); " "; XY!(8);
XY!(10); " "; XY!(11); " "; XY!(12); " "; XY!(12) - ASHFT!; " "; XY!(14); " "; XY!(15)
```

```
        I% = I% + 1
        LOOP
'
' SHUT THINGS DOWN
'
        CLOSE #1, #7
        PRINT #2, Page$
        END

'
SUB GAUSS
' INPUT DATA IS IN AN!(3,4) - OUTPUT IS XN!(3)
' SUBROUTINE IN BASIC TO DO A GAUSS ELIMINATION SOLUTION
' SET NOW FOR 3X3 MATRIX
' OUTPUT IS A VECTOR XN
N% = 3
M% = N% + 1
L% = N% - 1
' START REDUCTION TO TRIANGULAR FORM
FOR K% = 1 TO L%
         K1% = K% + 1
        JJ% = K%
        BG! = ABS(AN!(K%, K%))
' REM START OF SEARCH FOR LARGEST PIVOT ELEMENT
FOR I% = K1% TO N%
        AB! = ABS(AN!(I%, K%))
        IF BG! > AB! THEN BG! = AB!: JJ% = I%
NEXT I%
IF JJ% = K% GOTO REDUCE
' INTERCHANGES ROWS TO GET MAX PIVOT ELEMENT
FOR J% = K% TO M%
        TE! = AN!(JJ%, J%)
        AN!(JJ%, J%) = AN!(K%, J%)
        AN!(K%, J%) = TE!
NEXT J%
' DETERMINES REDUCED ELEMENTS OF TRIANGULAR SET
REDUCE:
FOR I% = K1% TO N%
         Q! = AN!(I%, K%) / AN!(K%, K%)
        FOR J% = K1% TO M%
                AN!(I%, J%) = AN!(I%, J%) - Q! * AN!(K%, J%)
        NEXT J%
NEXT I%
FOR I% = K1% TO N%
         AN!(I%, K%) = 0!
NEXT I%
NEXT K%
' BACK SUBSTITUTION FOR THE SOLUTIONS
XN!(N%) = AN!(N%, M%) / AN!(N%, N%)
FOR NN% = 1 TO L%
        SU! = 0!
        I% = N% - NN%
        I1% = I% + 1
        FOR J% = I1% TO N%
                SU! = SU! + AN!(I%, J%) * XN!(J%)
        NEXT J%
        XN!(I%) = (AN!(I%, M%) - SU!) / AN!(I%, I%)
        NEXT NN%
END SUB

SUB JFIT
'
' SUBROUTINE TO SET UP FUNCTION FOR A0 EVALUATION
' USES EQUATION aA Q \ + J/(2*SIGF) +B J ^ 2 + C J ^ 3, USES EQUATION a Q a00 + J/(2*SIGF) + B J ^ 2 + C J ^ 3
'
' INPUT IS RDAT% PAIRS OF a AND J IN VECTOR ARRAYS AM! AND JM!
'
FOR I% = 1 TO 3
         FOR J% = 1 TO 4
                 AN!(I%, J%) = 0!
        NEXT J%
NEXT I%
         JSUM! = 0
' DO SUMMATIONS FOR LEAST SQUARES
AN!(1, 1) = RDAT%
FOR I% = 1 TO RDAT%
                JSUM! = JSUM! + JX!(I%)
        AN!(1, 2) = AN!(1, 2) + JX!(I%)   2
        AN!(2, 2) = AN!(2, 2) + JX!(I%)   4
        AN!(1, 3) = AN!(1, 3) + JX!(I%)   3
        AN!(2, 3) = AN!(2, 3) + JX!(I%)   5
        AN!(3, 3) = AN!(3, 3) + JX!(I%)   6
        AN!(1, 4) = AN!(1, 4) + AX!(I%)
        AN!(2, 4) = AN!(2, 4) + AX!(I%) * JX!(I%)   2
```

```
        AN!(3, 4) = AN!(3, 4) + AX!(I%) * JX!(I%)   3
NEXT I%
         AN!(1, 4) = AN!(1, 4) - JSUM! / (2 * SFLOW!)
         AN!(2, 4) = AN!(2, 4) - AN!(1, 3) / (2 * SFLOW!)
         AN!(3, 4) = AN!(3, 4) - AN!(2, 2) / (2 * SFLOW!)
AN!(2, 1) = AN!(1, 2)
AN!(3, 1) = AN!(1, 3)
AN!(3, 2) = AN!(2, 3)
' NOW SOLVE THESE EQUATIONS USING GAUSS ELIMINATION FOR XN!
CALL GAUSS
'
PRINT "COEFFICIENTS OF INITIALIZATION ARRAY ARE: "
PRINT XN!(1), XN!(2), XN!(3)
PRINT #2, "COEFFICIENTS OF INITIALIZATION ARRAY ARE: "
PRINT #2, XN!(1), XN!(2), XN!(3)
' CHECK THE FIT
FOR I% = 1 TO RDAT%
        FF!(I%) = XN!(1) + JX!(I%) / (2 * SFLOW!) + XN!(2) * JX!(I%)   2 + XN!(3) * JX!(I%)
NEXT I%
' CALCULATION OF THE CORRELATION OF THE FIT
YM! = 0!
FOR I% = 1 TO RDAT%
         YM! = YM! + AX!(I%) / RDAT%
NEXT I%
SY2! = 0!
SYX2! = 0!
FOR I% = 1 TO RDAT%
         SY2! = SY2! + (AX!(I%) - YM!)   2 / (RDAT% - 1)
        SYX2! = SYX2! + (AX!(I%) - FF!(I%))   2 / (RDAT% - 2)
NEXT I%
RFIT! = SQR(1! - SYX2! / SY2!)
PRINT USING "& #.###"; "CORRELATION OF FIT = "; RFIT!
PRINT #2, USING "& #.###"; "CORRELATION OF FIT = "; RFIT!
END SUB

'
' ************************ SUBROUTINES ******************************
'
        SUB JQCALC
'
' SUBROUTINE TO GET JQ ESSENTIALLY USING E813-1987 VERSION
'
' PARAMETER DEFINITION
'
' FIT EQUATION J = C1 (DEL A ) ^ C2
'
        IF NUMDAT% < 4 THEN
        PRINT "TOO FEW DATA FOUND - FIX AND RE-RUN"
        STOP
        END IF
' OBTAIN THE REDUCED DATA SET FOR Jic CALCULATION
        J% = 1
        FOR I% = 1 TO NUMDAT%
                IF AM!(I%) - ASHFT! < DELAMIN! THEN GOTO 8801
                IF AM!(I%) - ASHFT! > DELALIM! THEN GOTO 8801
                IF JM!(I%) > JLIMIT! THEN GOTO 8801
                IF AM!(I%) - ASHFT! < JM!(I%) / (SLOPEM! * SFLOW!) + .15 THEN GOTO 8801
                IF AM!(I%) - ASHFT! > JM!(I%) / (SLOPEM! * SFLOW!) + 1.5 THEN GOTO 8801
                JZ!(J%) = JM!(I%)
                AZ!(J%) = AM!(I%) - ASHFT! 'NOW DELTA A'S
                J% = J% + 1
8801 :
        NEXT I%
        NFIT% = J% - 1
        IF NFIT% < 2 THEN
                PRINT "TO LITTLE DATA TO CALCULATE A SLOPE - JQCALC"
                STOP
        END IF
        FOR I% = 1 TO NFIT%
                X!(I%) = LOG(AZ!(I%))
                Y!(I%) = LOG(JZ!(I%))
        NEXT I%
        CALL SLOPE
        BQ# = EXP(BQ#)
'
' CALCULATE THE JIc VALUE USING A SIMPLE ITERATIVE TECHNIQUE
        AL9# = .5 ' INITIAL GUESSES
        JL9! = 200
ITERATE1:
        FL8! = -BQ# * AL9#   MQ# + SLOPEM! * SFLOW! * (AL9# - .2)
        FL9! = -BQ# * MQ# * AL9#   (MQ# - 1) + SLOPEM! * SFLOW!
        AQ# = AL9# - FL8! / FL9!
        JQ! = BQ# * AQ#   MQ#
        IF ABS((JQ! - JL9!) / JQ!) < .01 THEN GOTO GOTJIC
```

```
        AL9# = AQ#
        JL9! = JQ!
        GOTO ITERATE1
GOTJIC:
' LOOP TO GET DEL A MIN (NEWTON RAPHSON)
'

LOOPDELA:
        DELAX! = AQ#
ENTER1:
        FLN! = -BQ# * DELAX!   MQ# + (SFLOW! * SLOPEM!) * (DELAX! - .15)
        FLD! = -MQ# * BQ# * DELAX!   (MQ# - 1) + (SFLOW! * SLOPEM!)
        DELAMIN! = DELAX! - FLN! / FLD!
        IF (DELAMIN! - DELAX!) / DELAMIN! < .01 THEN GOTO LOOP1END
        DELAX! = DELAMIN!
        GOTO ENTER1
LOOP1END:
' LOOP TO GET DEL A LIM (NEWTON RAPHSON)
        DELMXX! = 2!
ENTER2:
        FLN! = -BQ# * DELMXX!   MQ# + (SFLOW! * SLOPEM!) * (DELMXX! - 1.5)
        FLD! = -MQ# * BQ# * DELMXX!   (MQ# - 1) + (SFLOW! * SLOPEM!)
        DELALIM! = DELMXX! - FLN! / FLD!
        IF (DELALIM! - DELMXX!) / DELALIM! < .01 THEN GOTO LOOP2END
        DELMXX! = DELALIM!
        GOTO ENTER2
LOOP2END:
'
' OUTPUT RESULTS
        PRINT NFIT%, " DATA SETS WERE FOUND IN THE EXCLUSION REGION "
        PRINT #2,
        PRINT
        PRINT " THE FIT COEFFICIENTS ARE: "
        PRINT #2, " THE FIT COEFFICIENTS ARE: "
        PRINT
        PRINT #2,
        PRINT USING "& #.###"; " POWER COEFFICIENT (C2) = "; MQ#
        PRINT #2, USING "& #.###"; " POWER COEFFICIENT (C2) = "; MQ#
        PRINT USING "& ####.#"; " AMPLITUDE COEFFICIENT (C1) = "; BQ#
        PRINT #2, USING "& ####.#"; " AMPLITUDE COEFFICIENT (C1) = "; BQ#
        PRINT USING "& #.####"; " FIT COEFFICIENT ( R) = "; RQ#
        PRINT #2, USING "& #.####"; " FIT COEFFICIENT ( R) = "; RQ#
        PRINT
        PRINT #2,
        PRINT USING "& ####.#"; " JQ = "; JQ!; " kJ/m 2"
        PRINT #2, USING "& ####.#"; " JQ = "; JQ!; " kJ/m 2"
        PRINT USING "& #.###"; " CRACK EXTENSION AT JQ = "; AQ#; " mm"
        PRINT #2, USING "& #.###"; " CRACK EXTENSION AT JQ = "; AQ#; " mm"
        PRINT USING "& ###.##"; " DEL A MIN = "; DELAMIN!; " mm"
        PRINT USING "& ###.##"; " DEL A LIM = "; DELALIM!; " mm"
        PRINT #2, USING "& ###.##"; " DEL A MIN = "; DELAMIN!; " mm"
        PRINT #2, USING "& ###.##"; " DEL A LIM = "; DELALIM!; " mm"
        PRINT
        PRINT #2,
        F9% = 0
END SUB

'
        SUB SLOPE
' SUBROUTINE TO CALCULATE LEAST SQUARES BEST FIT STRAIGHT LINE
'
        DIM B1#(3, 3), X1#(3)
        X1#(1) = 1
        FOR I% = 1 TO 3
                FOR J% = 1 TO 3
                        B1#(I%, J%) = 0
                NEXT J%
        NEXT I%
        FOR K% = 1 TO NFIT%
                X1#(2) = X!(K%)
                X1#(3) = Y!(K%)
                FOR I% = 1 TO 3
                FOR J% = I% TO 3
                 B1#(I%, J%) = B1#(I%, J%) + X1#(I%) * X1#(J%)
                NEXT J%
                NEXT I%
        NEXT K%
        Q1# = (B1#(1, 1) * B1#(2, 2) - B1#(1, 2)   2) / (B1#(1, 1) * (B1#(1, 1) - 1))
        Q2# = (B1#(1, 1) * B1#(3, 3) - B1#(1, 3)   2) / (B1#(1, 1) * (B1#(1, 1) - 1))
        MQ# = (B1#(1, 1) * B1#(2, 3) - B1#(1, 2) * B1#(1, 3)) / (B1#(1, 1) * B1#(2, 2) - B1#(1, 2)   2)
        BQ# = (B1#(1, 3) - MQ# * B1#(1, 2)) / B1#(1, 1)
        RQ# = MQ# * SQR(Q1# / Q2#)
END SUB
```

Standard Test Method for *J*-Integral Characterization of Fracture Toughness[1]

This standard is issued under the fixed designation E 1737; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the determination of fracture toughness as characterized by the *J*-integral. Three toughness properties are identified which vary with the amount of crack extension present at test termination: (*a*) instability without significant prior crack extension (J_c); (*b*) onset of stable crack extension (J_{Ic}); (*c*) stable crack growth resistance curve (*J-R*).[2] A fourth quantity (J_u) not currently interpretable as a toughness property may be measured at fracture instability following stable crack extension. The method applies specifically to geometries that contain notches and flaws that are sharpened with fatigue cracks. The recommended specimens are generally bend-type specimens that contain deep initial cracks. The loading rate is slow and environmentally assisted cracking is assumed to be negligible.

1.1.1 The recommended specimens are the pin-loaded compact (C(T)), the single, edge bend (SE(B)), and the pin-loaded disk-shaped compact (DC(T)) specimen. All specimens have in-plane dimensions of constant proportionality for all sizes.

1.1.2 Specimen dimensions are functions of the ratio of *J*-integral to the material effective yield strength, thus the specimen design details must be based on known or estimates mechanical properties.

1.1.3 The objective of this test method is to set forth a method and to specify limitations for testing prescribed bend-type specimens that will result in *J*-integral fracture toughness values of materials that will be geometry insensitive.

1.1.4 The single specimen elastic compliance method is detailed herein, but other techniques for measuring crack length are permissible if they equal or exceed the accuracy requirements of this test method. For example, a dc electric potential method is described in Annex A5.

1.1.5 A multiple specimen technique for J_{Ic} measurement requiring five or more identically prepared specimens tested to different crack extensions and displacements is presented in Annex A4.

1.2 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 4 Practices for Load Verification of Testing Machines[3]

E 399 Test Method for Plane-Strain Fracture Toughness of Metallic Materials[3]

E 616 Terminology Relating to Fracture Testing[3]

3. Terminology

3.1 Terminology E 616 is applicable to this test method.

3.2 *Definitions:*

3.2.1 *effective thickness* $B_e[L]$—for compliance-based crack extension measurements $B_e = B - (B - B_N)^2/B$.

3.2.2 *effective yield strength,* $\sigma_Y[FL^{-2}]$—an assumed value of uniaxial yield strength that represents the influence of plastic yielding upon fracture test parameters.

NOTE 1—σ is calculated as the average of the 0.2 % offset yield strength σ_{YS}, and the ultimate tensile strength σ_{TS}, for example:

$$\sigma_Y = \frac{\sigma_{YS} + \sigma_{TS}}{2}$$

NOTE 2—In estimating σ_Y, the influence of testing conditions, such as loading rate and temperature, should be considered.

3.2.3 *estimated crack extension,* $\Delta a[L]$—an increase in estimated crack size ($\Delta a = a - a_{oq}$).

3.2.4 *estimated crack size* $a[L]$—the distance from a reference plane to the observed crack front developed from measurements of elastic compliance or other methods. The reference plane depends on the specimen form, and it is normally taken to be either the boundary, or a plane containing either the load line or the centerline of a specimen or plate. The reference plane is defined prior to specimen deformation.

3.2.5 J_c, $J[FL^{-1}]$—a value of J (the crack extension resistance under conditions of crack-tip plane strain) at fracture instability prior to the onset of significant stable crack extension.

3.2.6 J_{Ic}, $J[FL^{-1}]$—a value of J (the crack extension resistance under conditions of crack tip plane strain) near the onset of stable crack extension as specified in this test method.

3.2.7 J_u, $J[FL^{-1}]$—a value of J measured at fracture instability after the onset of significant stable crack extension. It may be size dependent and a function of test specimen geometry.

3.2.8 *J-integral,* $J[FL^{-1}]$—a mathematical expression, a

[1] This test method is under the jurisdiction of ASTM Committee E-8 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.08 on Elastic-Plastic Fracture Mechanics Technology.

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[2] Information on *R*-curve round-robin data is available from ASTM as a research report. Request RR: E24-1011.

[3] *Annual Book of ASTM Standards,* Vol 03.01.

line or surface integral over a path that encloses the crack front from one crack surface to the other, used to characterize the local stress-strain field around the crack front. See Terminology E 616 for further discussion.

3.2.9 *J-R curve*—a plot of resistance to stable crack extension, Δa or Δa_p.

DISCUSSION—In this test method, the *J-R* curve is a plot of the far-field *J*-integral versus physical crack extension (Δa_p) or estimated crack extension (Δa). It is recognized that the far-field value of *J* may not represent the stress-strain field local to a growing crack.

3.2.10 *net thickness, $B_N[L]$*—distance between the roots of the side grooves in side-grooved specimens.

3.2.11 *original crack size, $a_o[L]$*—the physical crack size at the start of testing.

NOTE 3—In this test method, a_{oq} is the initial crack length estimated by elastic compliance.

3.2.12 *original uncracked ligament, $b_o[L]$*—distance from the original crack front to the back edge of the specimen, that is:

$$b_o = W - a_o$$

3.2.13 *physical crack extension, $\Delta a_p[L]$*—an increase in physical crack size ($\Delta a_p = a_p - a_o$).

3.2.14 *physical crack size, $a_p[L]$*—the distance from a reference plane to the observed crack front. This distance may represent an average of several measurements along the crack front. The reference plane depends on the specimen form, and it is normally taken to be either the boundary, or a plane containing either the load line or the centerline of a specimen or plate. The reference plane is defined prior to specimen deformation.

3.2.15 *precrack load, $P_M[F]$*—the allowable precrack load.

3.2.16 *remaining ligament, $b[L]$*—distance from the physical crack front to the back edge of the specimen, that is:

$$b = W - a_p$$

3.2.17 *specimen span, $S[L]$*—distance between specimen supports for the SE(B) specimen.

3.2.18 *specimen thickness, $B[L]$*—the side to side dimension of the specimen being tested.

3.2.19 *specimen width, $W[L]$*—a physical dimension on a test specimen measured from a reference position such as the front edge in a bend specimen or the load line in the compact specimen to the back edge of the specimen.

4. Summary of Test Method

4.1 This test method involves three-point bend loading or pin loading of fatigue precracked specimens and determination of J as a function of crack growth. Load versus load-line displacement is recorded. The J-integral is determined and plotted against estimated or physical crack growth, Δa or Δa_p, within specified limits of crack growth. The resulting data reflect the material's resistance to crack growth.

4.2 For J_c determination, J is evaluated from a load-displacement record which is terminated by fracture instability prior to significant stable crack extension. The value of J_c determined by this test method represents a measure of fracture toughness at instability without significant stable crack extension that is independent of in-plane dimensions. However, there may be a dependence of toughness on thickness which is equivalent to length of crack front.

4.3 For J_{Ic} determination, the J versus crack growth behavior is approximated with a best fit power law relationship. A construction line is drawn, approximating crack tip stretch effects. The construction line is calculated from material flow properties or determined experimentally. Draw an offset line parallel to the construction line but offset by 0.2 mm. The intersection of this line and the power law fit defines J_{Ic}, provided the requirements of this test method are satisfied.

4.4 For *J-R* curve determination, this test method describes a single specimen technique. The *J-R* curve consists of a plot of J versus crack extension, in the region of J-controlled growth, and is size independent provided that the requirements of this test method are satisfied. For the procedure described in this test method, crack length and crack extension are determined from elastic compliance measurements. These measurements are taken on a series of unloading/reloading segments spaced along the load-versus-displacement record. Other methods such as dc electric potential can be used to estimate crack length and crack extension.

4.5 An alternative, multi-specimen technique can be used to obtain J_{Ic}. This technique requires five or more identically prepared specimens tested to different crack opening displacements. This technique uses optical measurements of crack extension on the fracture surfaces after the test.

4.6 Supplemental information about the background of this test method and the rationale for many of the technical requirements of this test method are contained in Ref **(1)**.[4]

5. Significance and Use

5.1 The J-integral values measured by this test method characterize the toughness of ductile materials that lack sufficient size and thickness to be tested for K_{Ic} in accordance with the requirements of Test Method E 399.

5.1.1 The J-integral values can be used as indexes of material toughness for alloy design, materials processing, materials selection and specification, and quality assurance.

5.1.2 The J-integral value for most structural metals is independent of testing speed in the quasi-static regime. The value becomes a function of testing speed in the dynamic regime. Cyclic loads or environmental attack under sustained stress, or both, can cause additional contributions to crack extension. Therefore, the application of J-integral values in design of service components should be made with full cognizance of service conditions.

5.1.3 J-integral values can be used to evaluate materials in terms that can be significant to design, and for evaluation of materials with flaws.

5.1.4 This test method is applicable for a wide range of ductile engineering materials. However, there are high ductility, high toughness materials for which this test method is not applicable. The prescribed procedure may result in unsatisfactory results when applied to materials with extremely high tearing resistance because crack growth due to physical tearing of the material may be virtually indistin-

[4] The boldface numbers in parentheses refer to the references at the end of this test method.

guishable from extensive crack tip blunting.

5.2 The *J-R* curve characterizes, within the limits set forth in this test method, the resistance of metallic materials to slow stable crack growth after initiation from a pre-existing fatigue crack.

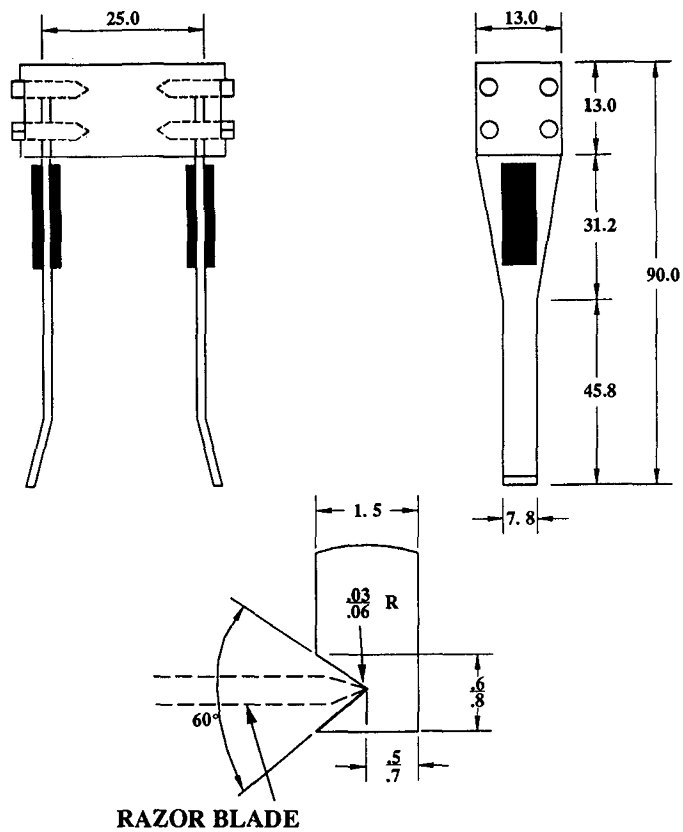
5.2.1 The *J-R* curve can be used to assess the significance of cracks in structural details in the presence of ductile tearing, with awareness of the difference that may exist between laboratory test and field conditions.

5.3 J_{Ic}, as determined by this test method, characterizes the toughness of materials near the onset of stable crack extension from a preexisting fatigue crack.

5.3.1 J_{Ic} and J_c values may be converted to their equivalents in terms of stress-intensity factor, K_I (**2**), if dominant elastic conditions for the application can be demonstrated. The K_I values from J_{Ic} correspond to the material toughness near the onset of stable crack extension in a dominant linear elastic stress field that contains a preexisting crack. The K_I values from J_c correspond to the material toughness near the onset of unstable crack extension in a dominant linear elastic stress field containing a preexisting crack. The J_{Ic} and J_c values according to this test method cannot be used to obtain K_{Ic} values according to Test Method E 399.

5.4 The value of J_c determined by this test method represents a measure of fracture toughness at instability without significant stable crack extension that is independent of in-plane dimensions. However, there may be a dependence of toughness on thickness, equivalent to a dependence on crack front length.

5.4.1 Values of J_c, may exhibit considerable variability and statistical techniques may be required in their interpretation and application.



NOTE—All dimensions are in millimetres.

FIG. 1 Clip Gage Design for a 8.0-mm (0.3-in.) and More Working Range

6. Apparatus

6.1 Measurements of applied load and load-line displacement are needed to determine the total energy absorbed by the specimen. Load versus load-line displacement may be recorded digitally for processing by computer or autographically with an *x-y* plotter.

6.2 Test fixtures for each specimen type are described in the applicable annex.

6.3 *Displacement Gage:*

6.3.1 Displacement measurements are needed for two purposes: to determine *J* from the measured area under the load-displacement record, and, for the elastic compliance method, to estimate crack extension, Δa, from elastic compliance calculations.

6.3.2 In compact specimens, displacement measurements on the load line are recommended. As a guide, select a displacement gage that has a working range of not more than twice the displacement expected during the test. When the expected displacement is less than 3.75 mm (0.15 in.), the gage recommended in Test Method E 399 may be used. When a greater working range is needed, an enlarged gage such as the one shown in Fig. 1 is recommended. Accuracy shall be within ±1 % of the full working range. In calibration the maximum deviation of the individual data points from a fit to the data shall be less than ±1 %, or ±0.2 % of the working range of the gage when using the elastic compliance method. Knife edges are recommended for friction-free seating of the gage. Maintain parallel alignment of the knife edges within ±1°.

6.3.3 The single edge bend specimen may require two displacement gages. A load-line displacement measurement is required for *J* computation. A crack mouth opening displacement gage may be used to estimate crack size using the elastic compliance technique. The gage shall meet the requirements of 6.3.2. Accuracy of the load-line displacement gage shall be within ±1 % of the full working range. In calibration, the maximum deviation of the individual data points from a fit to the data shall be less than ±1 %, or ±0.2 % of the working range of the gage when using the gage for compliance measurements. Direct methods for load-line displacement measurement are described in Refs (**3—6**). If a remote transducer is used for load-line displacement measurement, care shall be taken to exclude the elastic displacement of the load train measurement and elastic and inelastic deformations at the load points (**7**).

6.3.4 For the elastic compliance method, the suggested minimum digital signal resolution for displacement should be one part in 32 000 of the transducer signal range (*V*), and signal stability should be four parts in 32 000 of the transducer signal range (*V*) measured over a 10-min period. Signal noise should be less than two parts in 32 000 of the transducer signal range (*V*).

6.3.5 If an autographic method with expanded scales is used for elastic compliance measurements, displacement signal sensitivity is required which produces approximately

50 mm of pen travel on the displacement scale on each unload/reload sequence. Pen stability is required at the above sensitivity at ±3 mm for a 10-min period.

6.3.6 Gages other than those recommended in 6.3.2 and 6.3.3 are permissible if the required accuracy and precision can be met or exceeded.

6.4 *Load Transducers:*

6.4.1 Testing shall be performed in a testing machine conforming to the requirements of Test Method E 4. Applied load may be measured by any load transducer capable of being recorded continuously. Accuracy of load measurements shall be within ±1 % of the working range. In calibration, the maximum deviation of individual data points from a fit to the data shall be less than ±1 %, or ±0.2 % of the calibrated range of the load transducer when using elastic compliance.

6.4.2 For the elastic compliance method, the suggested minimum digital signal resolution on load should be one part in 4000 of the transducer signal range (V) and the signal stability should be four parts in 4000 of the transducer signal range (V) measured over a 10-min period. Recommended maximum signal noise should be less than two parts in 4000 of the transducer signal range (V).

6.4.3 If an autographic method with expanded scales is used for elastic compliance measurements, the load signal sensitivity which produces at least 100 mm of pen travel on each unloading/reloading sequence is recommended. The required load signal stability at this sensitivity is ±3 mm for a 10-min period.

6.5 Calibration accuracy of displacement transducers shall be verified with due consideration for the temperature and environment of the test. Load calibrations shall be documented periodically in accordance with Practices E 4.

7. Specimen Configurations, Dimensions, and Preparation

7.1 *Specimen Size*—For this test method, the specimen thickness, B, the remaining ligament, b, and the extent of crack growth shall satisfy the requirements of 9.8 and 9.9. In addition, the data shall be qualified by the criteria of 9.7. The initial selection of specimen dimensions can only be based on J values estimated from previous experience. Generally, the greater the ratio of toughness to strength the larger the specimen dimensions required to satisfy the size criteria of this test method.

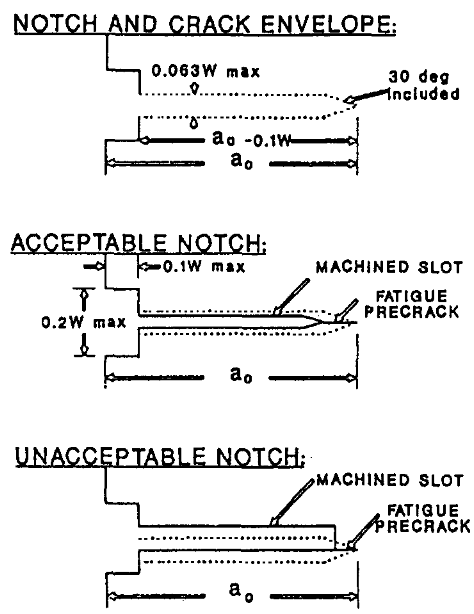
7.2 *Specimen Configurations:*

7.2.1 The standard specimen configurations are shown in annexes: Annex A1, Single Edge Bend Specimen *SE(B)*; Annex A2, Compact Specimen *C(T)*; Annex A3, Disk Shaped Compact Specimen *DC(T)*.

7.2.2 *Standard Specimens*—The initial crack length a_o (starter notch plus fatigue precrack) shall be in the range: $0.45\ W \leq a_o \leq 0.70\ W$. Experience indicates that a value of 0.6 times W is usually optimum for satisfying specimen dimension requirements and test method sensitivity needs. The ratio of width, W, to thickness, B, (W/B) is nominally equal to two.

7.3 The starter notch shall lie within an envelope extending a distance (a_o-0.1W) behind the crack-tip, as shown in Fig. 2. Recommendations for a wide notch and a narrow notch are made in Fig. 2. A wide notch can increase the apparent specimen compliance by 7 % **(8)** causing an error in crack length estimation. To obtain an accurate estimate of crack length from compliance, a narrow notch, such as that produced by electric discharge machining, is suggested. The crack length estimation accuracy of the elastic compliance method can be further improved by precracking beyond the minimum specified in 7.5.2.

7.4 *Side Grooves*—During *J-R* testing, specimens may need side grooves to ensure a straight crack front as specified in 9.7. The total thickness reduction may not exceed 0.25 B. The requirements of 9.7 will usually be met by machining side grooves with an included angle of 45° and a root radius 0.5 ± 0.25 mm (0.02 ± 0.01 in.). Side grooving after precracking will result in nearly straight crack fronts by



SUGGESTED NOTCH AND CRACK CONFIGURATIONS

	WIDE NOTCH	NARROW NOTCH
maximum notch thickness	0.063W	0.010W
maximum notch angle	60 deg	as machined
minimum precrack length	0.05 a_o	0.05 a_o

NOTE—Crack-starter notch must be centered between top and bottom specimen edges within 0.005 W.

FIG. 2 Envelope of Crack-Starter Notches and Suggested Configurations

removing areas of crack front curvature near the specimen surfaces.

7.5 *Fatigue Precracking:*

7.5.1 All specimens shall be precracked in fatigue at load values based upon the load $P_M[F]$. For *SE(B)* specimens use the following:

$$P_M = \frac{0.5\ \sigma_Y Bb^2}{S}$$

where S = specimen span.

For *C(T)* and *DC(T)* specimens use the following:

$$P_M = \frac{0.4\ \sigma_Y Bb^2}{(2W + a)}$$

The choice of σ_Y shall take into consideration differences in properties at the precracking temperature and the test temperature, in order to minimize yielding the specimen during precracking.

7.5.2 The length of the fatigue pre-crack extension from the machined notch shall not be less than 5 % of the total crack size, a_o, and not less than 1.3 mm (0.05 in.). For the final 50 % of fatigue pre-crack extension or 1.3 mm (0.05 in.), whichever is less, the maximum load shall be no larger than P_M, or a load such that the ratio of the maximum stress intensity applied during fatigue pre-cracking to the elastic modulus (K_{max}/E) is equal to or less than 1.6×10^{-4} m$^{1/2}$ (0.001 in.$^{1/2}$). The accuracy of these maximum load values shall be known within ±5 %. The stress intensity, K_{max}, may be calculated using the formulas for $K_{(i)}$ in the applicable Annex A1 of this test method.

7.5.3 The fatigue pre-cracking is to be done with the material in the same heat-treated condition as that in which it will be fracture tested. No intermediate treatments between fatigue pre-cracking and testing are allowed.

7.5.4 To facilitate fatigue pre-cracking at low stress ratios, the machined notch root radius can be on the order of 0.076 mm (0.003 in.). A chevron form of machined notch, as described in Test Method E 399, may be helpful when control of crack shape is a problem. Alternatively, a reverse loading of a straight-through notch specimen, to a load not to exceed P_M, may result in an acceptable fatigue crack front.

8. Procedure

8.1 *Testing Procedure*—The objective of the procedure described herein is to develop a *J-R* curve, consisting of *J*-integral values at evenly spaced crack extensions, Δa, as shown in Fig. 3. The J_{Ic} can be determined from this resistance curve. If fracture instability occurs prior to the onset of significant ductile crack extension, a J_c can be determined. This procedure describes the single specimen, elastic compliance method. Crosshead or actuator displacement control or displacement gage control shall be used. A multiple specimen test procedure for determination of J_{Ic} is described in Annex A4.

8.1.1 Details of specimen preparation and testing are presented in Annexes A1, A2, or A3, as applicable.

8.2 *Test System Preparation:*

8.2.1 It is recommended that the performance of the load and displacement measuring systems be verified every time the system is brought to test temperature or before beginning a continuous series of tests.

8.2.2 Specimens shall be loaded at a rate such that the time taken to reach the load, P_M, (see 7.6.1) lies between 0.1 and 10.0 min. The rate during unloadings may be as slow as needed to accurately estimate crack length, and shall not exceed the allowable loading rate.

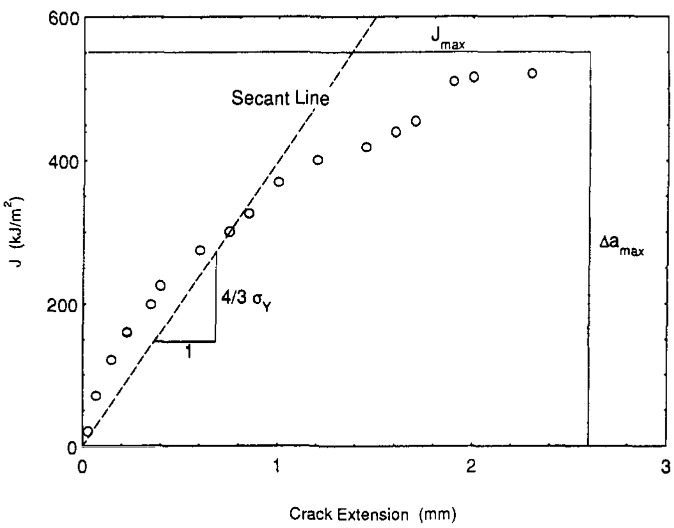


FIG. 3 Typical *J-R* Curve Data

8.2.3 The temperature of the specimen shall be stable and uniform to within ±3°C during the test. The temperature is measured on the specimen surface within a distance of *W*/4 from the crack tip. The determination of an appropriate soaking time shall be the responsibility of those conducting the test.

8.3 *Initial Crack Length Estimation*—For the elastic compliance method, an initial crack length estimate (a_{oq}) shall be determined from compliance measurements repeated at least three times. No individual value shall differ from the mean by more than ±0.002 *W*. The initial crack length determinations from elastic compliance should be carried out in the load range from 0.5 to 1.0 times the maximum final fatigue pre-cracking load.

8.4 *Collection of J-Crack Extension Data:*

8.4.1 The maximum range of unload/reload for crack extension measurement should not exceed the smaller of 0.5 P_M (7.5.1) or 50 % of the current load.

8.4.2 Calculation of Interim *J* and crack extension shall follow the procedures in Annexes A1, A2, or A3, as applicable.

8.4.3 The *J*-integral shall be determined from load, load-line displacement curves. At a given total deflection, the area under the load-displacement curve shall be evaluated with an accuracy of at least ±2 %. Accurate evaluation of *J* from these relationships requires small and uniform crack growth increments consistent with the elastic compliance spacing requirements of 8.4.4 or 8.4.5.

8.4.4 For *J-R* curve determination, crack extension shall be measured in a manner such that the data points are evenly spaced over the prescribed test region. Two J-Δa data points are required in the space between the ordinate of the plot and the secant line defined by $J = (4/3)\sigma_Y \Delta a$ (Fig. 3). Eight J-Δa data points are required between the secant line and the box defined by the Δa_{max} limit of 9.8.2.2 and J_{max} limit of 9.8.2.1.

8.4.5 If *J-R* curve data from 8.4.4 are to be used to determine J_{Ic}, a minimum of three J versus crack extension data pairs are required between $0.4J_Q$ and J_Q with J_Q as defined by 9.5, and five data pairs are required within the exclusion lines (see 9.9.2 and 9.9.3). To accomplish this, ten or more evenly spaced points over the first 1.5 mm (0.06 in.) of crack extension are recommended.

NOTE 4—Data placement limits previously noted are minimum requirements. Additional data points are recommended to more thoroughly define the J-R curve and J_{Ic}.

8.4.6 For many steels, load relaxation may occur prior to conducting compliance measurements causing a time dependent nonlinearity in the unloading slope. This effect may be minimized by holding the specimen at a constant displacement for a time to be determined by the user prior to initiating the unloading.

8.5 *Test Termination:*

8.5.1 If the test is terminated by fracture instability proceed to 8.5.5.

8.5.2 For fully ductile test, after completing the final unloading, the load shall be returned to zero without additional crosshead displacement beyond the then current maximum displacement.

8.5.3 Mark the crack according to one of the following methods. For steels and titanium alloys, heat tinting at about 300°C (570°F) for 30 min works well. For other materials, fatigue cycling can be used. The use of liquid penetrants is not recommended. For both recommended methods, the beginning of stable crack extension is marked by the end of the flat fatigue precracked area. The end of crack extension is marked by the end of heat tint or the beginning of the second flat fatigue area.

8.5.4 The specimen shall be broken to expose the crack, with care taken to minimize additional deformation. It may be helpful to cool ferritic steel specimens enough to ensure brittle behavior. Other materials may also benefit since cooling will reduce deformation.

8.5.5 Along the front of the fatigue crack and the front of the region of slow-stable crack extension, measure the crack size at nine equally spaced points centered on the specimen centerline and extending to 0.005 W from the root of the side groove or surfaces of plane-sided specimens. Calculate the original physical crack size, a_o, and the average physical crack extension, Δa_p, as follows: average the two near-surface measurements, combine the result with the remaining seven crack length measurements, and determine the average. The measuring instrument shall have an accuracy of 0.025 mm (0.001 in.).

8.6 *Alternative Methods:*

8.6.1 Alternative methods of determining crack extension, for example, the electric potential approach of Annex A5, are allowed. These methods shall be used to predict the crack lengths and the results shall meet the qualification requirements given in 9.7.

8.6.2 If displacement measurements are made in a plane other than that containing the load line, the ability to estimate load-line displacement shall be demonstrated using the test material under similar test temperatures and conditions. Estimated load-line displacement values shall be accurate to within ±1 % of the absolute values.

9. Calculation and Interpretation of Results

9.1 *Corrections and Adjustments to Data:*

9.1.1 A correction is applied to the estimated a_i data values to obtain an improved a_{oq}. This correction is intended to obtain the best value of a_{oq} based on the initial set of crack length estimates, a_i, data.

9.1.2 A modified construction line slope, M, can be calculated from a fit to the initial J_i and a_i data, and used for the calculation of J_{Ic}.

9.2 *Adjustment of* a_{oq}:

9.2.1 The value of J_Q is very dependent on the a_{oq} used to calculate the Δa_i quantities. The value obtained for a_{oq} in 8.3.1 might not be the correct value and the following adjustment procedure is required.

9.2.2 Identify all J_i and a_i pairs for which the load at the start of the unloading exceeded P_M and with $a_i \leq a_{min} + 2.5$ mm, where a_{min} is the smallest estimated crack length that meets the P_M requirement. Use this data to calculate a revised a_{oq} from the following equation:

$$a = a_{oq} + \frac{J}{2\sigma_Y} + BJ^2 + CJ^3$$

The coefficients of this equation shall be found using a least squares fit procedure. Example BASIC code to accomplish this fit is presented in Appendix X1.

9.2.3 If the number of data points of 9.2.2 is less than eight or the correlation of this fit is <0.96, the data set is not adequate to evaluate any toughness measures according to this test method.

9.3 If the optically measured crack length, a_o, differs from a_{oq} by more than 0.01 W, the data set is not adequate according to this test method.

9.4 Evaluate the final J_i values using the adjusted a_{oq} of 9.2 and the equations of the applicable ANNEX A1, A2, or A3.

9.5 *Calculation of an Interim* J_Q:

9.5.1 For each a_i value, calculate a corresponding Δa_i as follows:

$$\Delta a_i = a_i - a_{oq}$$

Plot J versus Δa as shown in Fig. 4. Determine a construction line in accordance with the following equation:

$$J = M\sigma_Y\Delta a$$

where the value of M is either taken as 2 or determined from the test data. In some cases the initial slope of the J-R curve is steeper than $2\sigma_Y$. For these materials, it is recommended that a J_Q value be determined using $M = 2$ such that an experimental M can then be evaluated and verified according to 9.6. An improved J_Q can then be evaluated. Under no circumstances can a value of M less than 2 be used for J_Q evaluation.

9.5.2 Plot the construction line, then draw an exclusion line parallel to the construction line intersecting the abscissa at 0.15 mm (0.006 in.). Draw a second exclusion line parallel to the construction line intersecting the abscissa at 1.5 mm (0.06 in.). Plot all J-Δa data points that fall inside the area enclosed by these two parallel lines and capped by $J_{limit} = b_o\sigma_Y/15$.

9.5.3 Plot an offset line parallel to the construction and exclusion lines at an offset value of 0.2 mm (0.008 in.).

9.5.4 At least one J-Δa point shall lie between the 0.15-

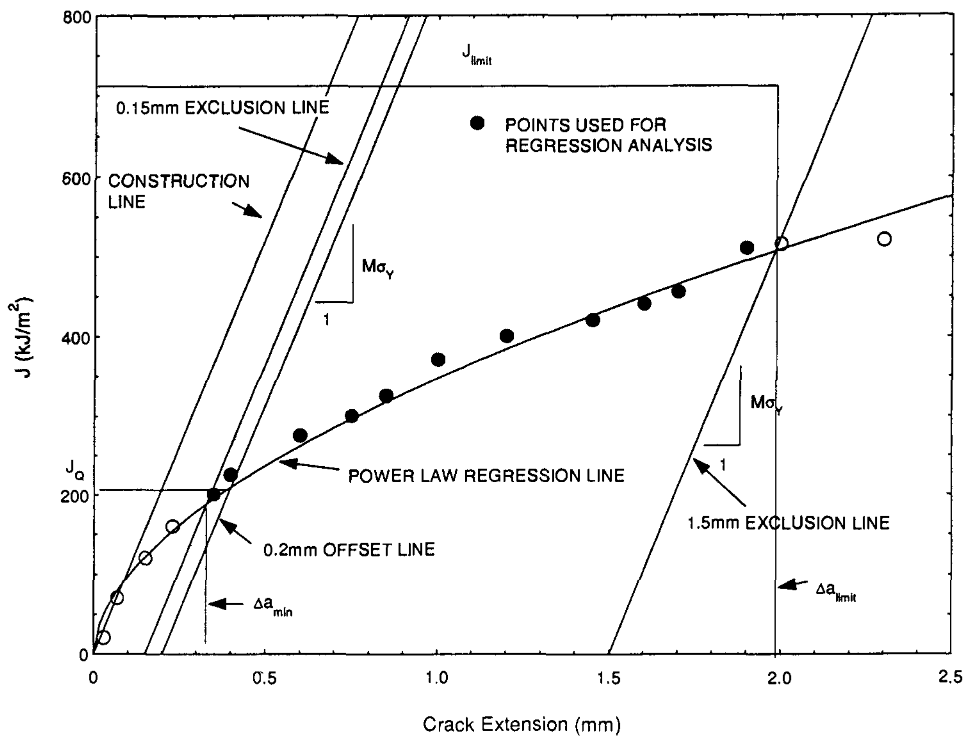


FIG. 4 Definitions for Data Qualification

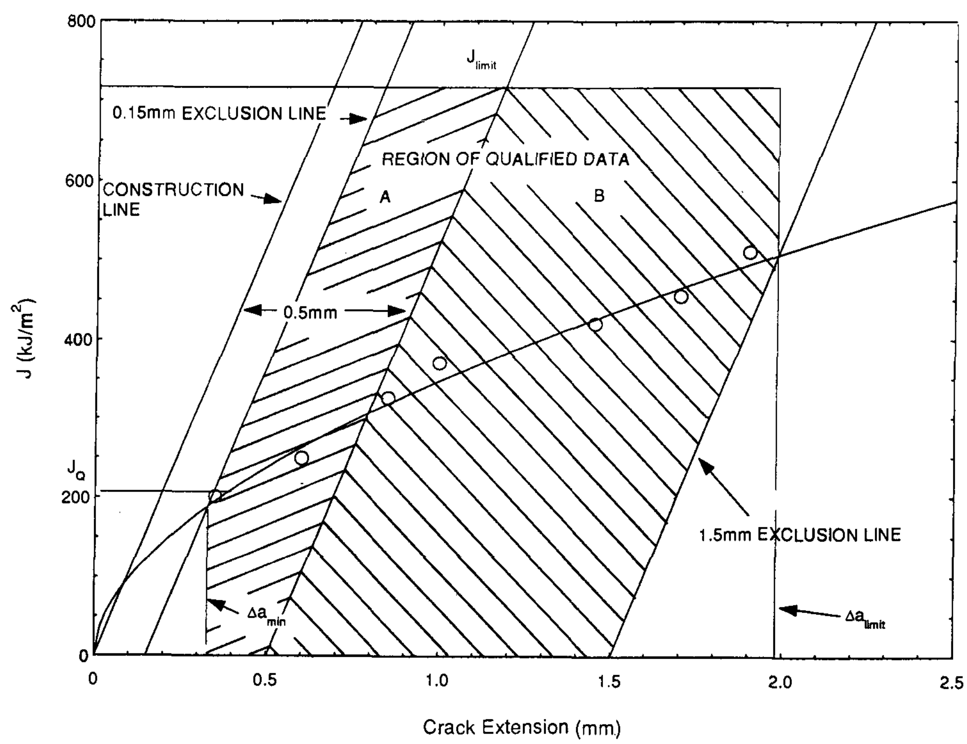


FIG. 5 Definition of Regions of Qualified Data

mm (0.006-in.) exclusion line and a parallel line with an offset of 0.5 mm (0.02 in.) from the construction line as shown in Fig. 5. At least one J-Δa point shall lie between the 0.5-mm offset line and the 1.5-mm (0.06-in.) exclusion line. Acceptable data are shown in Fig. 5. The other J-Δa pairs can be anywhere inside the exclusion zone.

9.5.5 Using the method of least squares determine a linear regression line of the following form:

$$lnJ = lnC_1 + C_2 ln\left(\frac{\Delta a}{k}\right)$$

where k = 1.0 mm or 0.0394 in. Use only the data which conform to the requirements stated in the previous sections. Draw the regression line as illustrated in Fig. 4.

9.5.6 The intersection of the regression line of 9.5.5 with the 0.2-mm offset line defines J_Q and Δa_Q. To determine this intersection the following procedure is recommended.

9.5.6.1 As a starting point estimate an interim $J_{Q(1)} = J_{Q(i)}$ value from the data plot of Fig. 4.

9.5.6.2 Evaluate $\Delta a_{(i)}$ from the following:

$$\Delta a_{(i)} = \frac{J_{Q(i)}}{M\sigma_Y} + 0.2 \text{ mm } (0.008 \text{ in.})$$

9.5.6.3 Evaluate an interim $J_{Q(i+1)}$ from the power law relationship as follows:

$$J_{Q(i+1)} = C_1 \left(\frac{\Delta a_{(i)}}{k}\right)^{C_2}$$

where k = 1.0 mm or 0.0394 in.

9.5.6.4 Increment i and return to 9.5.6.2 and 9.5.6.3 to get $\Delta a_{(i)}$ and interim $J_{Q(i+1)}$ until the interim J_Q values converge to within ±2 %.

9.6 An alternative construction line slope, M, can be calculated by fitting the least squares linear regression line to the initial J-R curve data for data in the region $0.2J_Q \leq J_i \leq 0.6J_Q$ as evaluated with $M = 2$. A minimum of six data points are required in the evaluation region to allow an experimental value of M. Only values of $M \geq 2$ are allowed by this test method. A revised J_Q can now be evaluated using this M by returning to 9.2 to 9.4.

9.7 *Qualification of Data*—The data shall satisfy all of the following requirements to be qualified according to this test method. If the data do not pass these requirements no fracture toughness values can be determined according to this test method.

9.7.1 All the test equipment requirements of Section 6 shall be met, along with the specimen tolerance and fatigue pre-cracking requirements of Section 7. The requirements on fixture alignment, test rate, and temperature stability, and accuracy specified in Section 8 and in the related annexes shall also be met.

9.7.2 *Original Crack Size*—None of the nine physical measurements shall differ by more than 5 % from the average defined in 8.5.5.

9.7.3 *Final Crack Size*—None of the nine physical measurements of final physical crack size, a_p, shall differ by more than 5 % from the average defined in 8.5.5. In subsequent tests, the side groove configuration may be modified within the requirements of 7.4 to facilitate meeting this requirement.

9.7.4 *Crack Extension*—None of the nine physical measurements of crack extension shall be less than 50 % of the average Δa_p.

9.7.5 *Crack Extension Prediction*—The crack extension predicted from elastic compliance (or other method) at the last unloading shall be compared with the measured physical crack extension. The difference between these shall not exceed 0.15 Δa_p for crack extensions less than $0.2b_o$, and the difference shall not exceed $0.03b_o$ thereafter.

9.7.6 The a_{oq} shall not differ from a_o by more than $0.01W$.

9.7.7 The number of points in the data set used to calculate a_{oq} shall be ≥8 and the correlation of the least squares fit of 9.2.1 shall be greater than 0.96.

9.7.8 If an experimental value of M is determined, at least six data points are required in the region $0.2J_Q \leq J_i \leq 0.6J_Q$. Only $M \geq 2.0$ can be used in this test method.

9.7.9 The power coefficient C_2 of 9.5.5 shall be less than 1.0.

9.8 *Qualifying the J-R Curve:*

9.8.1 The data shall meet the requirements of 9.7 to qualify as a J-R curve according to this test method.

9.8.2 The J-integral values and the corresponding crack extensions, calculated with the new a_{oq} value, shall be plotted as shown in Fig. 4. The J-R curve shall be defined by the data in a region bounded by the coordinate axes and the J_{max} and Δa_{max} limits specified in 9.8.2.1 and 9.8.2.2. Data spacing shall meet the requirements of 8.4.4.

9.8.2.1 To obtain J-R curves that are independent of specimen dimensions, J values shall not be used that exceed the smallest J_{max} defined by the following two dimensional limitations:

$$J_{max} = \frac{b_o \sigma_Y}{20}$$

or

$$J_{max} = \frac{B\sigma_Y}{20}$$

NOTE 5—If the available material has insufficient thickness, B, such that the latter of the two J_{max} requirements cannot be satisfied, a credible J-R curve can be developed using the remaining ligament, b, limitation only. The resulting J-R curve is usable, but is specific to the thickness tested.

9.8.2.2 The maximum crack extension capacity for a specimen is given by:

$$\Delta a_{max} = 0.1b_o.$$

Crack extension values that exceed Δa_{max} shall not be used.

NOTE 6—The status of current technology sets the limits for crack extension. However, measurement of J-R curves with crack extension beyond the limits for this test method as set forth in 9.8.2.2 is encouraged. Crack extension prediction accuracy requirements set forth in 9.7.5 shall be adhered to.

9.9 *Qualifying J_Q as J_{Ic}:*

9.9.1 The data shall meet the requirements of 9.7 to qualify J_Q as J_{Ic} according to this test method. Spacing of J versus crack extension data shall be in accordance with the requirements of 8.4.5.

9.9.2 Project the intercepts of the power law curve with the 0.15-mm (0.006-in.) and the 1.5-mm (0.06-in.) exclusion lines vertically down to the abscissa. This indicates Δa_{min} and Δa_{limit}, respectively. Eliminate all data points that fall outside of Δa_{min} and Δa_{limit} as shown in Fig. 5. Also eliminate all data points which lie above the J_{limit} where $J_{limit} = b_o \sigma_Y / 15$. The region of qualified data is shown in Fig. 5.

9.9.3 At least five data points shall remain between Δa_{min} and Δa_{limit} and the J_{limit}. Data point spacing shall meet the requirements of 9.5.4. If these data points are different than those used in 9.5, evaluate J_Q, return to 9.5, and obtain a new value of J_Q based only on qualified data.

9.9.4 $J_Q = J_{Ic}$ if:

9.9.4.1 Thickness $B > 25\ J_Q/\sigma_Y$,

9.9.4.2 Initial ligament, $b_o > 25\ J_Q/\sigma_Y$,

9.9.4.3 The slope of the power law regression line, dJ/da, evaluated at Δa_Q is less than σ_Y,

9.10 *Qualifying J_{Qc} as J_c:*

9.10.1 When fracture occurs before significant stable tearing, a size independent single point fracture toughness value, J_c, may be obtained. However, there may be a dependence of toughness on thickness, equivalent to a dependence on crack front length.

9.10.2 The J_{Qc} is calculated at the point of fracture instability using the J formulae in Annexes A1, A2, or A3.

9.10.3 The data shall meet the requirements of 9.7.1 and 9.7.2 to qualify J_{Qc} as J_c according to this test method.

9.10.4 $J_{Qc} = J_c$ if the following conditions are met:

9.10.4.1 B, a_o, $b_o > 200\ J_{Qc}/\sigma_Y$;

9.10.4.2 Crack extension $\Delta a_p < 0.2$ mm (0.008 in.) + $J_{Qc}/M\sigma_Y$.

9.10.4.3 The K_{max} (during the final 50 % of fatigue pre-cracking) $< 0.6(J_{Qc}E)^{1/2}$.

9.11 When fracture instability occurs after significant stable tearing where crack extension $\Delta a_p > 0.2$ mm (0.008 in.) + $J_{Qc}/M\sigma_Y$ and the data are qualified according to 9.7.1 and 9.7.2, a single-point fracture toughness value, $J_u = J_{Qc}$, is obtained. The J_u may be size dependent, a function of test specimen geometry, or both.

10. Report

10.1 Report the following information for each test:

10.1.1 Material yield strength and tensile strength at room temperature,

10.1.2 Test temperature,

10.1.3 Material yield strength and tensile strength at the test temperature and elastic modulus used for calculations,

10.1.4 Crack plane orientation according to Terminology E 616 identification codes.

10.1.5 Specimen thickness, B, and net thickness, B_N.

10.1.6 Specimen width, W.

10.1.7 Specimen initial uncracked ligament size, b_o.

10.1.8 Maximum load used in fatigue pre-cracking for the last increment of crack growth.

10.1.9 Fatigue precracking conditions in terms of maximum stress intensity, K_{max} for the final increment of crack growth.

10.1.10 Original crack size, a_o, from nine-point measurement.

10.1.11 Maximum deviation of a single original crack size measurement from the average value.

10.1.12 Physical crack extension, Δa_p, from nine-point measurement.

10.1.13 Fracture surface and crack front appearance in the stable crack growth regime.

10.1.14 Load displacement record and associated calculations.

10.1.15 Report J_i, a_i, and Δa_i results and a_{oq}, and

10.1.16 For cases of estimated displacement measurement, describe measurements, and any corrections or extrapolations employed.

10.2 *Information Required for J_{Ic} Calculation:*

10.2.1 Report J_{Ic},

10.2.2 Report coefficients of power law regression line, and

10.2.3 Report M.

10.3 *Information Required for J_c or J_u Calculation:*

10.3.1 Report J_c or J_u,

10.3.2 Amount of ductile crack extension measured on specimen fracture surface, and

10.3.3 Report the value of 0.2 mm (0.008 in.) + $J_{Qc}/M\sigma_Y$.

11. Precision and Bias

11.1 *Precision:*

11.1.1 The precision of J versus crack growth is a function of material variability, the precision of the various measurements of linear dimensions of the specimen and testing fixtures, precision of the displacement measurement, precision of the load measurement, as well as the precision of the recording devices used to produce the load-displacement record used in calculating J and crack length. The required load and displacement accuracy, linearity, and digital signal resolution of 6.3 and 6.4 are readily obtainable with modern test equipment. The variation in areas under the load-displacement curve used for J-calculations resulting from these requirements is ±2 %. However, in general the crack length measurement makes a more significant contribution to the variation in the J-R curve although this is difficult to isolate as it is coupled to the analysis procedure and measurement of elastic compliance slopes. These considerations form the basis for the recommended requirements for physical crack straightness of 9.7.2 and 9.7.3, crack extension straightness of 9.7.4, and the final crack length prediction accuracy requirement of 9.7.5. The maximum allowable error in final crack growth prediction is intended to produce a predicted crack growth within ±15 % of the real growth at each measurement point on the J-R curve.

11.1.2 Although it is impossible to separate the contributions from each of the proceding sources of variability, an overall measure of variability in J versus crack extension is available from the results of an interlaboratory test program in which 19 laboratories participated **(9, 10)**. These data, obtained on a homogeneous 5 Ni steel, showed maximum deviation of J values of 10 % for all compact specimens tested, and a maximum deviation of R-curve slope approaching 22 % for all compact specimen results. For compact specimen tests which comprised the majority of the results, estimation of initial and final crack length, with one exception, were within 10 % of the physical post test measurements. Single edge bend results were limited and statistical analysis of six specimens from three laboratories was conducted **(9, 10)**.

11.1.3 Although it is impossible to separate the contributions from each of the preceding sources of variability, an overall measure of variability in J_{Ic} is available from the results of an interlaboratory test program **(11)**.

11.1.4 The precision of J_c is equivalent to any single J measurement, that is, within ±2 %. Since very limited crack extension is allowed before a J_c evaluation, crack extension measurement error does not contribute to measurement error of J_c.

11.2 *Bias*—There is no accepted standard value for J_{Ic}, J_c, or J versus crack extension for any material. In the absence of such a true value, no meaningful statement can be made concerning bias of data.

12. Keywords

12.1 crack initiation; ductile fracture; elastic-plastic fracture toughness; J-integral; resistance curve; stable crack growth

ANNEXES

(Mandatory Information)

A1. SPECIAL REQUIREMENTS FOR TESTING SINGLE-EDGE BEND (SE(B)) SPECIMENS

A1.1 *Specimen:*

A1.1.1 The standard bend specimen is a beam with a fatigue-cracked, single-edge notch loaded in three-point bending with a support span, *S*, nominally equal to four times the width, *W*. The general proportions of the specimen configuration are shown in Fig. A1.1.

A1.1.2 Alternative specimens may have $1 \leq W/B \leq 4$. These specimens shall also have a nominal support span equal to $4W$.

A1.2 *Specimen Preparation:*

A1.2.1 For generally applicable specifications concerning specimen size and preparation see Section 7.

A1.2.2 It is recommended that bend specimens be pre-cracked using three-point bend loading. If the bend specimens are pre-cracked in cantilever bending, the applied load should not exceed 0.5 P_M for the bend specimen as given in 7.5.1.

A1.3 *Apparatus:*

A1.3.1 *Bend Test Fixture*—The general principles of the bend test fixture are illustrated in Fig. A1.2. This fixture is designed to minimize frictional effects by allowing the support rollers to rotate and move apart slightly as the specimen is loaded, thus permitting rolling contact. Thus, the support rollers are allowed limited motion along plane surfaces parallel to the notched side of the specimen, but are initially positively positioned against stops that set the span length and are held in place by low-tension springs (such as rubber bands). Fixtures and rolls shall be made of high hardness (greater than 40 HRC) steels.

A1.3.2 *Displacement Gage*—For generally applicable details concerning the displacement gage see 6.3.

A1.4 *Procedure:*

A1.4.1 *Measurement*—The dimensions B_N, B, and W shall be measured to the nearest 0.050 mm (0.002 in.) or 0.5 %, whichever is larger.

A1.4.2 *Bend Testing*—Set up the bend test fixture so that the line of action of the applied load passes midway between the support roll centers within ±1 % of the distance between the centers. Measure the span to within ±0.5 % of the nominal length. Locate the specimen so that the crack tip is midway between the rolls to within ±1 % of the span, and square the roll axes within ±2°.

A1.4.3 When the load-line displacement measurement is referenced from the loading jig there is potential for introduction of error from two sources, the elastic compression of the fixture as the load increases and indentation of the specimen at the loading points. If a remote transducer is used for load-line displacement measurement, care shall be taken to exclude the elastic displacement of the load train measurement and elastic and inelastic deformations at the load points.

A1.5 *Calculations:*

A1.5.1 Calculations of *J*-integral are made from load, load-point displacement curves obtained using the procedure outlined in Section 8.

A1.5.2 For the SE(B) specimen—Calculate *J* as follows:

$$J = J_{el} + J_{pl} \tag{A1.1}$$

where:

J_{el} = elastic component of *J*, and
J_{pl} = plastic component of *J*.

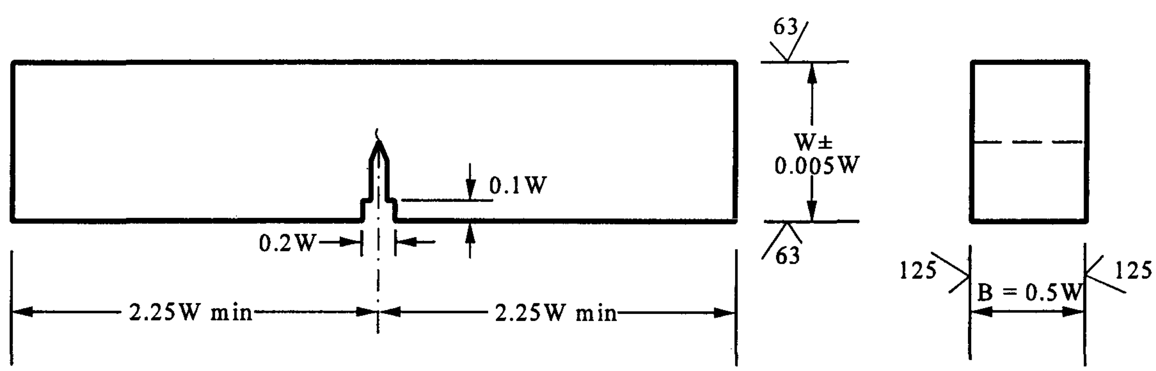
A1.5.3 For the SE(B) specimen at a point corresponding to V_i and P_i on the specimen load versus load-line displacement record as follows:

$$J_{(i)} = \frac{(K_{(i)})^2 (1 - \nu^2)}{E} + J_{pl(i)} \tag{A1.2}$$

where:

$$K_{(i)} = \left[\frac{P_i S}{(BB_N)^{1/2} W^{3/2}}\right] f(a_i/W) \tag{A1.3}$$

with:



NOTE 1—The two side planes and the two edge planes shall be parallel and perpendicular as applicable to within 0.5°.
NOTE 2—The machined notch shall be perpendicular to specimen length and thickness to within ±2°.
NOTE 3—See Fig. 2.

FIG. A1.1 Recommended SE(B) Specimen

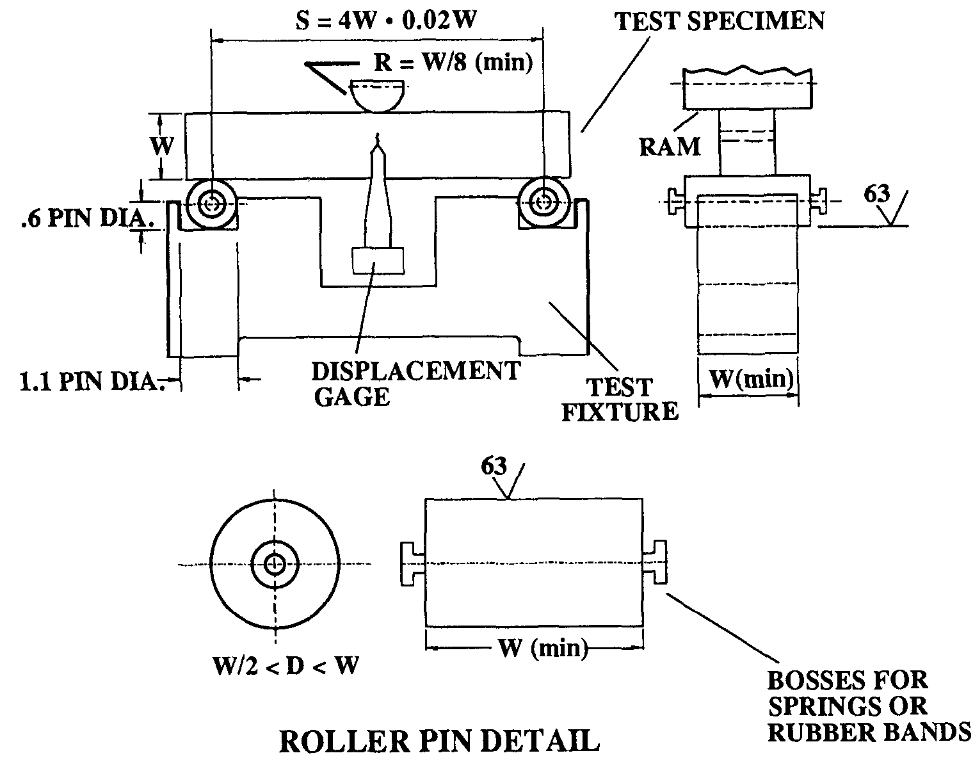


FIG. A1.2 Fixture for SE(B) Specimen Testing

$$f(a_i/W) = \frac{3(a_i/W)^{1/2}\,[1.99 - (a_i/W)\,(1 - a_i/W) \times (2.15 - 3.93\,(a_i/W) + 2.7\,(a_i/W)^2)]}{2(1 + 2a_i/W)\,(1 - a_i/W)^{3/2}} \quad \text{(A1.4)}$$

and:

$$J_{pl(i)} = \left[J_{pl(i-1)} + \left(\frac{2}{b_{(i-1)}}\right)\left(\frac{A_{pl(i)} - A_{pl(i-1)}}{B_N}\right)\right]\left[1 - \frac{a_{(i)} - a_{(i-1)}}{b_{(i-1)}}\right] \quad \text{(A1.5)}$$

In Eq A1.5, the quantity $A_{pl(i)} - A_{pl(i-1)}$ is the increment of plastic area under the load versus load-line displacement record between lines of constant displacement at points *i*-1 and *i*, as shown in Fig. A1.3. The quantity $J_{pl(i)}$ represents the total crack growth corrected plastic *J* at point *i* and is obtained in two steps by first incrementing the existing $J_{pl(i-1)}$ and then by modifying the total accumulated result to account for the crack growth increment. Accurate evaluation of $J_{pl(i)}$ from the above relationship requires small and uniform crack growth increments consistent with the suggested data spacing of 8.4.4. The quantity $A_{pl(i)}$ can be calculated from the following equation:

$$A_{pl(i)} = A_{pl(i-1)} + [P_{(i)} + P_{(i-1)}]\,[V_{pl(i)} - V_{pl(i-1)}]/2 \quad \text{(A1.6)}$$

where:

$V_{pl(i)}$ = plastic part of the load-line displacement = $V_{(i)} - (P_i C_{LL(i)})$

$C_{LL(i)}$ = slope $(\Delta V/\Delta P)_i$ required to give the current crack length, a_i.

$C_{LL(i)}$ can be determined from knowledge of a_i/W using the following equation:

$$C_{LL(i)} = \frac{1}{E'B_e}\left(\frac{S}{W - a_i}\right)^2 \{[1.193 - 1.98(a_i/W) + 4.478\,(a_i/W)^2 - 4.443\,(a_i/W)^3 + 1.739\,(a_i/W)^4]\} \quad \text{(A1.7)}$$

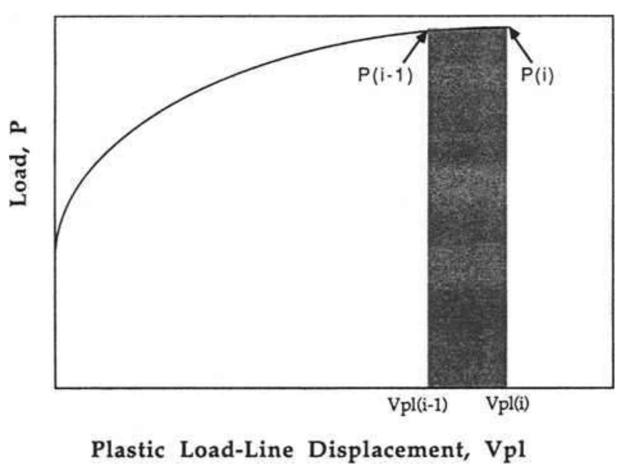


FIG. A1.3 Definition of Plastic Area for Resistance Curve *J* Calculation

A1.5.4 For SE(B) specimens where the span to width ratio is four with crack mouth opening displacements measured at the notched edge, the crack length is:

$$a_i/W = 0.999748 - 3.9504\,U_x + 2.9821\,U_x^2 - 3.21408\,U_x^3 + 51.51564\,U_x^4 - 113.031\,U_x^5 \quad \text{(A1.8)}$$

where:

$$U_x = \frac{1}{\left[\frac{B_e W E' C_i}{S/4}\right]^{1/2} + 1} \quad \text{(A1.9)}$$

C_i = specimen crack mouth opening elastic compliance $(\Delta V_m/\Delta P)_i$ on an loading/reloading sequence,
V_m = crack mouth opening displacement at notched edge,
ΔV_m = increment of crack mouth opening displacement,
E' = $E/(1 - \nu^2)$.

A1.5.5 Other compliance equations are acceptable if the resulting accuracy is equal to or greater than those described and the accuracy has been verified experimentally.

A2. SPECIAL REQUIREMENTS FOR TESTING COMPACT (C(T)) SPECIMENS

A2.1 *Specimen:*

A2.1.1 The standard compact specimen is a single-edge notched and fatigue-cracked plate loaded in tension. Two specimen geometries which have been used successfully are shown in Fig. A2.1.

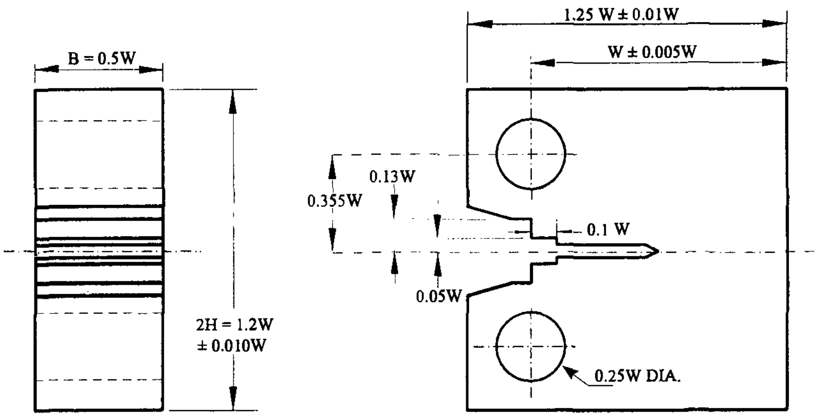
A2.1.2 Alternative specimens may have $2 \leq W/B \leq 4$ but with no change in other proportions.

A2.2 *Specimen Preparation*—For generally applicable specifications concerning specimen size and preparation see Section 7.

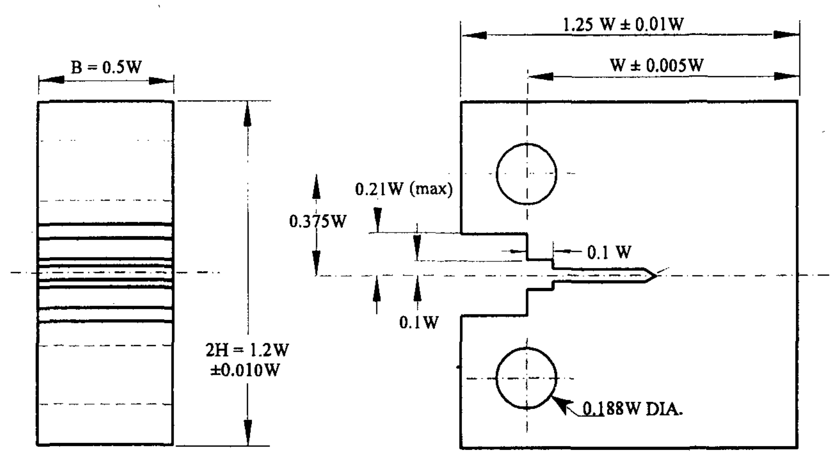
A2.3 *Apparatus:*

A2.3.1 *Tension Testing Clevis:*

A2.3.1.1 A loading clevis suitable for testing compact specimens is shown in Fig. A2.2. Both ends of the specimen



COMPACT TEST SPECIMEN FOR PIN OF 0.24W (+0.000W/-0.005W) DIAMETER



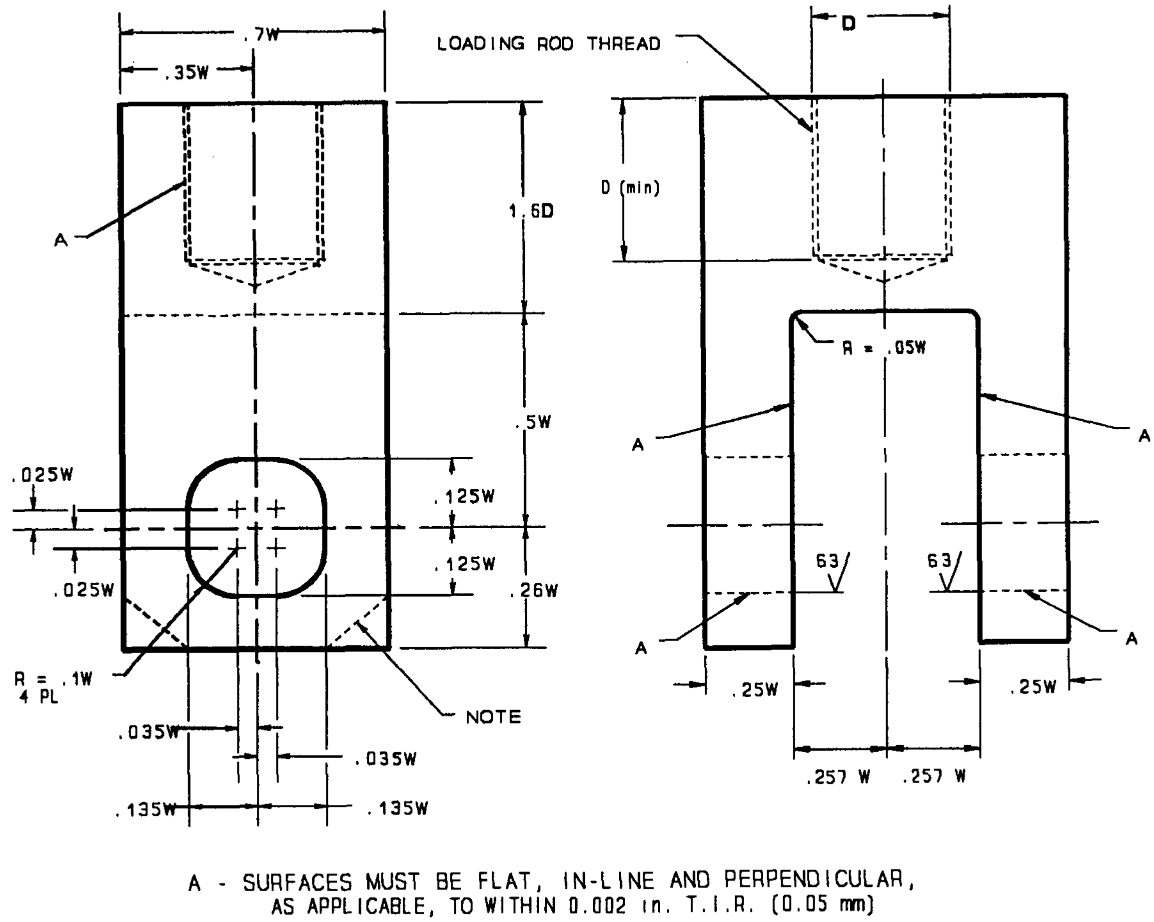
COMPACT TEST SPECIMEN FOR PIN OF 0.1875W(+0.000W/-0.001W)DIAMETER

NOTE 1—A surface shall be perpendicular and parallel as applicable within 0.002 TIR.

NOTE 2—The intersection of the crack starter notch tips on each surface of the specimen shall be equally distant within 0.005 *W* from the centerline of the loading holes.

NOTE 3—See Fig. 2.

FIG. A2.1 Two Compact Specimen Designs That Have Been Used Successfully



NOTE—Corners may be removed as necessary to accommodate the clip page.

FIG. A2.2 Clevis for C(T) Specimen Testing

are held in such a clevis and loaded through pins, in order to allow rotation of the specimen during testing. In order to provide rolling contact between the loading pins and the clevis holes, these holes are provided with small flats on the loading surfaces. Other clevis designs may be used if it can be demonstrated that they will accomplish the same result as the design shown. Clevises and pins should be fabricated from steels of sufficient strength (greater than 40 HRC) to elastically resist indentation loads.

A2.3.1.2 The critical tolerances and suggested proportions of the clevis and pins are given in Fig. A2.2. These proportions are based on specimens having $W/B = 2$ for $B \geq 12.7$ mm (0.5 in.) and $W/B = 4$ for $B < 12.7$ mm. If a 1930-MPa (280 000-psi) yield strength maraging steel is used for the clevis and pins, adequate strength will be obtained. If lower-strength grip material is used, or if substantially larger specimens are required at a given σ_{YS}/E ratio, then heavier grips will be required. As indicated in Fig. A2.2, the clevis corners may be cut off sufficiently to accommodate seating of the clip gage in specimens less than 9.5 mm (0.375 in.) thick.

A2.3.1.3 Careful attention should be given to achieving good alignment through careful machining of all auxiliary gripping fixtures.

A2.3.2 *Displacement Gage*—For generally applicable details concerning the displacement gage see 6.3.

A2.4 *Procedure:*

A2.4.1 *Measurement*—Measure the dimensions, B_N, B, and W to the nearest 0.05 mm (0.002 in.) or 0.5 %, whichever is larger.

A2.4.2 Loading pin friction and eccentricity of loading can lead to errors in J determinations. Keep the centerline of the upper and lower loading rods coincident within 0.76 mm (0.03 in.) during the test. Center the specimen with respect to the clevis opening within 0.76 mm. Seat the displacement gage in the knife edges firmly by wiggling the gage lightly.

A2.5 *Calculation:*

A2.5.1 Calculations of J-integral are made from load, load-point displacement curves obtained using the procedure outlined in Section 8.

A2.5.2 Calculate J as follows:

$$J = J_{el} + J_{pl} \tag{A2.1}$$

where:

J_{el} = elastic component of J, and
J_{pl} = plastic component of J.

A2.5.3 At a point corresponding to V_i, P_i on the specimen load versus load-line displacement record as follows:

$$J_{(i)} = \frac{(K_{(i)})^2 (1 - \nu^2)}{E} + J_{pl(i)} \tag{A2.2}$$

where:

$$K_{(i)} = \left[\frac{P_i}{(BB_NW)^{1/2}}\right] f(a_i/W) \quad \text{(A2.3)}$$

with:

$$f(a_i/W) = \frac{[(2 + a_i/W)\,(0.886 + 4.64\,(a_i/W) - 13.32\,(a_i/W)^2 + 14.72\,(a_i/W)^3 - 5.6\,(a_i/W)^4)]}{(1 - a_i/W)^{3/2}} \quad \text{(A2.4)}$$

and:

$$J_{pl(i)} = \left[J_{pl(i-1)} + \left(\frac{\eta_{(i-1)}}{b_{(i-1)}}\right)\frac{A_{pl(i)} - A_{pl(i-1)}}{B_N}\right]\left[1 - \gamma_{(i-1)}\frac{a_{(i)} - a_{(i-1)}}{b_{(i-1)}}\right] \quad \text{(A2.5)}$$

where:

$\eta_{(i-1)} = 2.0 + 0.522\, b_{(i-1)}/W$, and

$\gamma_{(i-1)} = 1.0 + 0.76\, b_{(i-1)}/W$.

A2.5.4 In Eq A2.5, the quantity $A_{pl(i)} - A_{pl(i-1)}$ is the increment of plastic area under the load versus load-line displacement record between lines of constant displacement at points $i-1$ and i, see Fig. A1.3. The quantity $J_{pl(i)}$ represents the total crack-growth-corrected plastic J at point i and is obtained in two steps by first incrementing the existing $J_{pl(i-1)}$ and then by modifying the total accumulated result to account for the crack growth increment. Accurate evaluation of $J_{pl(i)}$ from the relationship in A2.5 requires small and uniform crack growth increments consistent with the data spacing requirements of 8.4.4. The quantity $A_{pl(i)}$ can be calculated from the following equation:

$$A_{pl(i)} = A_{pl(i-1)} + \frac{[P_{(i)} + P_{(i-1)}]\,[V_{pl(i)} - V_{pl(i-1)}]}{2} \quad \text{(A2.6)}$$

where:

$V_{pl(i)}$ = plastic part of the load-line displacement = $V_i - (P_iC_{ci})$, and

C_{ci} = corrected compliance (see A2.5.5) required to give the current crack length, a_i.

For test methods that do not utilize the elastic compliance techniques, C_i can be determined from knowledge of a_i/W using the following equation:

$$C_i = \frac{1}{E'B_e}\left(\frac{W + a_i}{W - a_i}\right)^2 2.1630 + 12.219\,(a_i/W) - 20.065\,(a_i/W)^2 - 0.9925\,(a_i/W)^3 + 20.609\,(a_i/W)^4 - 9.9314\,(a_i/W)^5] \quad \text{(A2.7)}$$

A2.5.5 For C(T) specimens, the crack length is given by:

$$a_i/W = 1.000196 - 4.06319\,U_x + 11.242\,U_x^2 - 106.043\,U_x^3 + 464.335\,U_x^4 - 650.677\,U_x^5 \quad \text{(A2.8)}$$

where:

$$U_x = \frac{1}{[B_eE'C_{ci}]^{1/2} + 1} \quad \text{(A2.9)}$$

where:

E' = $E/(1 - \nu^2)$,

C_{ci} = corrected specimen crack opening compliance on an unloading/reloading sequence,

$$C_{ci} = \frac{C_i}{\left[\frac{H^*}{R}\sin\theta - \cos\theta\right]\left[\frac{D}{R}\sin\theta - \cos\theta\right]} \quad \text{(A2.10)}$$

and (Fig. A2.3):

C_i = measured specimen elastic compliance (at the load line),

H^* = initial half-span of the load points (center of pin holes),

R = radius of rotation of the crack centerline, $(W + a)/2$ where a is the updated crack length,

D = one-half of the initial distance between the displacement measurement points,

θ = angle of rotation of a rigid body element about the unbroken midsection line, or

θ = $\sin^{-1}[(d_m/2 + D)/(D^2 + R^2)^{1/2}] - \tan^{-1}(D/R)$, and

d_m = total measured load-line displacement.

A2.5.6 Other compliance equations are acceptable if the resulting accuracy is equal to or greater than those described and the accuracy has been verified experimentally.

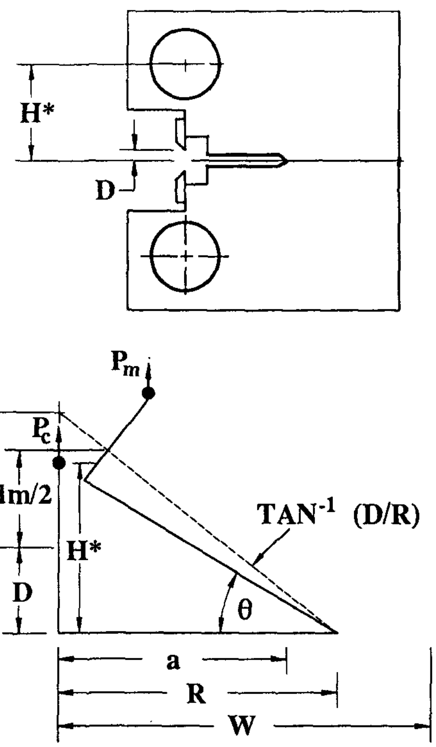


FIG. A2.3 Elastic Compliance Correction for Specimen Rotation

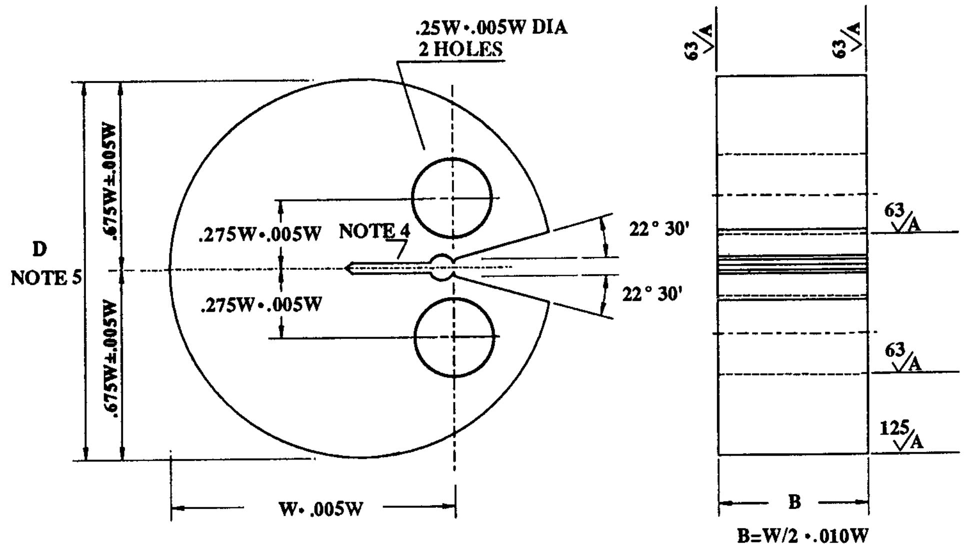
A3. SPECIAL REQUIREMENTS FOR TESTING DISK-SHAPED COMPACT (DC(T)) SPECIMENS

A3.1 *Specimen:*

A3.1.1 The standard disk-shaped compact specimen, DC(T), is a single-edge notched and fatigue-cracked plate loaded in tension **(11)**. A specimen geometry which has been used successfully is shown in Fig. A3.1.

A3.1.2 Alternative specimens may have $2 \leq W/B \leq 4$ but with no change in other proportions.

A3.2 *Specimen Preparation:*



NOTE 1—A surface shall be perpendicular and parallel as applicable within 0.002 *W* TIR.

NOTE 2—The intersection of the crack starter notch tips on each surface of the specimen shall be equally distant within 0.005 *W* from the centerline of the loading holes.

NOTE 3—Integral or attached knife edges for clip gage attachment to the crack mouth may be used.

NOTE 4—For starter notch and fatigue crack configuration see Fig. 2.

NOTE 5—Circularity requirements measure radius at eight equally spaced points around the circumference. One of these points shall be the notch plane. Average readings to obtain radius. All values shall be within 5 % of the average.

FIG. A3.1 Disk-Shaped Compact Specimen *DC(T)* Standard Proportions and Tolerances

A3.2.1 For generally applicable specifications concerning specimen size and preparation, see Section 7.

A3.3 *Apparatus:*

A3.3.1 *Tension Testing Clevis:*

A3.3.1.1 A loading clevis suitable for testing compact specimens is shown in Fig. A2.2. Both ends of the specimen are held in such a clevis and loaded through pins, in order to allow rotation of the specimen during testing. In order to provide rolling contact between the loading pins and the clevis holes, these holes are provided with small flats on the loading surfaces. Other clevis designs may be used if it can be demonstrated that they will accomplish the same result as the design shown. Clevises and pins should be fabricated from steels of sufficient strength to elastically resist indentation loads (>40 HRC).

A3.3.1.2 The critical tolerance and suggested proportions of the clevis and pins are given in Fig. A2.2. These proportions are based on specimens having $W/B = 2$ for $B \geq$ 12.7 mm (0.5 in.) and $W/B = 4$ for $B <$ 12.7 mm (0.5 in.). If a 1930-MPa (280 000-psi) yield strength maraging steel is used for the clevis and pins, adequate strength will be obtained. If lower strength grip material is used, or if substantially larger specimens are required at a given σ_{YS}/E ratio, then heavier grips will be required. As indicated in Fig. A2.2, the clevis corners may be cut off sufficiently to accommodate seating of the clip gage in specimens less than 9.5 mm (0.375 in.) thick.

A3.3.1.3 Careful attention should be given to achieving good alignment through careful machining of all auxiliary gripping fixtures.

A3.3.2 *Displacement Gage*—For generally applicable details concerning the displacement gage see 6.3.

A3.4 *Procedure:*

A3.4.1 *Measurement*—The analysis assumes the specimen was machined from a circular blank and therefore measurements of circularity as well as width, *W*, crack length, *a*, and thicknesses, *B* and B_N should be made. Measure the dimensions, B_N and *B* to the nearest 0.05 mm (0.002 in.) or 0.5 %, whichever is larger.

A3.4.1.1 The specimen blank should be checked for circularity before specimen machining. Measure the radius at eight equally spaced points around the circumference of the specimen blank. One of these points should lie in the intended notch plane. Average these readings to obtain the radius, *r*. If any measurement differs from *r* by more than 5 %, machine the blank to the required circularity. Otherwise, $D = 2r = 1.35\ W$.

A3.4.1.2 Measure the width, *W*, and the crack length, *a*, from the plane of the centerline of the loading holes (the notched edge is a convenient reference line but the distance from the centerline of the holes to the notched edge shall be subtracted to determine *W* and *a*). Measure the width, *W*, to the nearest 0.05 mm (0.002 in.) or 0.5 %, whichever is larger, at not less than three positions near the notch location and record the average value.

A3.5 *Calculation:*

A3.5.1 *Calculation of J*—For the disk compact specimen calculate *J* as follows:

$$J = J_{el} + J_{pl} \qquad \text{(A3.1)}$$

where:

J_{el} = elastic component of *J*, and

J_{pl} = plastic component of *J*.

For the DC(T) specimen at a point corresponding to a_i, v_i, and P_i on the specimen load versus load-line displacement record as follows:

$$J_{(i)} = \frac{(K_{(i)})^2 (1 - \nu^2)}{E} + J_{pl(i)} \qquad \text{(A3.2)}$$

$$K_{(i)} = \left[\frac{P_i}{(BB_N W)^{1/2}}\right] f(a_i/W) \qquad \text{(A3.3)}$$

where:

$$f(a_i/W) = \frac{(2 + a_i/W)\,(0.76 + 4.8a_i/W - 11.58\,(a_i/W)^2 + 11.43\,(a_i/W)^3 - 4.08\,(a_i/W)^4)}{(1 - a_i/W)^{3/2}} \quad (A3.4)$$

$$J_{pl(i)} = \left[J_{pl(i)} + \left(\frac{\eta_{i-1}}{b_{i-1}}\right)\frac{(A_{pl(i)} - A_{pl(i-1)})}{B_N}\right]\left[1 - \gamma_{i-1}\frac{(a_i - a_{i-1})}{b_{i-1}}\right] \quad (A3.5)$$

where:

$\eta_{(i-1)} = 2.0 + 0.522\, b_{(i-1)}/W$, and

$\gamma_{(i-1)} = 1.0 + 0.76\, b_{(i-1)}/W$.

A3.5.2 In Eq A3.5, the quantity $A_{pl(i)} - A_{pl(i-1)}$ is the increment of plastic area under the load versus load-line displacement record between lines of constant displacement at points $i-1$ and i, see Fig. A1.3. The quantity $J_{pl(i)}$ represents the total crack growth corrected plastic J at point i and is obtained in two steps by first incrementing the existing $J_{pl(i-1)}$ and then by modifying the total accumulated result to account for the crack growth increment. Accurate evaluation of $J_{pl(i)}$ from the above relationship requires small and uniform crack-growth increments consistent with the data spacing requirements of 8.4.4. The quantity $A_{pl(i)}$ can be calculated from the following equation:

$$A_{pl(i)} = A_{pl(i-1)} + \frac{(P_i + P_{i-1})\,(V_{pl(i)} - V_{pl(i-1)})}{2} \quad (A3.6)$$

where:

$V_{pl(i)}$ = plastic part of the load-line displacement = $V_i - (P_i C_{LL(i)})$, and

$C_{LL(i)}$ = compliance, $(\Delta V/\Delta P)_i$ required to give the current crack length, a_i.

For test methods that do not utilize the elastic compliance techniques, C_i can be determined from knowledge of a_i/W using the following equation:

$$C_i = \frac{[1.62 + 17.80\,(a_i/W) - 4.88\,(a_i/W)^2 + 1.27\,(a_i/W)^3]}{E'B_e\,[1 - (a_i/W)]^2} \quad (A3.7)$$

A3.5.3 *Calculation of Crack Length*—For a single-specimen method using an elastic compliance technique on disk-shaped compact specimens with crack opening displacements measured at the load-line, the crack length is given as follows:

$$a_i/W = 0.998193 - 3.88087\,U_x + 0.187106\,U_x^2 + 20.3714\,U_x^3 - 45.2125\,U_x^4 + 44.5270\,U_x^5 \quad (A3.8)$$

where:

$$U_x = \frac{1}{[(B_e E' C_{ci})^{1/2} + 1]} \quad (A3.9)$$

where:

C_{ci} = corrected specimen crack opening compliance $(\Delta v/\Delta P)$ on an unloading/reloading sequence,

$$C_{ci} = \frac{C_i}{\left[\frac{H^*}{R}\sin\theta - \cos\theta\right]\left[\frac{D}{R}\sin\theta - \cos\theta\right]} \quad (A3.10)$$

where (Fig. A2.3):

C_i = measured specimen elastic compliance (at the load-line),

H^* = initial half-span of the load points (center of the pin holes),

R = radius of rotation of the crack centerline, $(W + a)/2$, where a is the updated crack length,

D = one-half of the initial distance between the displacement measuring points,

θ = angle of rotation of a rigid body element about the unbroken midsection line, or

$\theta = \sin^{-1}\,[(d_m/2 + D)/(D^2 + R^2)^{1/2}] - \tan^{-1}\,(D/R)$,

d_m = total measured load-line displacement.

$E' = E/(1 - \nu^2)$,

$B_e = B - (B - B_N)^2/B$.

A3.5.4 Other compliance equations are acceptable if the resulting accuracy is equal to or greater than those described and the accuracy has been verified experimentally.

A4. SPECIAL REQUIREMENTS FOR MULTISPECIMEN TESTING

A4.1 *Overview*—Multispecimen test methods can be used to evaluate a J_{Ic} toughness parameter in accordance with this test method. In a multispecimen method each specimen is used to develop a single point on the $J - \Delta a_p$ curve and an assemblage of five or more of these points can, by use of the construction of Fig. 5, give a value of J_Q, that is a conditional J_{Ic} value. Because the J values developed are not corrected for crack growth, the resulting *J-R* curve is not qualified according to this test method.

A4.2 *Procedure:*

A4.2.1 All requirements set forth in this test method are applicable for specimen dimensions, specimen preparation, and test apparatus. Only the test procedure and the calculations of J are different for the multispecimen method where all needed crack length measurements are obtained using optical methods from the fracture surface of the broken test sample according to 8.5.5.

A4.2.2 The multiple specimen technique involves loading specimens to selected different displacement levels and marking the amount of crack extension that occurred during loading.

A4.2.3 Load specimens at a rate such that the time taken to reach P_M is between 0.1 and 10.0 min.

A4.2.4 *Number of Specimens*—Several specimens are used to generate the required power law curve. It is suggested that a minimum of six specimens be prepared. All shall be machined to the same dimensions. The initial precrack lengths should be as close as possible. The objective is to replicate the initial portion of the load versus load-line displacement traces as much as possible.

A4.2.5 Take each specimen individually through the following steps:

A4.2.5.1 Load to a selected displacement level that is judged to produce Δa_p in a desired position on the *J-R* curve. A good practice would be to aim for the first significant load drop on the first specimen so that subsequent displacement levels can be better estimated from the first record. Use displacement or clip gage control so that crack growth beyond maximum load can be controlled. Record load and displacement(s) autographically or digitally.

A4.2.5.2 Unload the specimen and mark the crack according to one of the following methods. For steels and titanium alloys, heat tinting at about 300°C (570°F) for 30 min works well. For other materials, fatigue cycling can be used. The use of liquid penetrants is not recommended. For both recommended test methods, the beginning of stable crack extension is marked by the end of the flat fatigue pre-cracked area. The end of crack extension is marked by the end of heat tint or the beginning of the second flat fatigue area.

A4.2.5.3 Break the specimen to expose the crack, with care taken to minimize additional deformation. Cooling ferritic steel specimens enough to ensure brittle behavior may be helpful. Other materials may also benefit since cooling will reduce deformation.

A4.2.5.4 Measure the fatigue and final crack lengths according to 8.5.5.

A4.2.5.5 Calculate $\Delta a_p = a_p - a_o$.

A4.2.5.6 Judge the displacement level needed on the next specimen to obtain a favorable Δa_p position between the parallel exclusion lines (see Fig. 4). Repeat the iteration until at least five data points are favorably positioned to satisfy the conditions of 9.9.3.

A4.3 *Calculation:*

A4.3.1 Calculations of J-integral are made from load, load-point displacement curves obtained using the procedure outlined in Section 8. At a given total deflection, the area under the load-displacement curve is found in square centimetres or square inches accurate to ±2 %. A polar planimeter is commonly used. Alternatively, numerical integration can be used with computer techniques. The measured area is cross-hatched in Fig. A4.1. Areas are then converted to energy units according to the load scale and displacement scale used.

A4.3.2 Calculate J according to the following equation:

$$J = J_{el} + J_{pl} \tag{A4.1}$$

where:

J_{el} = elastic component of J, and

J_{pl} = plastic component of J.

For the SE(B) specimen at a point corresponding to V_i and P_i on the specimen load versus load-line displacement record as follows:

$$J = \frac{K^2(1-\nu^2)}{E} + J_{pl} \tag{A4.2}$$

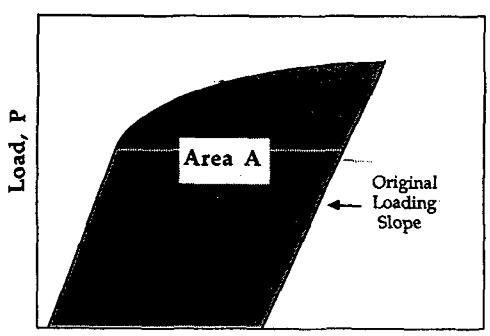


FIG. A4.1 Definition of Area for J Calculation

where:

$$K = \left[\frac{PS}{(BB_N)^{1/2}\,W^{3/2}}\right] f(a_o/W) \tag{A4.3}$$

with:

$$f(a_o/W) = \frac{3(a_o/W)^{1/2}\,[1.99 - (a_o/W)(1 - a_o/W) \times (2.15 - 3.93\,(a_o/W) + 2.7\,(a_o/W)^2)]}{2(1 + 2a_o/W)(1 - a_o/W)^{3/2}} \tag{A4.4}$$

and

$$J_{pl} = \frac{2A_{pl}}{B_N b_o} \tag{A4.5}$$

where:

A_{pl} = area A as shown in Fig. A4.1.

For the C(T) specimen at a point corresponding to V_i, P_i on the specimen load versus load-line displacement record as follows:

$$J = \frac{K^2(1-\nu^2)}{E} + J_{pl} \tag{A4.6}$$

where:

$$K = \left[\frac{P}{(BB_N W)^{1/2}}\right] f(a_o/W) \tag{A4.7}$$

for the C(T) specimen:

$$f(a_o/W) = \frac{(2 + a_o/W)(0.886 + 4.64\,(a_o/W) - 13.32\,(a_o/W)^2 + 14.72\,(a_o/W)^3 - 5.6\,(a_o/W)^4)}{(1 - a_o/W)^{3/2}} \tag{A4.8}$$

and for the DC(T) specimen:

$$f(a_o/W) = \frac{(2 + a_o/W)(0.76 + 4.8\,a_o/W - 11.58\,(a_o/W)^2 + 11.43\,(a_o/W)^3 - 4.08\,(a_o/W)^4)}{(1 - a_o/W)^{3/2}} \tag{A4.9}$$

and:

$$J_{pl} = \frac{\eta A_{pl}}{B_N b_o} \tag{A4.10}$$

where:

η = 2 + 0.522 b_o/W.

A_{pl} = Area A as shown in Fig. A4.1.

A4.3.3 Plot J versus Δa as shown in Fig. 5. Determine a construction line in accordance with the following equation:

$$J = 2\sigma_Y \Delta a \tag{A4.11}$$

Plot the construction line, then draw an exclusion line parallel to the construction line intersecting the abscissa at 0.15 mm (0.006 in.). Draw a second exclusion line parallel to the construction line intersecting the abscissa at 1.5 mm (0.06 in.). Plot all J-Δa data points that fall inside the area enclosed by these two parallel lines and capped by $J_{limit} = b_o\sigma_Y/15$. Make sure that data spacing meets the requirements of 9.9.3.

A4.3.4 Plot an offset line parallel to the construction and exclusion lines at an offset value of 0.2 mm (0.008 in.).

A4.3.5 Using a method of least squares determine a linear regression line of the following form:

$$\ln J = \ln C_1 + C_2 \ln(\Delta a/k) \tag{A4.12}$$

where k = 1.0 mm or 0.0394 in. Use only the data which conform to the requirements stated in the previous sections. Plot the regression line as illustrated in Fig. 4.

A4.3.6 The intersection of the regression line of A4.3.5

with the offset line of A4.3.4 defines J_Q and Δa_Q. To determine this intersection the following procedure is recommended.

A4.3.6.1 Estimate an interim $J_{Q(1)}$ value from the data plot.

A4.3.6.2 Evaluate $\Delta a_{(1)}$ from:

$$\Delta a_{(1)} = \frac{J_{Q(1)}}{2\sigma_Y} + 0.2 \text{ mm } (0.008 \text{ in.}) \quad \text{(A4.13)}$$

A4.3.6.3 Evaluate an interim $J_{Q(2)}$ from the following power law relationship:

$$J_{Q(2)} = C_1(\Delta a_{(1)}/k)^{C_2} \quad \text{(A4.15)}$$

where k = 1.0 mm or 0.0394 in.

A4.3.6.4 Return to A4.3.6.2 and A4.3.6.3 to get $\Delta a_{(i+1)}$ and interim $J_{Q(i+2)}$ until the J_Q values converge to within ±2 %.

A4.4 Qualify this J_Q value as J_{Ic} using the applicable requirements of 9.7, (that is, 9.7.1, 9.7.2, 9.7.3, 9.7.4, 9.7.9), and 9.9.

A5. GUIDELINES FOR DIRECT CURRENT ELECTRIC POTENTIAL DETERMINATION OF CRACK SIZE

A5.1 *Applications*—Electric potential (EP) procedures for crack-size determination are applicable to virtually any electrically conducting material in a wide range of testing environments. The d-c EP technique relies on simple calibrations for standard geometries, and can yield a higher density of points to define a *J-R* curve than is typically achievable using elastic compliance procedures. The procedures discussed herein are those for which two-dimensional models can be used both for the specimen configuration and for the electric potential.

A5.2 *Measurement Principles*—Determining crack size from electric potential measurements relies on the principle that the electric field in a cracked sample with a current flowing through it is a function of the sample geometry, and in particular the crack size. For a constant current flow, the electric potential or voltage difference across the crack plane will increase with increasing crack size due to modification of the electrical field and associated perturbation of the current streamlines. The change in voltage can be related to crack size through analytical or experimental calibration relationships.

A5.3 *Basic Method:*

A5.3.1 A constant current is passed through the sample resulting in a two dimensional electric field which is constant through the thickness at all points. The large scale crack tip plasticity associated with fracture of ductile materials can increase the measured electric potential due to resistivity changes without crack extension. These resistivity changes shall be properly accounted for in order to accurately determine crack extension in ductile materials.

A5.3.2 Changes in the sample or instrumentation may result in proportional changes in the measured voltage. For example, a 1°C change in specimen temperature can result in a significant change in the EP signal due to the change in the material's electric resistivity. Also, some materials exhibit time-dependent conductivity changes while at elevated temperatures. Variations in the gain of amplifiers or calibration of voltmeters may also result in a proportional scaling of the measured voltages. To compensate for these effects, voltage measurements can be normalized using additional voltage measurements taken at a reference location. The reference location may be either on the test sample or on an alternate material sample in the same environment. If the reference measurements are made directly on the test sample, the location shall be chosen so that the reference voltage is not affected by crack size. Since all material and instrument variations are also included in the reference measurements,

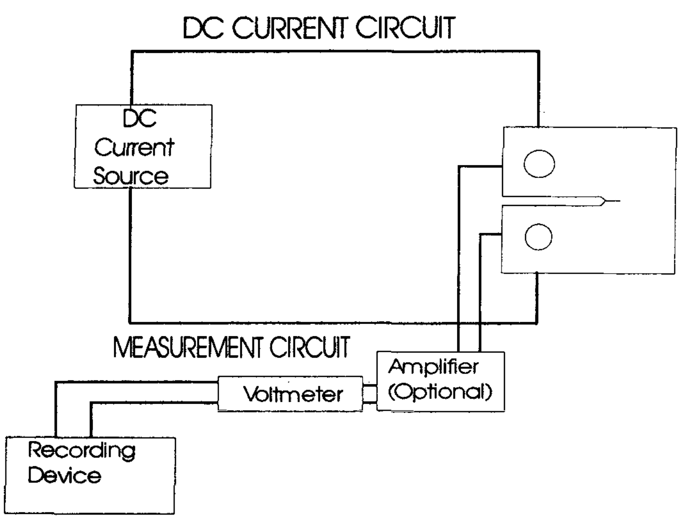


FIG. A5.1 Schematic Diagram of the dc Potential System

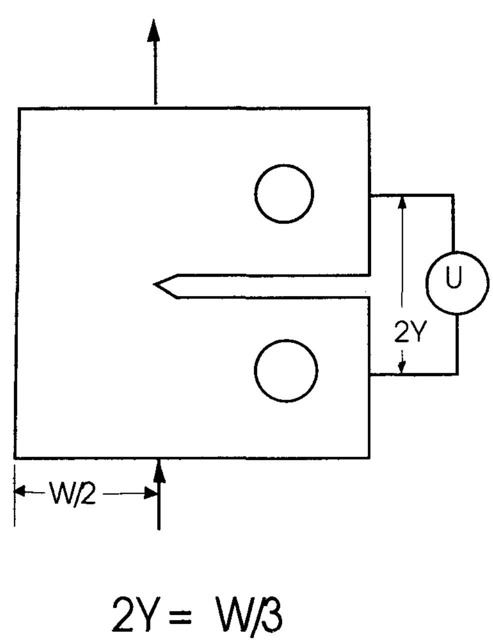


FIG. A5.2 Schematic of C(T) Specimen dc Potential Lead Connections

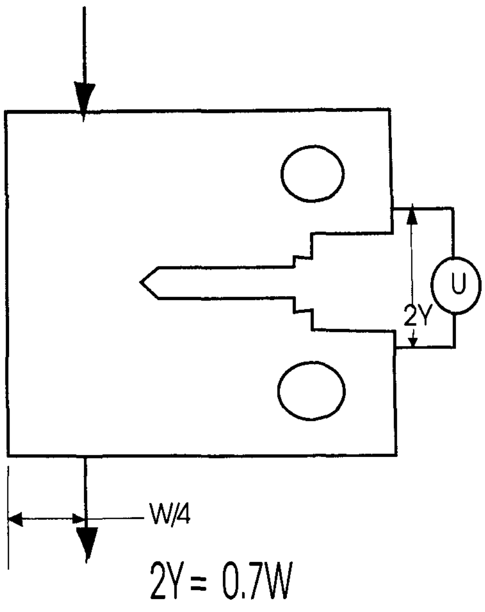


FIG. A5.3 Alternative C(T) Specimen dc Potential Lead Positions

the normalization process should eliminate them. Use of reference voltage measurements can significantly increase crack size resolution for some materials.

A5.3.3 Typical apparatus for the d-c EP technique is shown in Fig. A5.1. The output voltages are typically in the 0.1 to 50.0 mV range for common current magnitudes (5 to 50 *A*), sample dimensions, and materials. Precise measurements (typically ±0.1 %) of these relatively small output voltages shall be made to obtain accurate crack size values. To obtain sufficient voltage resolution usually requires special care in eliminating electrical noise and drift.

A5.3.4 The d-c method is susceptible to thermoelectric effects which produce d-c potentials in addition to those due to the sample electrical field. These thermoelectric voltages can be a substantial fraction of the total measured voltage. Since the thermoelectric effect is present even without the input current, it is possible to account for it by subtracting voltage measurements taken with the current off from the measurements made with the current on. An alternative method corrects for the thermoelectric effect by taking voltage measurements while reversing the direction of current flow. Corrected EP measurements are then equal to one half of the difference of the measured potential readings taken at each current polarity.

A5.4 *Current Generating Equipment*—A constant current shall be maintained by the power supply with sufficient short- and long-term stability. The required stability is a function of the resolution of the voltage measurement equipment (see A5.5) and the desired crack size resolution. For optimum conditions, the relative stability of the power supply should be equal to the effective resolution of the voltage measurement system; that is, if the voltage measurement system can effectively resolve one part in 1000 of the output voltage from the sample (including electric noise, inherent inaccuracies such as nonlinearity, etc.), then the power supply should be stable to one part in 1000.

A5.5 *Voltage Measurement Equipment*—Voltage measurements shall be made with any equipment that has sufficient resolution, accuracy, and stability characteristics. The dc method requires equipment capable of measuring small changes in dc voltage (for example, 0.05 to 0.5 μv) with relatively low dc signal to noise ratios. Although there are a variety of ways to implement the voltage measurement system, three commonly used systems include amplifier/autographic recorder, amplifier/microcomputer analog to digital converter, and digital voltmeter/microcomputer. Autographic recorders are commonly available with suitable sensitivity and can be used to record the output voltage directly from the sample. A preamplifier can be used to boost the direct voltage output from the sample before recording. Another common technique uses a preamplifier to boost the direct output from the sample to a level that can be digitized using a conventional analog to digital converter and microcomputer. A third method makes use of a digital voltmeter with a digital output capability. The advantage of this type of system is that all of the sensitive analog circuits are contained within a single instrument.

A5.6 *Crack Length Versus Electric Potential Relationships:*

A5.6.1 Closed form solutions for the relationship between electric potential versus crack size have been analytically derived for the SE(B) and C(T). These are described in A5.7.

A5.6.2 It is also possible to empirically develop relationships for virtually any type of sample geometry used in *J-R* curve testing. Such empirical relationships can be advantageous in instances when sample geometries are complex, or wire placement has been altered. Analytical or empirical relationships should be experimentally verified using alternative measurements at various crack sizes in the range of interest (optical surface measurements, compliance measurements, or post-test fracture surface measurements). Such measurements should be reported and may be used for correcting crack lengths estimated from closed form equations.

A5.6.3 Voltage wire placements are usually a compromise between good sensitivity to crack size changes and immunity to errors caused by minor variations in lead location from sample to sample. Near crack tip lead locations yield better sensitivity to changes in crack size or to crack initiation. The difficulty with this type of arrangement is that the electrical field is, in general, highly nonuniform in the near tip region. Thus, minor variations in lead placement from one sample to the next may produce significant differences in measured voltage for the same crack size. In most cases those positions which give greatest sensitivity to crack size changes also have the greatest sensitivity to variations in lead wire positioning.

A5.6.4 Current input wire locations also represent a compromise between uniformity and sensitivity. Placement of the current inputs near the crack tip region focuses the current streamlines there resulting in increased sensitivity to crack initiation. Placement of the current leads midway across the remaining ligament tends to provide a more uniform current field for crack growth.

A5.7 *Specimen Geometries:*

A5.7.1 Specimen geometries for J_{IC}/*J-R* curve testing covered in this annex are the compact tension, C(T), and single-edge notched bend, SE(B). The equations listed in the following sections are derived under dc conditions using either closed form or experimental calibrations.

A5.7.2 *C(T) Geometry Voltage Versus Crack Size Relationship:*

A5.7.2.1 A closed form expression that applies approximately for the C(T) geometry is as follows:

$$\frac{a}{W} = \frac{2}{\pi} cos^{-1} \left[\frac{cosh\left(\frac{\pi y}{2W}\right)}{cosh\left[\left(\frac{U}{U_0}\right) cosh^{-1}\left[\frac{cosh\left(\frac{\pi y}{2W}\right)}{cos\left(\frac{\pi a_0}{2W}\right)}\right]\right]} \right] \quad (A5.1)$$

where:

U = electric potential signal,
U_o = initial electric potential signal,
a = crack length,
a_o = initial crack length,
W = specimen width, and
y = $W/6$ (see Fig. A5.2).

A5.7.2.2 An experimental calibration for the *C(T)* specimen has been developed based on data from Ref **(13)** which involved current inputs at the $W/4$ position as shown in Fig. A1.3. A fifth-order polynomial fit to the data over the range from a/W = 0.45 to a/W = 0.8 yields the following expression:

$$\frac{a}{W} = \left[0.2864\left(\frac{U}{U_o} - 0.5\right)\right]^{0.3506} \quad (A5.2)$$

A5.7.3 *SE(B) Geometry Voltage Versus Crack Size Relationship:*

A5.7.3.1 The closed form expression provided in A5.7.2 has been found to apply to SE(B) specimens for the case where the current input leads are at the $W/2$ location as shown in Fig. A5.4.

A5.7.3.2 An experimental calibration developed for the SE(B) specimen has been developed based on data from Ref **(13)** which involved current inputs at the $W/4$ position as shown in Fig. A5.3. A fifth-order polynomial fit to the data over the range from a/W = 0.45 to a/W = 0.8 yields the following expression:

$$\frac{a}{W} = \left[0.4512\left(\frac{U}{U_o} - 0.5\right)\right]^{0.4688} \quad (A5.3)$$

NOTE 7—Regardless of which EP versus crack-size expression is used, the use of a reference probe is encouraged (see A5.3). This reference probe should be located on the test specimen (or another specimen at the identical test conditions) in a region unaffected by crack growth. When employing such a reference probe, the EP measurements made for crack-size determination (U in Eq A5.1, A5.2, and A5.3) are divided by the ratio U_{ref}/U_{ref0}:

where:
U_{ref} = reference probe voltage measured at the same time as the EP crack voltage is measured, and
U_{ref0} = initial reference probe voltage.

A5.8 *Effects of Plasticity on Electric Potential:*

A5.8.1 The analytical/experimental calibrations described in A5.7 do not account for the effects of plasticity on the measured potential. It is therefore necessary to separate changes in the potential due to plasticity from those due to crack extension. Within the requirements of this test method, it is assumed that all of the significant plasticity in the fracture specimen occurs prior to crack initiation. The electric potential signal change prior to the attainment of crack initiation as defined in 9.6 is therefore ignored and the remainder of the EP signal change is used to establish the *J-R* curve. It has been found that a plot of EP versus crack mouth-opening displacement will generally remain linear until the onset of crack extension. Such a plot (Fig. A5.6) can be useful in determining the amount of the electric potential signal to attribute to plasticity versus crack extension.

A5.9 *Determination of Crack Length:*

A5.9.1 Construct a plot of electric potential measured during the test as a function of crack-opening displacement, v, as shown in Fig. A5.6. Determine the best-fit of the equation $U = F \times v + G$ to the data over the range from 0.1 to 0.5 P_{max} using the method of least-squares. Plot the equation, $U = F \times v + 1.05(G)$. The intersection of this line with the data shall define the point v_B, U_B. When using Eq A5.1 to calculate crack length, $U_B = U_o$. If Eq A5.2 or A5.3 is used to calculate the crack length, the value U_o must first be calculated from the following expressions:
for the C(T) specimen using Eq A5.2, calculate U_o from the following equation:

$$U_o = \frac{U_B}{3.4916\left(\frac{a_o}{W}\right)^{2.851} + 0.5} \quad (A5.4)$$

and for the SE(B) specimen using Eq A5.3, calculate U_o from the following equation:

$$U_o = \frac{U_B}{2.216\left(\frac{a_o}{W}\right)^{2.133} + 0.5} \quad (A5.5)$$

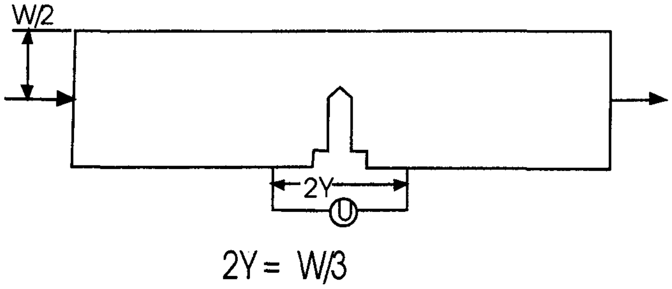


FIG. A5.4 Schematic of SE(B) dc Potential Lead Connections

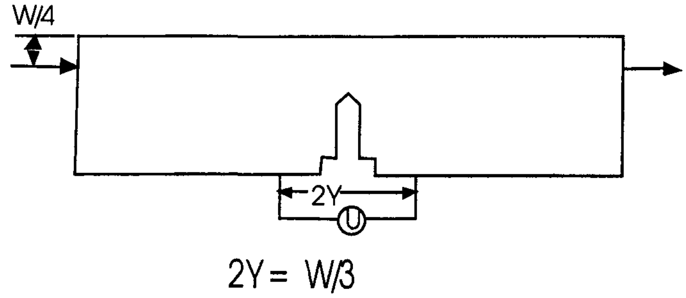


FIG. A5.5 Alternative SE(B) dc Potential Lead Connections

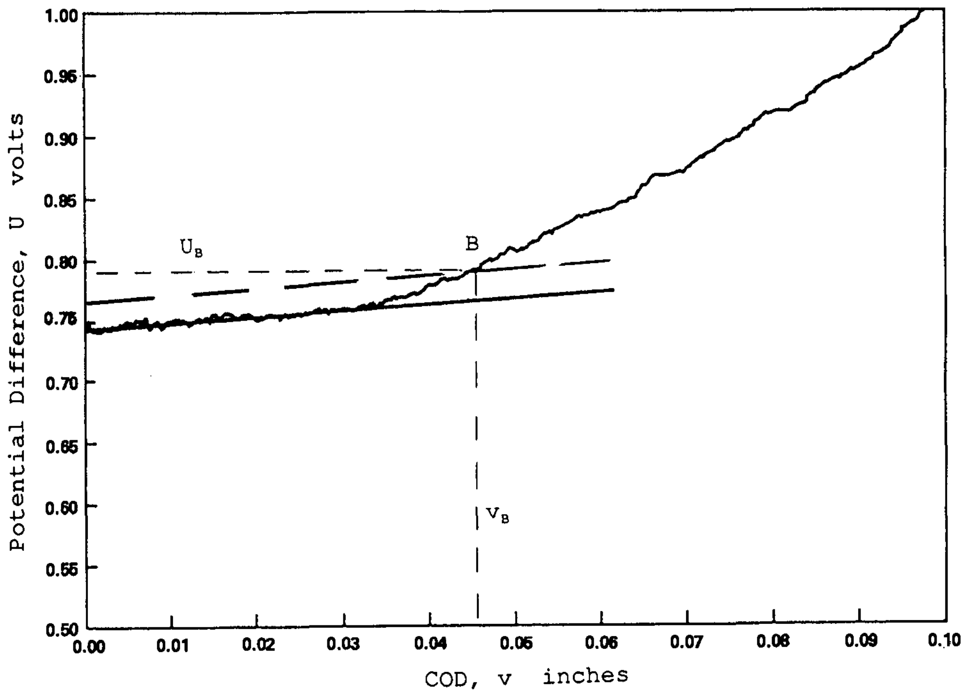


FIG. A5.6 Potential Rise Versus Crack Opening Displacement for a Structural Steel (10)

A5.9.2 For each data point in the test record prior to the intersection Point B defined by $v = v_B$, as shown in A5.9.1, calculate crack extension from the relationship $\Delta a = J/(2\sigma_Y)$. For all data after this point, calculate the crack length from the appropriate equation, for example, A5.1, A5.2, or A5.3, using the value of U_o determined in A5.9.1 and an initial crack length equal to $a_o + \Delta a_B$, where $\Delta a_B = J_B/(2\sigma_Y)$ calculated at Point B.

A5.9.3 The predicted crack length at the end of the test shall be within $0.05\Delta a/W$ of the final physical crack size determined in 8.5.4.

A5.10 *Gripping Considerations*—The electric potential method of crack size determination relies on a current of constant magnitude passing through the sample when the potential voltage is measured. During such potential measurements it is essential that very little of the applied current be shunted in a parallel circuit through the test machine. For most commercially available test machines and grip assemblies the resistance through the test frame is considerably greater than that of the test sample. In some situations an alternative path for the applied current may exist through the test frame. In such cases, additional steps to provide isolation between the specimen and load frame may be necessary. Users of the potential method should ensure that the electric resistance measured between the grips (with no specimen in place) is several orders of magnitude higher than the resistance of the specimen between the current input locations. The specimen resistance should be determined for the range of crack sizes encountered during the test. A resistance ratio (test frame resistance divided by the specimen resistance) of 10^4 or greater is sufficient for most practical applications. Isolation of the specimen from the load frame is particularly important when using power supplies with non-isolated (ground-referenced) outputs. Use of this type of power supply may require isolating both ends of the test specimen from the test frame to avoid ground loop problems.

A5.11 *Wire Selection and Attachment*—Careful selection and attachment of current input and voltage measurement wires can avoid many problems associated with the electric potential method. This is particularly important in elevated temperature environments where the strength, melting point, and oxidation resistance of the wires must be taken into account.

A5.11.1 *Current Input Wires*—Selection of current input wire should be based on current carrying ability, and ease of attachment (weldability, connector compatibility). Wires must be of sufficient gage to carry the required current under test conditions and may be mechanically fastened or welded to the sample or gripping apparatus.

A5.11.2 *Voltage Measurement Wires*—Voltage wires should be as fine as possible to allow precise location on the sample and minimize stress of the wire during loading which could cause detachment. Ideally, the voltage sensing wires should be resistance-welded to the sample to ensure a reliable, consistent joint. Lead wires may be fastened using mechanical fasteners for materials which exhibit poor welding characteristics (for example certain aluminum alloys) provided that the size of the fastener is accounted for when determining location of voltage sensing leads.

A5.12 *Resolution of Electric Potential Systems*—The effective resolution of EP measurements depends on a number of factors including voltmeter resolution or amplifier gain, or both, current magnitude, sample geometry, voltage measurement and current input wire locations, and electric conductivity of the sample material. Here, effective resolution is defined as the smallest change in crack size which can be distinguished in actual test operation, not simply the best resolution of the recording equipment. For common laboratory-sized samples, a direct current in the range from 5 to 50A and voltage resolution of approximately ±0.1 μV or ±0.1 % of U_o will yield a resolution in crack size of better than 0.1 % of the sample width. For highly conductive materials (for example, aluminum, copper) or lower current levels, or both, the resolution would decrease, while for materials with a lower conductivity (that is, titanium, nickel) resolutions of better than 0.01 % of the sample width have been achieved. For a given specimen geometry, material, and instrumentation, crack-size resolution shall be analyzed and reported.

NOTE 8—To illustrate the magnitude of voltages measured on a standard specimen type, 1*T* C(T) samples of 25-mm (1-in.) width, 20 % side-grooved, with an initial *a/W* ratio of 0.65, input current of 60 A at the *W*/4 position, and potential outputs on the front face (Fig. A5.3) produce the following results:

Material	Approximate EP at 60 A
Aluminum (5456)	0.4 mV
Steel (A106)	0.7 mV
Stainless steel (304)	3.0 mV

A5.13 *Techniques to Reduce Voltage Measurement Scatter:*

A5.13.1 Because of the low-level signals which must be measured with the d-c current method, a number of procedures should be followed to improve voltage measurement precision.

A5.13.2 *Induced EMF*—Voltage-measurement lead wires should be as short as possible and should be twisted to reduce stray voltages induced by changing magnetic fields. Holding the wires rigid also helps reduce the stray voltages that can be generated by moving the wires through any static magnetic fields that may exist near the test frame. In addition, routing the voltage measurement leads away from motors, transformers, or other devices which produce strong magnetic fields is recommended.

A5.13.3 *Electrical Grounding*—Proper grounding of all devices (current source, voltmeters, and so forth) should be made, avoiding ground loops.

A5.13.4 *Thermal Effects*—For d-c systems thermal EMF measurement and correction is critically important. A minimum number of connections should be used and maintained at a constant temperature to minimize thermoelectric effects. All measuring devices (amplifiers/preamplifiers, voltmeters, analog-to-digital converters) and the sample itself should be maintained at a constant temperature. Enclosures to ensure constant temperatures throughout the test may prove beneficial. Some voltmeters for d-c systems have built-in automatic correction for internal thermoelectric effects. These units may be of benefit in cases where it is not possible to control the laboratory environment.

A5.13.5 *Selection of Input Current Magnitude*—The choice of current magnitude is an important parameter: too low a value may not produce measurable output voltages; too high a value may cause excessive specimen heating or arcing. To minimize these problems, current densities should be kept to the minimum value which can be used to produce the required crack-size resolution. The maximum current that can be used with a particular sample can be determined by monitoring the sample temperature while increasing the current in steps, allowing sufficient time for the sample to thermally stabilize. Particular care should be exercised when testing in vacuum, as convection currents are not available to help maintain the sample at ambient temperature.

A5.13.6 *D-C Current Stabilization Period*—Allow a sufficient stabilization period after turning the d-c electric potential current either ON or OFF before making a voltage measurement. Most solid-state power sources can stabilize the output current within a period of 1 or 2 s for a step change in output, however this should be verified for each particular sample and experimental setup.

NOTE 9: *Precautions*—Care must be taken to demonstrate that the applied current does not affect crack tip damage processes and crack growth characteristics. Large-scale crack tip plasticity can increase measured electrical potentials due to resistivity increases without crack extension. These changes must be accounted for by methods such as those outlined previously (A5.8) for accurate determinations of crack length from d-c EP.

APPENDIX

(Nonmandatory Information)

X1. RECOMMENDED DATA FITTING TECHNIQUE

X1.1 To fit the equation of 9.2.1 to the RDAT J_i, a_i data using the method of least squares, the following equation must be set up and solved for a_{oq}, B, and C:

$$\begin{Bmatrix} \Sigma a_i - \dfrac{\Sigma J_i}{2\sigma_Y} \\ \Sigma a_i J_i^2 - \dfrac{\Sigma J_i^3}{2\sigma_Y} \\ \Sigma a_i J_i^3 - \dfrac{\Sigma J_i^4}{2\sigma_Y} \end{Bmatrix} = \begin{bmatrix} RDAT & \Sigma J_i^2 & \Sigma J_i^3 \\ \Sigma J_i^2 & \Sigma J_i^4 & \Sigma J_i^5 \\ \Sigma J_i^3 & \Sigma J_i^5 & \Sigma J_i^6 \end{bmatrix} \begin{Bmatrix} a_{oq} \\ B \\ C \end{Bmatrix}$$

X1.2 This equation can be set up and solved using a standard spreadsheet. The Microsoft QuickBASIC program which follows can also be used to accomplish this process.

```
SUB JFIT
'
' SUBROUTINE TO SET UP FUNCTION FOR Aoq EVALUATION
'
' USES EQUATION a = Aoq + J/(2*SFLOW) + B J ^ 2 + C J ^ 3
'
' WRITTEN BY J. A. Joyce USNA, Annapolis, 1993
'
' INPUT IS RDAT% PAIRS OF a AND J IN VECTOR ARRAYS AM! AND
JM!
'
' NEED IN MAIN PROGRAM A COMMON SHARED RDAT%, AM!(),
JM!(),
'   XN!(), FF!(), AN!(), SFLOW!
'
' INITIALIZATION
FOR I% = 1 TO 3
  FOR J% = 1 TO 4
  AN!(I%,J%) = 0.
  NEXT J%
NEXT I%
' DO SUMMATIONS FOR LEAST SQUARES
AN!(1,1) = RDAT%
JISUM! = 0.
FOR I% = 1 TO RDAT%
  JISUM! = JISUM! + JM!(I%)
  AN!(1,2) = AN!(1,2) + JM!(I%) ^ 2
  AN!(2,2) = AN!(2,2) + JM!(I%) ^ 4
  AN!(1,3) = AN!(1,3) + JM!(I%) ^ 3
  AN!(2,3) = AN!(2,3) + JM!(I%) ^ 5
  AN!(3,3) = AN!(3,3) + JM!(I%) ^ 6
  AN!(1,4) = AN!(1,4) + AM!(I%)
  AN!(2,4) = AN!(2,4) + AM!(I%)*JM!(I%) ^ 2
  AN!(3,4) = AN!(3,4) + AM!(I%)*JM!(I%) ^ 3
NEXT I%
AN!(2,1) = AN!(1,2)
AN!(3,1) = AN!(1,3)
AN!(3,2) = AN!(2,3)
AN!(1,4) = AN!(1,4) - JISUM!/(2*SFLOW!)
AN!(2,4) = AN!(2,4) - AN!(1,3)/(2*SFLOW!)
AN!(3,4) = AN!(3,4) - AN!(2,2)/(2*SFLOW!)
' NOW SOLVE THESE EQUATIONS USING GAUSS ELIMINATION
' FOR XN!
CALL GAUSS
PRINT "COEFFICIENTS OF INITIALIZATION ARRAY ARE:"
PRINT XN!(1),.XN!(2), XN!(3)
'
' CHECK THE FIT
FOR I% = 1 TO RDAT%
  FF!(I%) =
XN!(1)+JM!(I%)/(2*SFLOW!)+XN!(2)*JM!(I%) ^ 2+XN!(3)*JM!(I%) ^ 3
'   PRINT JM!(I%), AM!(I%), FF!(I%)
NEXT I%
' CALCULATION OF THE CORRELATION OF THE FIT
YM! = 0.
FOR I% = 1 TO RDAT%
  YM! = YM! + AM!(I%)/RDAT%
NEXT I%
SY2! = 0.
SYX2! = 0.
FOR I% = 1 TO RDAT%
  SY2! = SY2! + (AM!(I%) - YM!) ^ 2/(RDAT%-1)
  SYX2! = SYX2! + (AM!(I%) - FF!(I%)) ^ 2/(RDAT%-2)
NEXT I%
RFIT! = SQR(1.0 - SYX2!/SY2!)
PRINT "CORRELATION OF FIT = ";RFIT!
PRINT #2,"CORRELATION OF FIT = ";RFIT!
END SUB
SUB GAUSS
' INPUT DATA IS IN AN!(3,4) - OUTPUT IS XN!(3)
' SUBROUTINE IN BASIC TO DO A GAUSS ELIMINATION SOLUTION
' SET NOW FOR 3X3 MATRIX
' OUTPUT IS A VECTOR XN
N% = 3
M% = N% + 1
L% = N% - 1
' START REDUCTION TO TRIANGULAR FORM
FOR K% = 1 TO L%
  K1% = K% + 1
  JJ% = K%
  BG! = ABS(AN!(K%,K%))
' REM START OF SEARCH FOR LARGEST PIVOT ELEMENT
FOR I% = K1% TO N%
  AB! = ABS(AN!(I%,K%))
  IF BG! > AB! THEN BG! = AB!: JJ% = I%
NEXT I%
IF JJ% = K% GOTO REDUCE
' INTERCHANGES ROWS TO GET MAX PIVOT ELEMENT
FOR J% = K% TO M%
  TE! = AN!(JJ%,J%)
  AN!(JJ%,J%) = AN!(K%,J%)
  AN!(K%,J%) = TE!
NEXT J%
'
'  DETERMINES REDUCED ELEMENTS OF TRIANGULAR SET
' REDUCE:
FOR I% = K1% TO N%
  Q! = AN!(I%, K%)/AN!(K%, K%)
  FOR J% = K1% TO M%
    AN!(I%, J%) = AN!(I%, J%) - Q!*AN!(K%, J%)
  NEXT J%
NEXT I%
FOR I% = K1% TO N%
  AN!(I%,K%) = 0.
NEXT I%
NEXT K%
' BACK SUBSTITUTION FOR THE SOLUTIONS
XN!(N%) = AN!(N%,M%)/AN!(N%, N%)
FOR NN% = 1 TO L%
  SU! = 0.
  I% = N% - NN%
  I1% = I% + 1
  FOR J% = I1% TO N%
    SU! = SU! + AN!(I%, J%) * XN!(J%)
  NEXT J%
  XN!(I%) = (AN!(I%, M%) - SU!)/AN!(I%,I%)
NEXT NN%
END SUB
```

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Designation: E 1290 – 93

Standard Test Method for Crack-Tip Opening Displacement (CTOD) Fracture Toughness Measurement[1]

This standard is issued under the fixed designation E 1290; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the determination of critical crack-tip opening displacement (CTOD) values at one or more of several crack extension events. These CTOD values can be used as measures of fracture toughness for metallic materials, and are especially appropriate to materials that exhibit a change from ductile to brittle behavior with decreasing temperature. This test method applies specifically to notched specimens sharpened by fatigue cracking. The recommended specimens are three-point bend [SE(B)] or compact [C(T)] specimens. The loading rate is slow and influences of environment (other than temperature) are not covered. The specimens are tested under crosshead or clip gage displacement controlled loading.

1.1.1 The recommended specimen thickness, B, is that of the material in thicknesses intended for an application. Superficial surface machining may be used when desired.

1.1.2 For the recommended three-point bend specimens [SE(B)], width, W, is either equal to, or twice, the specimen thickness, B, depending upon the application of the test. (See 4.3 for applications of the recommended specimens.) For SE(B) specimens the recommended initial normalized crack size is $0.45 \leqq a_o/W \leqq 0.55$. The span-to-width ratio (S/W) is specified as 4.

1.1.3 For the recommended compact specimen [C(T)] the initial normalized crack size is $0.45 \leqq a_o/W \leqq 0.55$. The half-height-to-width ratio (H/W) equals 0.6 and the width to thickness ratio is within the range $2 \leqq W/B \leqq 4$.

1.2 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 4 Practices for Force Verification of Testing Machines[2]

E 8 Test Methods for Tension Testing of Metallic Materials[2]

E 399 Test Method for Plane-Strain Fracture Toughness of Metallic Materials[2]

E 616 Terminology Relating to Fracture Testing[2]

E 813 Test Method for J_{Ic}, A Measure of Fracture Toughness[2]

E 1152 Test Method for Determining J-R Curves[2]

3. Terminology

3.1 Terminology E 616 is applicable to this test method.

3.2 *Definitions:*

3.2.1 *crack tip opening displacement, (CTOD),* $\delta[L]$—the crack displacement due to elastic and plastic deformation at variously defined locations near the original (prior to an application of load) crack tip.

Discussion—In this test method, CTOD is the displacement of the crack surfaces normal to the original (unloaded) crack plane at the tip of the fatigue precrack, a_o.

In CTOD testing, δ_c [L] is the value of CTOD at the onset of unstable brittle crack extension (see 3.2.13) or pop-in (see 3.2.7) when $\Delta a_p < 0.2$ mm (0.008 in.). The load P_c and the clip gage displacement v_c, for δ_c are indicated in Fig. 1.

In CTOD testing, δ_u [L] is the value of CTOD at the onset of unstable brittle crack extension (see 3.2.13) or pop-in (see 3.2.7) when the event is preceded by $\Delta a_p > 0.2$ mm (0.008 in.). The load P_u and the clip gage displacement v_u, for δ_u are indicated in Fig. 1.

In CTOD testing, δ_m [L] is the value of CTOD at the first attainment of a maximum load plateau for fully plastic behavior. The load P_m and the clip gage displacement v_m, for δ_m are indicated in Fig. 1.

3.2.2 *effective yield strength,* σ_Y $[FL^{-2}]$—an assumed value of uniaxial yield strength that represents the influence of plastic yielding upon fracture test parameters.

Discussion—The calculation of σ_Y is the average of the 0.2 % offset yield strength (σ_{YS}), and the ultimate tensile strength (σ_{TS}), that is $(\sigma_{YS} + \sigma_{TS})/2$. Both σ_{YS} and σ_{TS} are determined in accordance with Test Methods E 8.

3.2.3 *original crack size,* a_o $[L]$—see Terminology E 616.

3.2.4 *original uncracked ligament,* b_o $[L]$—the distance from the original crack front to the back surface of the specimen at the start of testing, $b_o = W - a_o$.

3.2.5 *physical crack extension,* Δa_p $[L]$—an increase in physical crack size, $\Delta a_p = a_p - a_o$.

3.2.6 *physical crack size,* a_p $[L]$—see Terminology E 616.

Discussion—In CTOD testing, $a_p = a_o + \Delta a_p$.

3.2.7 *pop-in*—a discontinuity in the load versus clip gage displacement record. The record of a pop-in shows a sudden increase in displacement and, generally, a decrease in load. Subsequently, the displacement and load increase to above their respective values at pop-in.

3.2.8 *slow stable crack extension* $[L]$—a displacement controlled crack extension beyond the stretch zone width (see 3.2.12). The extension stops when the applied displacement is held constant.

3.2.9 *specimen span,* S $[L]$—the distance between spec-

[1] This test method is under the jurisdiction of ASTM Committee E-8 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.08 on Elastic-Plastic Fracture Mechanics Technology.

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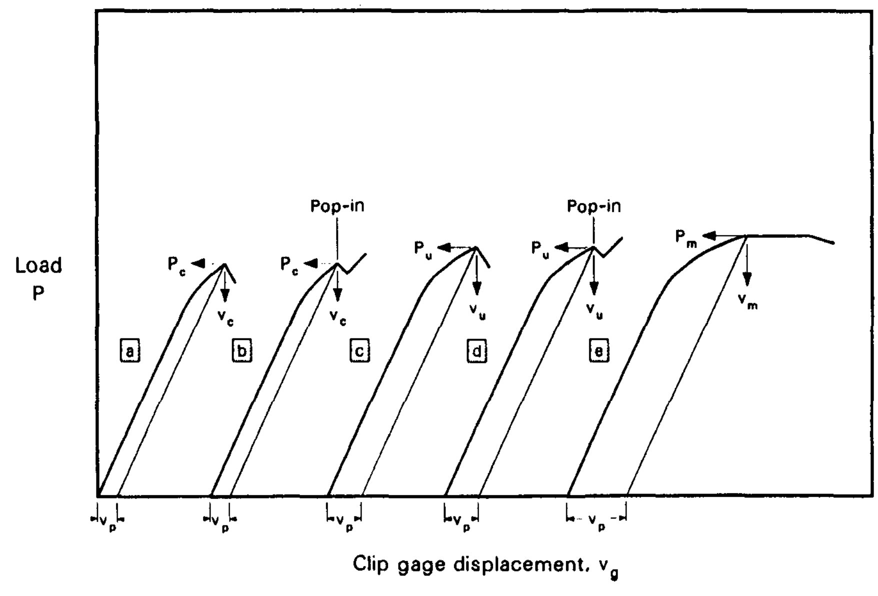
[2] *Annual Book of ASTM Standards*, Vol 03.01.



NOTE 1—Construction lines drawn parallel to the elastic loading slope to give v_p, the plastic component of total displacement, v_g.
NOTE 2—In curves b and d, the behavior after pop-in is a function of machine/specimen compliance, instrument response, etc.

FIG. 1 Types of Load Versus Clip Gage Displacement Records

imen supports in a bend specimen.

3.2.10 *specimen thickness, B*[*L*]—see Terminology E 616.

3.2.11 *specimen width, W* [*L*]—see Terminology E 616.

3.2.12 *stretch zone width, SZW* [*L*]—the length of crack extension that occurs during crack-tip blunting, for example, prior to the onset of unstable brittle crack extension, pop-in, or slow stable crack extension. The SZW is in the same plane as the original (unloaded) fatigue precrack and refers to an extension beyond the original crack size.

3.2.13 *unstable brittle crack extension* [*L*]—an abrupt crack extension that occurs with or without prior stable crack extension in a standard test specimen under crosshead or clip gage displacement control.

4. Summary of Test Method

4.1 The objective of the test is to determine the value of CTOD at one or more of several crack extension events. The values of CTOD may correspond to: δ_c, the onset of unstable brittle crack extension with no significant prior slow stable crack extension (see 3.2.1); δ_u, the onset of unstable brittle crack extension following prior slow stable crack extension; δ_m, at the first attainment of a maximum load plateau for fully plastic behavior.

4.2 The test method involves crosshead or clip gage displacement controlled three-point bend loading or pin loading of fatigue precracked specimens. Load versus clip gage crack opening displacement is recorded, for example, Fig. 1. The loads and displacements corresponding to the specific events in the crack initiation and extension process are used to determine the corresponding CTOD values. For values of δ_c, δ_u and δ_m, the corresponding load and clip gage displacements are obtained directly from the test records.

4.3 The rectangular section bend specimen and the compact specimen are intended to maximize constraint and these are generally recommended for those through-thickness crack types and orientations for which such geometries are feasible. For the evaluation of surface cracks in structural applications for example, orientations T-S or L-S (Terminology E 616), the square section bend specimen is recommended. Also for certain situations in curved geometry source material or welded joints, the square section bend specimen may be preferred. Square section bend specimens may be necessary in order to sample an acceptable volume of a discrete microstructure.

5. Significance and Use

5.1 The CTOD values determined by this test method may be used to characterize the toughness of materials that: (*a*) are too ductile or lack sufficient size to be tested for K_{Ic} in accordance with the requirements of Test Method E 399, or (*b*) show a propensity for unstable crack extension that would invalidate tests in accordance with the requirements of Test Method E 813.

5.2 The different values of CTOD determined by this test method characterize the resistance of a material to crack initiation and early crack extension at a given temperature.

5.3 The values of CTOD may be affected by specimen dimensions. It has been shown that values of CTOD determined on SE(B) specimens using the square section geometry may not be the same as those using the rectangular section geometry, and may differ from those obtained with C(T) specimens (see 4.3).

5.4 The values of CTOD determined by this test method may serve the following purposes:

5.4.1 In research and development, CTOD testing can show the effects of certain parameters on the fracture toughness of metallic materials significant to service performance. These parameters include material composition, thermo-mechanical processing, welding, and thermal stress relief.

5.4.2 For specifications of acceptance and manufacturing quality control of base materials, weld metals, and weld heat affected zones.

5.4.3 For inspection and flaw assessment criteria, when used in conjunction with fracture mechanics analyses.

6. Apparatus

6.1 This procedure involves measurement of applied load, *P*, and clip gage crack opening displacement, *v*. Load versus displacement is autographically recorded on an *x-y* plotter for visual display, or converted to digital form for accumulation in a computer information storage facility and subsequent processing. Testing is performed under crosshead or clip gage displacement control in a compression or tension testing machine, or both, that conforms to the requirements of Practices E 4.

6.2 *Fixturing for Three-Point Bend Specimens*—A recommended SE(B) specimen fixture is shown in Fig. 2. Friction effects between the support rollers and specimen are reduced by allowing the rollers to rotate during the test. The use of high hardness steel of the order of 40 HRC or more is recommended for the fixture and rollers to prevent indentation of the platen surfaces.

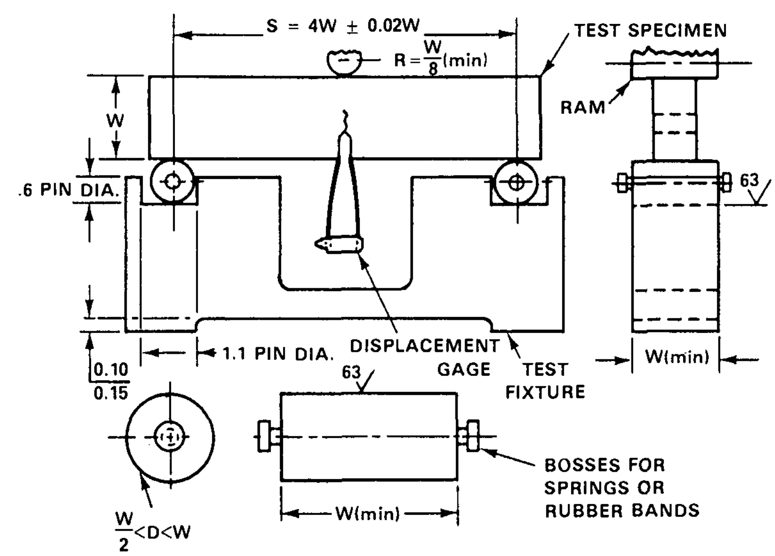
6.3 *Tension Testing Clevis*—A loading clevis suitable for testing C(T) specimens is shown in Fig. 3. Each leg of the specimen is held by such a clevis and loaded through pins, in order to allow rotation of the specimen during testing. To provide rolling contact between the loading pins and the clevis holes, these holes are produced with small flats on the loading surfaces. Other clevis designs may be used if it can be demonstrated that they will accomplish the same result as the design shown. Clevises and pins should be fabricated from steels of sufficient strength and hardness (greater than 40 HRC) to elastically resist indentation loads. The critical tolerances and suggested proportions of the clevis and pins are given in Fig. 3. These proportions are based on specimens having $W/B = 2$ for $B > 12.7$ mm (0.5 in.) and $W/B = 4$ for $B \leqq 12.7$ mm (0.5 in.). If a 1930 MPa (280 000 psi) yield strength maraging steel is used for the clevis and pins, adequate strength will be obtained. If lower strength grip material is used, or if substantially larger specimens are required at a given σ_{YS}/E ratio, then heavier grips will be required. As indicated in Fig. 3, the clevis corners may be cut off sufficiently to accommodate seating of the clip gage in specimens less than 9.5 mm (0.375 in.) thick. Attention should be given to achieving good alignment through careful machining of all auxiliary gripping fixtures.

6.4 *Displacement Measuring Devices:*

6.4.1 Displacement measuring gages are used to measure opening displacements on SE(B) specimens at either knife edges a distance *z* beyond the crack mouth, Fig. 4a, or at the crack mouth ($z = 0$) in the case of integral knife edges, Fig. 4b. For C(T) specimens, where the opening displacement is not measured on the load line, the difference between the load line and the displacement measuring point shall constitute the dimension *z* (see 9.2). Alternatively, when the opening displacements on C(T) specimens are made on or within $\pm 0.002\ W$ of the load line, it may be assumed that $z = 0$.

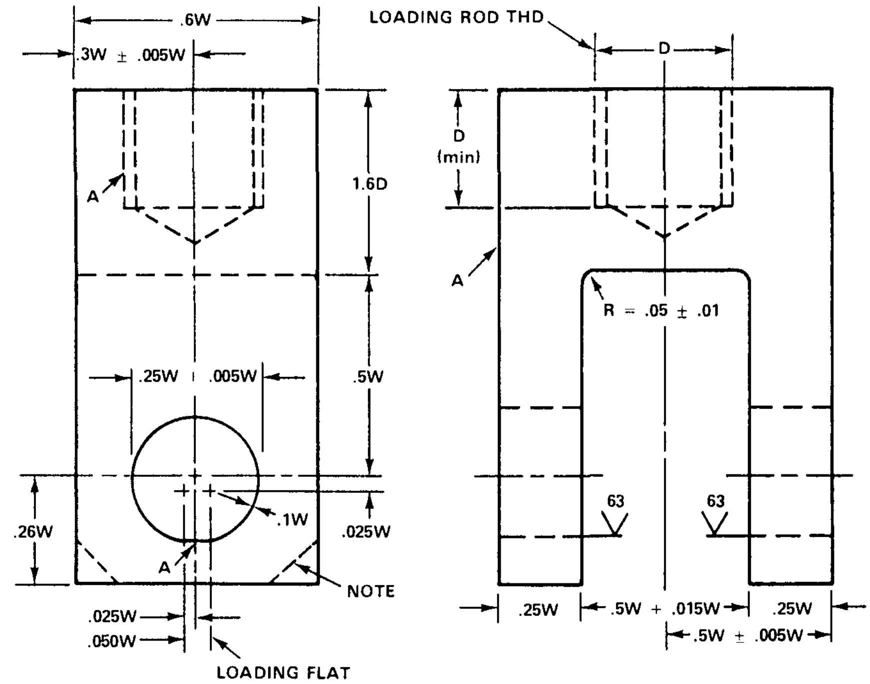
6.4.2 The clip gage recommended in Test Method E 399 may be used in cases where the total expected displacement is 2.5 mm (0.1 in.) or less. Sensitivity and linearity requirements specified in Test Method E 399, shall be met over the full working range of the gage. In addition, the gage is to be calibrated to within ±1 % of the working range.

6.4.3 For cases where a linear working range of up to 8 mm (0.3 in.) or more is needed, an enlarged gage such as that shown in Fig. 5 can be used. Both linearity and accuracy of



NOTE 1—Roller pins and specimen contact surface of loading ram must be parallel to each other within 0.002W.
NOTE 2— 0.10 in. = 2.54 mm; 0.15 in. = 3.81 mm.

FIG. 2 SE(B) Test Fixture Design



A — SURFACES MUST BE FLAT, IN-LINE & PERPENDICULAR, AS APPLICABLE TO WITHIN 0.002 IN T.I.R. (.05 mm)

NOTE—Corners of the clevis may be removed as necessary to accommodate the clip gage.

FIG. 3 Clevis for C(T) Specimen Testing

the equipment or system used shall be demonstrated to be within ±1 % of the working range of the equipment.

6.4.4 The seating between the clip gage and knife edges shall be firm and free from friction drag.

6.5 *Load Measurement*—The sensitivity of the load sensing device shall be sufficient to avoid distortion caused by over amplification and the device shall have a linearity identical to that for the displacement signal. The combination of force sensing device and recording system shall permit the force P to be determined from the test record within an accuracy of ±1 %.

7. Specimen Configurations, Dimensions, and Preparation

7.1 The SE(B) specimens, shown in Figs. 6 and 7, are tested with a span to width ratio, S/W, of 4. Therefore, it is suggested that overall specimen length should be at least 4.5 W.

7.1.1 The standard bend specimens shall be of thickness, B, at least equal to that employed in the specific structural application of interest, or the original product form thickness. The specimen should be one of the types shown in Figs. 6 and 7.

7.1.2 The recommended original crack size, a_o, of the SE(B) specimen shall be within the range 0.45 $W \leqq a_o \leqq 0.55$ W.

7.1.3 In order to machine fatigue crack-starter notches to depths greater than 2.5 mm (0.1 in.), a stepped width notch is an allowed exception. This is acceptable, provided that: (a) the stepped width notch falls completely within the envelope shown in Fig. 8, and, (b) the length of the fatigue precrack extension from the machined notch tip satisfies the requirement of 7.3.2. Separate or integral knife edges for accommodating clip gages are shown in Fig. 4.

7.2 The recommended C(T) specimen designs are shown in Fig. 9. These are similar to the configurations recommended in Test Methods E 813 and E 1152. The designs are suitable for use with flat bottom clevises of Test Method E 399 design (see Fig. 3). A cut-out section on the front face provides room to attach razor blade edges on the load line of the specimen. The sharp edges of the blades shall be square with respect to specimen surfaces and parallel within 0.5°. A specially prepared spacer block can be used to achieve these requirements.

7.2.1 The C(T) specimen shall be of thickness, B, at least equal to that employed in the specific structural application of interest, or the original product form thickness.

7.2.2 The C(T) specimen half-height to width ratio H/W is 0.6, and the width W to thickness B ratio shall be within the range $2 \leqq W/B \leqq 4$.

7.2.3 The original crack length, a_o, of the compact specimen shall be within the range 0.45 $W \leqq a_o \leqq 0.55$ W.

7.3 *Fatigue Precracking:*

7.3.1 All specimens shall be precracked in fatigue at load values no greater than the load P_f calculated in accordance with the following equations.

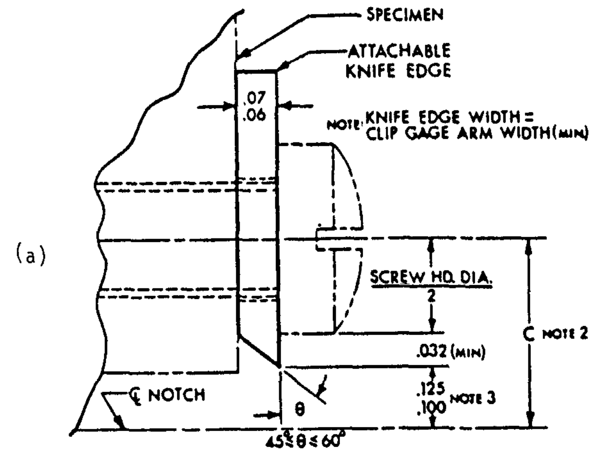
For SE(B) specimens use:

$$P_f = 0.5(Bb_o^2\sigma_Y/S)$$

For C(T) specimens use:

$$P_f = 0.4\ Bb_o^2\sigma_Y/(2W + a_o)$$

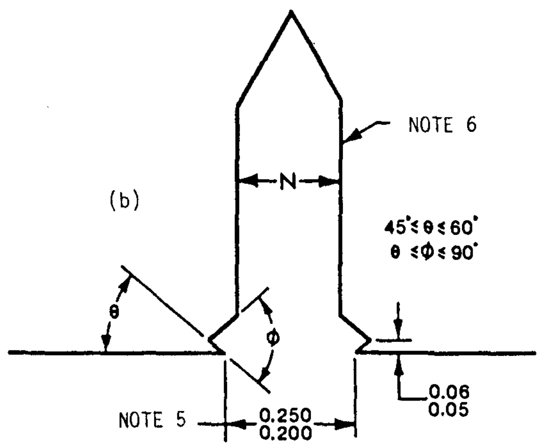
7.3.2 The length of the fatigue precrack extension from



NOTE 1—Dimensions are in inches.
NOTE 2—Effective gage length = 2C + Screw Thread Diameter ≤ $W/2$. (This will always be greater than the gage length specified in Test Method E 399, A1.1.)
NOTE 3—Dimension shown corresponds to clip gage spacer block dimension in Test Method E 399, Annex A1.

Metric Equivalents

in.	0.032	0.06	0.07	0.100	0.125
mm	0.81	1.5	1.8	2.54	3.18

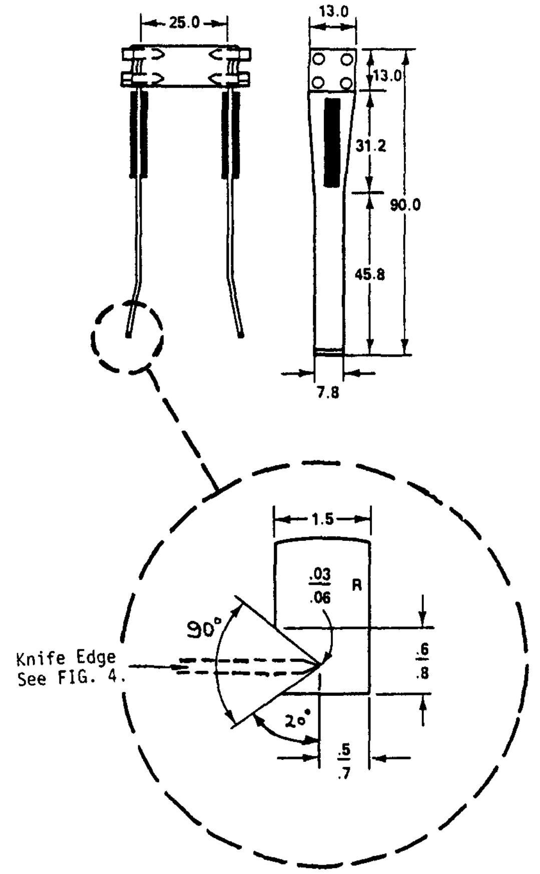


NOTE 4—Dimensions in inches.
NOTE 5—Gage length shown corresponds to clip gage spacer block dimensions shown in Test Method E 399, Annex A1, but other gage lengths may be used provided they are appropriate to the specimen.
NOTE 6—For starter notch configurations see Fig. 8.

Metric Equivalents

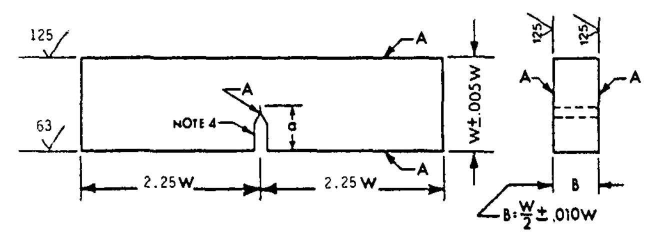
in.	0.050	0.060	0.200	0.250
mm	1.3	1.5	5.1	6.4

FIG. 4 Knife Edges for Location of Clip Gages



NOTE—All dimensions in mm.

FIG. 5 Clip Gage Design for 8 mm (0.3 in.) and More Working Range (See 6.4.3.)

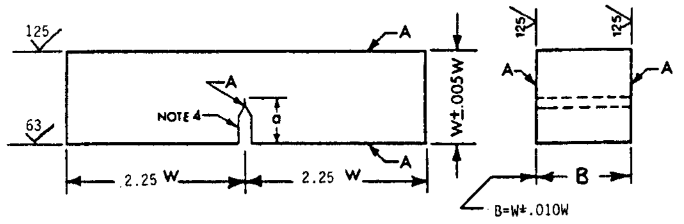


NOTE 1—A surfaces shall be perpendicular and parallel as applicable within 0.001 W TIR.
NOTE 2—Crack starter notch shall be perpendicular to specimen surfaces to within ±2°.
NOTE 3—Integral or attachable knife edges for clip gage attachment may be used (see Fig. 4).
NOTE 4—For starter notch and fatigue crack configurations see Fig. 8.

FIG. 6 Proportional Dimensions and Tolerances for Rectangular Section SE(B) Specimens

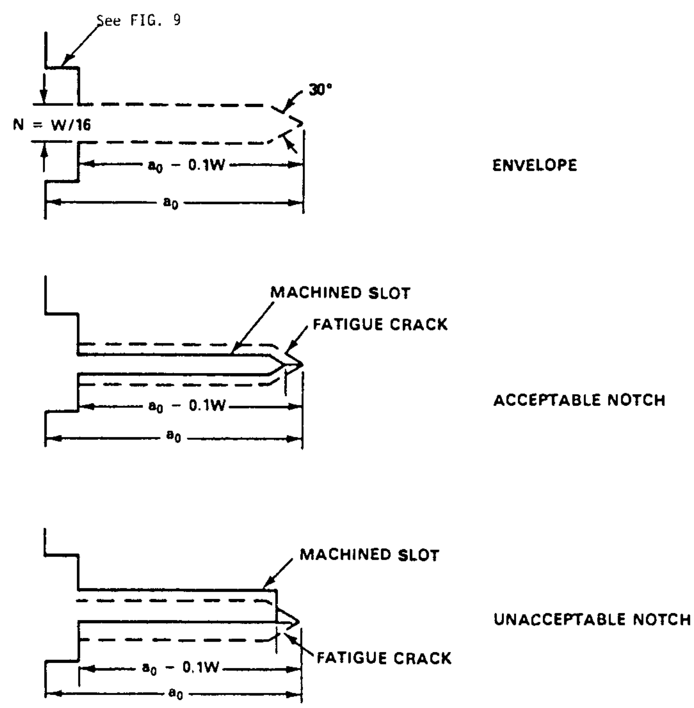
the machined notch shall not be less than 5 % of the total crack length, a_o, and not less than 1.3 mm (0.05 in.). For the final 50 % of fatigue precrack extension or 1.3 mm (0.05 in.), whichever is less, the maximum load shall be no larger than: (a) P_f, or, (b) a load such that the ratio of stress intensity factor range to Young's modulus ($\Delta K/E$) is equal to or less than 0.005 mm$^{1/2}$ (0.001 in.$^{1/2}$), whichever is less. The accuracy of these maximum load values shall be known within ±5 %. The ratio of minimum precracking load to maximum precracking load shall not exceed 0.10. The stress intensity range ΔK may be calculated using the formulae in 9.2.

7.3.3 Normally, the fatigue precracking should be done at room temperature with the material in the condition (metallurgical and thermal-mechanical processing) in which it will be tested. Intermediate treatments between fatigue precracking and testing are only allowed when such treatments



NOTE 1—*A* surfaces shall be perpendicular and parallel as applicable within 0.001 *W* TIR.
NOTE 2—Crack starter notch shall be perpendicular to specimen surfaces to within ±2°.
NOTE 3—Integral or attachable knife edges for clip gage attachment may be used (see Fig. 4).
NOTE 4—For starter notch and fatigue crack configurations see Fig. 8.

FIG. 7 Proportional Dimensions and Tolerances for Square Section SE(B) Specimens



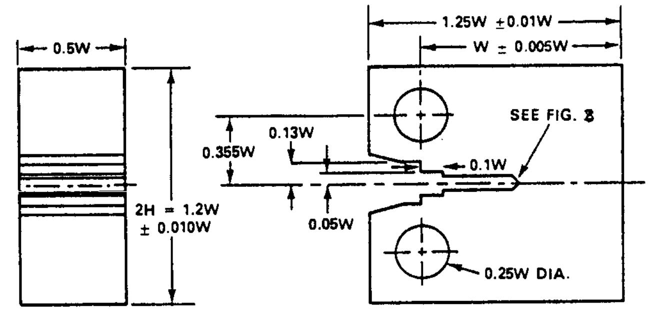
NOTE 1—*N* must not exceed *W*/16.
NOTE 2—The intersection of the crack starter surfaces with the two specimen faces shall be equidistant from the top and bottom edges of the specimen within 0.005 *W*.

FIG. 8 Envelope of Crack-Starter Notches

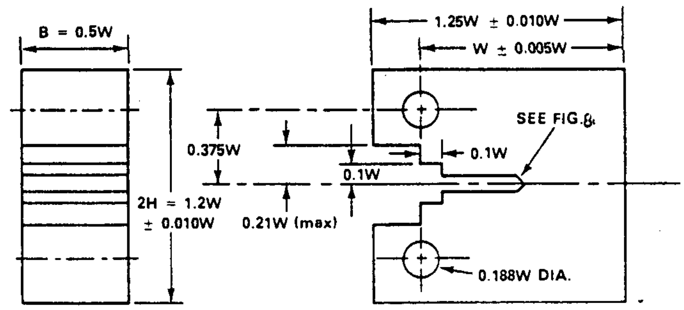
are used to simulate a specific structural application of interest.

7.3.4 To promote early fatigue crack initiation, and promote planar crack growth, a notch tip radius of 0.08 mm (0.003 in.) or less should be used. Additionally, there may be an advantage in using a Chevron notch (see appropriate figure in Test Method E 399), or by statically preloading the specimen. In the latter case, the specimen is loaded in such a way that the straight-through notch tip is compressed in a direction normal to the intended crack plane, but without allowing the applied load to exceed P_f.

7.3.5 The fatigue crack shall fall within the limiting envelope as shown in Fig. 8.



C(T) Specimen for pin of 0.24*W* (+0.000 *W*/−0.005*W*) diameter



C(T) Specimen for pin of 0.1875*W* (+0.000*W*/−0.001*W*) diameter

FIG. 9 Alternative C(T) Specimen Designs

8. Procedure

8.1 The objective of the procedure described herein is to identify the critical CTOD values that can be used as measures of the fracture toughness of materials. These values are derived from measurements of load and clip gage displacement, as described in Section 9.

8.2 After completion of the test, proceed as follows:

8.2.1 Heat tint or fatigue crack the specimen to mark the amount of slow stable crack extension. If fatigue crack marking is used, this should be done using a maximum cyclic load less than the previously applied monotonic load with the minimum cyclic load equal to 70 % of the maximum cyclic load. The maximum cyclic load should be of sufficient magnitude to prevent damage to the fracture surfaces by crack closure.

8.2.2 Break the specimen open to expose the crack, taking care to minimize additional deformation. Cooling ferritic steels enough to ensure brittle behavior may be helpful.

8.2.3 Measure the original crack length, a_o, and physical crack length after slow stable crack extension, a_p, in accordance with 8.9.4.

8.3 *Testing Rate*—Load the specimen such that the rate of increase of stress intensity factor to the load P_f is within the range from 0.55 to 2.75 MPa m$^{1/2}$/s (30 000 to 150 000 psi in.$^{1/2}$/min). Carry out the test under either crosshead or clip gage displacement control (see 6.1 and 10.1.4).

8.4 *Specimen Test Temperature*—Control the specimen test temperature to an accuracy of ±2°C (±3°F). It is recommended that tests be made in situ in suitable low or high temperature media, as appropriate. In a liquid medium, hold the specimen at least 30 s/mm (12 min/in.) after the specimen surface has reached the test temperature and prior to testing. When using a gaseous medium, use a soaking time significantly longer than 30 s/mm (12 min/in.) of thickness. The determination of an appropriate soaking time in a gaseous medium shall be the responsibility of those conducting the test.

8.5 *SE(B) Testing*—Install the bend fixture so that the line of action of the applied load passes mid-way between the support roller centers within 0.5 % of the distance between these centers. Position the specimens with the notch centerline mid-way between the rollers to within 0.5 % of the span, and position square to the roller axes within 2°.

8.6 *C(T) Testing*—To minimize errors from loading pin friction and eccentricity of loading from misalignment, the axes of the loading rods should be kept coincident within 0.8 mm (0.03 in.) during the test. Center the specimen with respect to the clevis opening within 0.8 mm (0.03 in.).

8.7 *Clip Gage Seating*—Seat the displacement gage in the knife or razor edges firmly, by lightly rocking the gage.

8.8 *Recording:*

8.8.1 The test records shall consist of autographic plots or digital records, or both, of the output of the load sensing device versus the output from the clip gage.

8.8.2 *Test Record*—The linear elastic portion of the load versus deflection test record shall exhibit a slope between 0.7 and 1.5. Maximum load can be estimated from 2.5 P_f, where P_f is as specified for SE(B) and C(T) specimens in 7.3.1.

8.9 *Measurements*—All specimen dimensions shall be within the tolerances shown in Figs. 6, 7, and 9.

8.9.1 *Thickness*—Measure the specimen thickness, B, before testing, accurate to the nearest 0.05 mm (0.002 in.) or 0.5 %B, whichever is larger, at three locations along the uncracked ligament of the specimen. Record the average B.

8.9.2 *SE(B) Specimen Width*—Prior to testing, measure the width, W, adjacent to the notch on both sides accurate to the nearest 0.05 mm (0.002 in.) or 0.1 %W, whichever is larger. Record average W.

8.9.3 *C(T) Specimen Width*—Prior to testing, measure the width, W, from the load line to the back edge of the specimen on both sides of the notch, accurate to the nearest 0.05 mm (0.002 in.) or 0.1 %W, whichever is larger. Record average W.

8.9.4 *Crack Length*—After completion of the test (and, if necessary, breaking open the specimen after heating tinting or fatigue cracking in accordance with 8.2), examine the fracture surface. Along the front of the fatigue crack, and along the front of any slow stable crack extension, including the SZW, measure the crack length at nine equally spaced points across the specimen thickness, centered about the specimen centerline and extending to 0.005W from the specimen surfaces. Calculate the original (fatigue) crack length, a_o, and the final physical crack length, a_p (which includes the tear length and SZW), as follows: average the two near-surface measurements, add this result to the remaining seven crack length measurements, and average this total length by dividing by eight (see 9.4 for crack geometry validity criteria). The individual crack length measurements should be accurate to within the nearest 0.03 mm (0.001 in.).

9. Analysis of Experimental Data

9.1 *Assessment of Load/Clip Gage Displacement Records*—The applied load-displacement record obtained from a fracture test on a notched specimen will usually be one of the five types shown in Fig. 1.

9.1.1 In the case of a smooth continuous record in which the applied load rises with increasing displacement up to the onset of unstable brittle crack extension or pop-in, and where no significant slow stable crack growth has occurred (see 3.2 and Figs. 1a and 1b), the critical CTOD, δ_c shall be determined from the load and plastic component of clip gage displacement, v_p, corresponding to the points P_c and v_c. If failure occurs close to the linear range, apply the procedure of Test Method E 399 to test whether a valid K_{Ic} measurement can be made.

9.1.2 In the event that significant slow stable crack extension (see 3.2) precedes either unstable brittle crack extension or pop-in, or a maximum load plateau occurs, the load-displacement curves will be of the types shown in Figs. 1c, 1d, and 1e, respectively. These figures illustrate the values of v and P to be used in the calculation of δ_u or δ_m, whichever is appropriate.

9.1.3 If the pop-in is attributed to an arrested unstable brittle crack extension in the plane of the fatigue precrack, the result must be considered as a characteristic of the material tested.

NOTE 1—Splits and delaminations can result in pop-ins with no arrested brittle crack extension in the plane of the fatigue precrack.

For this method, such pop-in crack extension can be assessed by a specific change in compliance, and also a post-test examination of the specimen fracture surfaces. When the post-test examination shows that the maximum pop-in crack extension has exceeded 0.04 b_o, calculate values of δ_c or δ_u corresponding to the loads P_c or P_u and displacements of v_c or v_u, respectively (for example, point B in Fig. 10a), in accordance with 9.2. When the post-test examination of the fracture surface shows no clear evidence that the maximum pop-in crack extension has exceeded 0.04 b_o, the following procedure may be used to assess the significance of small pop-ins (see 3.2 and Figs. 1b and 1d). Referring to Fig. 10:

9.1.3.1 Draw the tangent OA and a parallel line BC through the maximum load point associated with the particular pop-in under consideration.

9.1.3.2 Draw the line BD parallel to the load axis.

9.1.3.3 Mark the point E at 0.95BD.

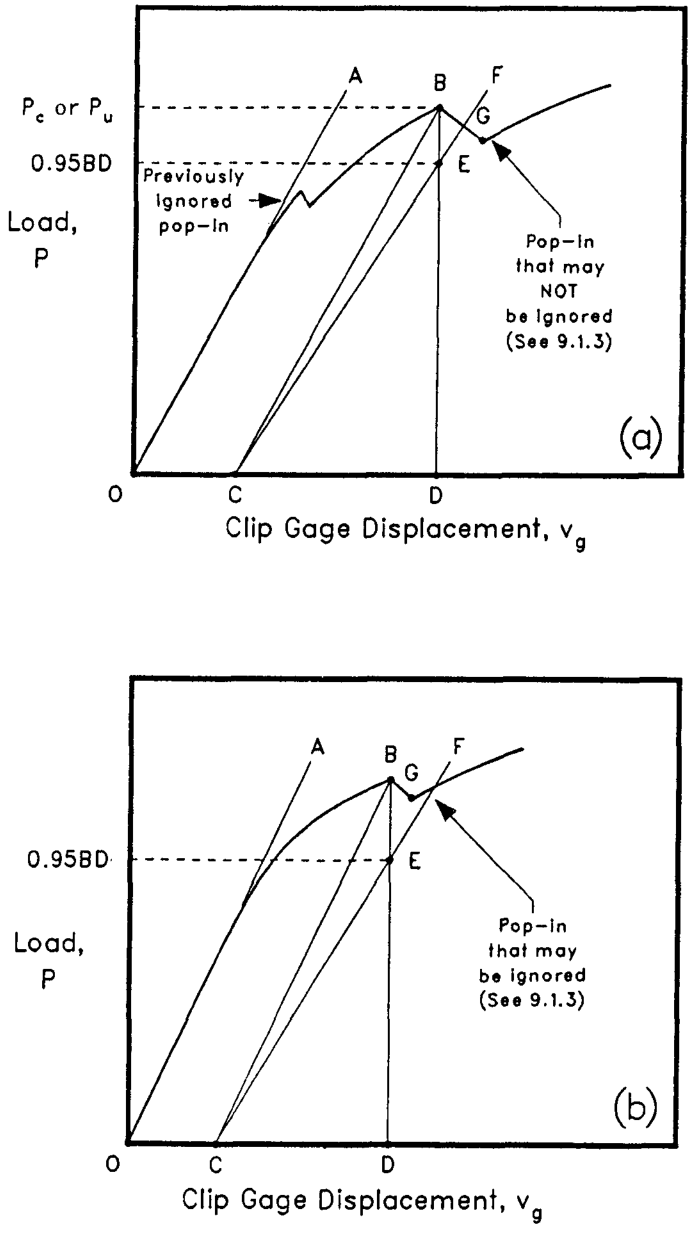
9.1.3.4 Draw the line CEF.

9.1.3.5 Mark the point G corresponding to the load and displacement at pop-in crack arrest.

9.1.3.6 When the point G is outside the angle BCF, calculate values of δ_c or δ_u corresponding to the loads P_c or P_u and displacements v_c or v_u, respectively (for example, point B in Fig. 10a), in accordance with 9.2.

9.1.3.7 When the point G is within the angle BCF, the pop-in may be ignored (Fig. 10b).

NOTE 2—Although an individual pop-in may be ignored on the basis of these criteria, this does not necessarily mean that the lower bound of fracture toughness has been measured. For instance, in an inhomogeneous material such as a weld, a small pop-in may be recorded because of fortuitous positioning of the fatigue precrack tip. Thus, a



NOTE—Slope of line CF is exaggerated for clarity.

FIG. 10 Significance of Pop-In

slightly different fatigue precrack position may give a larger pop-in, which could not be ignored. In such circumstances the specimens should be sectioned after testing, and examined metallographically to ensure that the crack tips have sampled the weld or base metal region of interest (see Ref. (**1**)).[3]

9.2 *Methods for Calculation of* δ_c, δ_u, *or* δ_m—Having obtained the required value of the clip gage displacement, it is necessary to convert this to the relevant CTOD using the following relationship for SE(B) specimens and C(T) specimens having $0.45 \leqq a_o/W \leqq 0.55$ (see 1.1.2 and 7.1.2). To calculate δ_c, δ_u or δ_m:

$$\delta = K^2(1 - \nu^2)/2\sigma_{YS}E + r_p(W - a_o)v_p/[r_p(W - a_o) + a_o + z]$$

where:

$K = YP/[BW^{1/2}]$, and

Y is determined as follows:

(a) SE(B) Specimen having $S = 4W$:

$$Y = \frac{6(a_o/W)^{1/2}(1.99 - a_o/W[1 - a_o/W] \cdot [2.15 - 3.93a_o/W + 2.7(a_o/W)^2])}{(1 + 2a_o/W)(1 - a_o/W)^{3/2}}$$

(b) C(T) Specimen:

$$Y = \frac{(2 + a_o/W)(0.886 + 4.64a_o/W - 13.32(a_o/W)^2 + 14.72(a_o/W)^3 - 5.6(a_o/W)^4)}{(1 - a_o/W)^{3/2}}$$

Values of Y for the SE(B) and C(T) specimens are summarized in Tables 1 and 2, respectively.

P = load corresponding to P_c, P_u or P_m. See Fig. 1,

ν = Poisson's ratio,

σ_{YS} = yield or 0.2 % offset yield strength at the temperature of interest,

E = Young's modulus at the temperature of interest,

v_p = plastic component of clip gage opening displacement corresponding to v_c, v_u or v_m. See Fig. 1,

z = distance of knife edge measurement point from front face (notched surface) on SE(B) specimen, or from load line in C(T) specimen (see 6.4.1), and

r_p = plastic rotation factor = 0.4 $(1 + \alpha)$.

(c) for SE(B) specimen:

$\alpha = 0.1$, and

$r_p = 0.44$.

(d) for C(T) specimens:

$$\alpha = 2\sqrt{[(a_o/b_o)^2 + a_o/b_o + 1/2]} - 2(a_o/b_o + 1/2)$$

and

$$r_p = 0.47 \text{ for } 0.45 \leqq a_o/W \leqq 0.50, \text{ or}$$

$$r_p = 0.46 \text{ for } 0.50 < a_o/W \leqq 0.55$$

9.3 *Discontinued Test*—If the test is terminated by some fault in the testing system, or the load-displacement recording exceeds the range of the clip gage or recording chart, report δ as being greater than that concomitant with the last load recorded. In the latter case, report the maximum load as greater than the load recorded at chart run-out.

9.4 *Qualifying CTOD Values:*

9.4.1 The critical CTOD values, for example, δ_c and δ_u, are valid if:

9.4.1.1 These values of CTOD are equal to or less than the measurement capacity of the specimen, which corresponds to δ_m.

9.4.1.2 The difference between the maximum and minimum of all 9 crack length measurements of the fatigue crack does not exceed 0.10 the original (fatigue) crack length a_o,

9.4.1.3 No part of the fatigue crack front is closer to the machined notch than the lesser of 0.025 W or 1.3 mm (0.05 in.),

9.4.1.4 The plane of the fatigue crack surface does not exceed an angle of 10° from the plane of the notch, and

9.4.1.5 The fatigue crack front is not multi-planar or branched.

10. Report

10.1 Report the following information for each test:

[3] The boldface numbers in parentheses refer to the list of references at the end of this test method.

TABLE 1 Stress Intensity Coefficients (Y) for SE(B) Specimens Having $S/W = 4$

a/W	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
0.45	9.142	9.169	9.196	9.223	9.250	9.278	9.305	9.333	9.361	9.389
0.46	9.417	9.445	9.473	9.502	9.530	9.559	9.588	9.617	9.646	9.675
0.47	9.704	9.734	9.763	9.793	9.823	9.853	9.883	9.913	9.944	9.974
0.48	10.01	10.04	10.07	10.10	10.13	10.16	10.19	10.22	10.26	10.29
0.49	10.32	10.35	10.38	10.42	10.45	10.48	10.52	10.55	10.58	10.62
0.50	10.65	10.68	10.72	10.75	10.79	10.82	10.86	10.89	10.93	10.96
0.51	11.00	11.03	11.07	11.10	11.14	11.18	11.21	11.25	11.29	11.32
0.52	11.36	11.40	11.43	11.47	11.51	11.55	11.59	11.63	11.66	11.70
0.53	11.74	11.78	11.82	11.86	11.90	11.94	11.98	12.02	12.06	12.10
0.54	12.15	12.19	12.23	12.27	12.31	12.35	12.40	12.44	12.48	12.53
0.55	12.57									

NOTE—For rectangular and square section specimens see Figs. 6 and 7.

TABLE 2 Stress Intensity Coefficients (Y) for C(T) Specimens

a/W	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
0.45	8.340	8.363	8.387	8.410	8.434	8.458	8.482	8.506	8.531	8.555
0.46	8.579	8.604	8.629	8.654	8.678	8.704	8.729	8.754	8.779	8.805
0.47	8.830	8.856	8.882	8.908	8.934	8.960	8.987	9.013	9.040	9.066
0.48	9.093	9.120	9.147	9.175	9.202	9.230	9.257	9.285	9.313	9.341
0.49	9.369	9.398	9.426	9.455	9.483	9.512	9.541	9.571	9.600	9.629
0.50	9.659	9.689	9.719	9.749	9.779	9.810	9.840	9.871	9.902	9.933
0.51	9.964	10.00	10.03	10.06	10.09	10.12	10.16	10.19	10.22	10.25
0.52	10.29	10.32	10.35	10.39	10.42	10.45	10.49	10.52	10.56	10.59
0.53	10.63	10.66	10.70	10.73	10.77	10.80	10.84	10.87	10.91	10.95
0.54	10.98	11.02	11.06	11.10	11.13	11.17	11.21	11.25	11.29	11.33
0.55	11.36									

10.1.1 The specimen configuration.

10.1.2 The crack plane orientation in accordance with appropriate figures in Terminology E 616.

10.1.3 Specimen test temperature, °C (°F), and environment.

10.1.4 The crosshead displacement rate for testing systems in which the rate of change of crosshead displacement can be set, mm/min (in./min).

10.1.5 The time to reach the load P_f, min.

10.1.6 Material yield strength and tensile strength at room temperature.

10.1.7 Material yield strength and tensile strength at the temperature corresponding to the CTOD test conditions.

10.1.8 CTOD, δ_c, δ_u, or δ_m, mm (in.), as appropriate, to an accuracy of two significant figures.

10.1.9 Specimen thickness B, mm (in.).

10.1.10 Specimen width W, mm (in.).

10.1.11 SE(B) specimen load span S, mm (in.).

10.1.12 Specimen initial uncracked ligament size b_o, mm (in.).

10.1.13 Distance of clip gage away from SE(B) surface or from C(T) load line, z, mm (in.).

10.1.14 Crack length a_o, mm (in.), and, if applicable, Δa_p, mm (in.).

10.1.15 Load-displacement record.

10.1.15.1 The appropriate plastic component v_p of the clip gage opening displacement v_c, v_u, or v_m, mm (in.).

10.1.15.2 The appropriate applied force P_c, P_u, or P_m, N (lbf).

10.1.16 Fatigue precracking parameters and observations.

10.1.16.1 Range of stress intensity factor, ΔK, for the final portion of precrack growth, MPa$\sqrt{m}$ (ksi$\sqrt{in.}$).

10.1.16.2 The temperature of the specimen during precracking, °C (°F).

10.1.16.3 The load ratio, $R = P_{min}/P_{max}$.

10.1.16.4 Details of any pop-in that may have been ignored in accordance with the assessment procedure in 9.1.3.

11. Precision and Bias

11.1 *Precision:*

11.1.1 This practice contains four indices of fracture toughness, each of which derives variability from unique sources. Materials tested at upper shelf temperatures are characterized by δ_m for the onset of a maximum load plateau. The CTOD at maximum load, δ_m, can be sensitive to the quality of the autographic equipment used, especially the responsiveness to small changes in load or displacement, or both. The selection of the point of first onset of a maximum load plateau can be somewhat subjective and is a significant problem with very ductile materials that show extensive displacement approaching the maximum load.

11.1.2 The CTOD toughness of ferritic materials tested in the transition temperature range is characterized in this method by δ_c or δ_u. Subtle differences in constraint from geometry differences can promote inconsistency. Also in the mid-transition, data inconsistency, even among specimens of identical dimensions, is commonly encountered. This method recommends testing practices and specimen geometries that affect reasonable control over variability in CTOD outcome. Laboratories should replicate tests in order to assess the effects of variability on CTOD values.

11.1.3 An interlaboratory test program involving eleven laboratories was conducted to assess: (a) the measurement precision of the estimation of specific values of CTOD, and (b) the correlation between rectangular section SE(B) and C(T) specimens. CTOD fracture toughness was estimated for two materials at: (a) initiation of stable crack extension, (b) initiation of unstable crack extension, or (c) the onset of a maximum load plateau. The participants used either single-specimen unloading compliance, electric potential drop, or multiple-specimen heat tinting to estimate the CTOD at initiation of crack extension.[4]

11.2 *Bias:*

11.2.1 Bias suggests a consistent difference from a standard value or set of standard values. There are no "standard" CTOD values for any material. However, bias due to geometry variations can be expected in CTOD values for a particular material. In particular, specimen size and/or remaining ligament size are known to affect the CTOD transition temperature behavior in ferritic steels. Thicker specimens of a given material are expected to have a higher transition temperature. Also, for upper shelf behavior, the value of δ_m can be expected to be larger in specimens of larger plan view size or in specimens of larger remaining ligament size.

11.2.2 Differences in CTOD values for a given specimen thickness and test temperature have been observed between SE(B) and C(T) specimens. However, the present test method attempts to minimize such differences.

11.2.3 Finally, it should be noted that the plastic rotation factor r_p is not a constant factor. The parameter r_p is a complex function of specimen configuration and size, applied loading and material. The values of r_p used in this test method are slightly larger than those in other CTOD test methods **(2, 3)**. The values in this test method are based on an examination of published experimental data (see Refs **4–6**), and rigid plastic slip line field analyses **(7, 8)**.

[4] Data on the round robin results are on file at ASTM Headquarters. Request RR: E-24-1013.

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