Ductile fracture toughness testing is useful for evaluating a material’s structural integrity. Three different techniques are explored here.

Ductile fracture toughness determination, such as the J-integral vs. crack growth resistance (J-R) curve, is a useful tool for evaluating a material’s structural integrity in the presence of preexisting defects. The J-R curve can calculate the work (energy) per unit of fracture surface area needed to drive crack growth. A typical J-R curve is shown in Fig. 1. From it, the material fracture toughness near the initiation of stable crack growth (Jq) can be derived. In addition, tearing modulus (TR), representing the material’s resistance to stable crack growth, can be calculated based on the slope of the J-R curve between two exclusion lines (dashed red lines in Fig. 1). Since the introduction of the J-R curve, there have been extensive efforts devoted to developing simple and reliable methods to determine this aspect of various materials. This article briefly reviews three widely used J-R curve test methods in metals: Elastic unloading compliance (EUC), normalization, and direct current potential drop (DCPD). The main differences between these methods involve crack size determination. More details about performing the J-R curve test can be found in ASTM standard E1820-11[1].

Specimen configuration and test apparatus
Different types of specimens can be used for the J-R curve test. Figure 2 illustrates three commonly used configurations: A standard compact C(T) specimen, single edge bend SE(B) specimen, and standard disk-shaped compact DC(T) specimen. After machining, the sample undergoes fatigue precracking to create the initial sharp crack. Initial crack size is usually controlled to be ~a/W=0.5 where a is the crack size and W is the specimen width. Afterwards, side-grooving on both sides of the specimen (e.g., C(T) and SE(B) specimens in Fig. 2) is usually performed to ensure a straight crack front. Total thickness reduction of 20% (10% on each side) due to side-grooving functions well for many materials.

Both servo-hydraulic and electromechanical load frames can be used for the J-R curve test. Figures 3 and 4 show the experimental apparatus for performing this test on a C(T) and SE(B) specimen, respectively. The experimental setup of a DC(T) specimen is similar to that of a C(T) specimen. As shown in Fig. 3, the J-R curve test apparatus for a C(T) specimen consists of a pair of clevises with pins for loading the specimen and a displacement gage for measuring the specimen’s crack mouth opening displacement (CMOD). In contrast, the test fixture for a SE(B) specimen (Fig. 4) employs a central pin to press the specimen, plus two roller pins to support it. The load line...
displacement of the SE(B) specimen is measured from the displacement of the specimen notch root by a LVDT sensor. Alternatively, the CMOD of the SE(B) specimen is measured by a displacement gage. For both C(T) and SE(B) specimens, a load cell (not shown in Figs. 3 and 4) measures specimen load.

**Elastic unloading compliance (EUC)**

Because a J-R curve consists of two parts, J-Integral and crack growth, determining this curve naturally involves calculating both aspects. In elastic unloading compliance (EUC), the J-Integral is calculated as:

\[ J(i) = J_{el(i)} + J_{pl(i)} \]  

where \( J_{el(i)} \) and \( J_{pl(i)} \) are the elastic and plastic components of J-Integral, respectively. For \( J_{el(i)} \):

\[ J_{el(i)} = \frac{K(i)^2(1 - \nu^2)}{E} \]

where \( \nu \) is Poisson’s ratio, \( E \) is Young’s modulus, and \( K(i) \) is the stress intensity factor. \( K(i) \) depends on specimen configuration, load level, crack size, and other factors. The equation for calculating \( J_{pl(i)} \) follows:

\[ J_{pl(i)} = \left[ J_{pl(i-1)} + \frac{\eta_{pl(i-1)} A_{pl(i-1)} - A_{pl(i-1)}}{B_N} \right] - \left[ J_{pl(i-1)} + \frac{\eta_{pl(i-1)} A_{pl(i-1)} - A_{pl(i-1)}}{B_N} \right] \]

where \( a(i) \) is the current crack size, \( b(i) \) is the unbroken ligament size, \( B_N \) is the specimen net thickness, \( A_{pl(i-1)} \) is the plastic area under the load versus load-line displacement record for the specimen, \( \eta_{pl(i-1)} \) equals 1.9 for a SE(R) specimen and \( 2.7 + 0.522b(i-1)/W \) for a C(T) or DC(T) specimen, and \( y \) equals 0.9 for a SE(B) specimen and \( (1+0.76b(i-1)/W) \) for a C(T) or DC(T) specimen. In order to obtain the real-time crack growth value, EUC measures the material compliance (the ratio of displacement increment to force increment) by periodic unloading and reloading of the specimen. For instance, a typical load-displacement record for a J-R curve test using EUC is shown in Fig. 5(a). Each short straight line in Fig. 5(a) represents an unloading-reloading sequence. The rest of the curve resembles a load-displacement curve in a tensile test, i.e., initial elastic deformation followed by plastic deformation and load drop after passing the maximum load level. Once the material compliance value is obtained, equations in ASTM standard E1820-11\(^{11}\) can be applied to convert the compliance result to the estimated real-time crack size. Eventually, combining the J-Integral and crack growth results yields the J-R data as shown in Fig. 5(b).

Since its introduction, the EUC method has gained wide popularity for the J-R curve test. However, EUC still faces considerable challenges for testing in extreme environments. For example, in elevated temperature testing (above 500°C), the compliance measurement in EUC is affected by the material relaxation behavior and increased friction between loading clevises and pins, which results in unreliable crack size measurement. In addition, EUC is relatively time-consuming due to the periodic unloading-
reloading requirement. In order to solve these issues, alternative J-R curve test methods, such as normalization and DCPD, could be used.

**Normalization**

The normalization technique was initially developed by Herrera and Landes et al. and later studied by Joyce and Lee. In some cases, this method can be applied to determine a J-R curve directly from a load-displacement record taken together with initial and final crack size measurements from the specimen fracture surface. Because the compliance measurement is eliminated, the load-displacement curve in the normalization method does not require the unloading-reloading portion as in EUC—see Fig. 6(a)—greatly simplifying the test and reducing test time.

The J-Integral calculation for the normalization method is the same as that in EUC, described previously. In addition to initial and final crack size measurements, intermediate crack sizes are required to derive the full J-R curve. In the normalization method, detailed procedures for deriving intermediate crack sizes are lengthy and complicated. In principle, the normalized load ($P_{Ni}$) and plastic displacement ($ν_{pli}$)—both of which are functions of the current crack size $a_i$—are calculated first using only measured initial and final crack size data. After calculation, the normalized load and plastic displacement are fitted with the following normalization function:

$$P_{Ni} = \frac{a + bv_{pli}' + cv_{pli}'^3}{d + v_{pli}'}$$

where $a$, $b$, $c$, and $d$ are fitting constants. Afterwards, the normalized load is recalculated with an assumed crack size and compared with the normalized load from Eq. (4). Then the assumed crack size used for calculating the normalized load is adjusted until the deviation between the calculated normalized load and the normalized load from Eq. (4) is within the ±0.1% range. After repeating this procedure, all intermediate crack sizes are derived and the J-R curve is determined in the normalization method, which reveals an excellent agreement with the J-R curve from EUC. See Fig. 6(b).

The normalization technique is more favorable for tests with high loading rates or in extreme environments. Despite these advantages, this method has a very strict requirement for crack growth—the final physical crack extension must be within the lesser of 4 mm or 15% of the initial uncracked ligament. Unlike EUC, real-time crack growth estimates are not available in the normalization method. Therefore, strict crack growth control may be difficult to realize during the test for the normalization method.

**Direct current potential drop (DCPD)**

As an alternative J-R curve test method, direct current potential drop (DCPD) combines the advantages of both the EUC and normalization methods. It does not require the unloading compliance measurement, so the load-displacement test record is simplified and the same as the normalization method in Fig. 6(a). In addition, DCPD provides experimental real-time crack size measurements as in EUC. DCPD relies on passing a constant direct current through the specimen, then measuring the voltage generated across an area in the specimen. See Fig. 7(a). As the crack propagates in the specimen, less area is available for the passage of the constant current, resulting in an increase of the effective electrical resistance and potential measurement, i.e., the potential drop in Fig. 7(b). Thus, a correlation can be made between crack length and potential drop in DCPD. In order to convert the potential drop measurement to the crack size, Johnson’s equation is usually applied:

$$a = \frac{2W}{\pi} \sqrt{\frac{\cosh(\pi y/2W)}{\cos(\pi y/2W) \cosh(\pi a_0/2W) \cosh(\pi y/2W)}}$$

where $a$ is the crack length corresponding to potential drop $U$, $W$ is specimen width, $y$ is one-half of the potential gage span, and $a_0$ and $U_0$ are initial crack length and potential drop, respectively. During the J-R curve test...
with DCPD, potential drop is measured continuously or periodically from the specimen, so a real-time crack size measurement is available. The \( J \)-Integral calculation is performed in the same manner as EUC or normalization to yield the J-R curve.

Once the original J-R curve from DCPD is obtained, adjustments are needed to differentiate potential drop due to stable crack growth from material deformation\(^7, 13\). Although difficulties still exist in adjusting DCPD data to yield valid J-R curve results, new methodology\(^14\) shows improved results over previous DCPD adjustment methods\(^15\) with promising J-R curve results. As shown in Fig. 8, after incorporating the new adjustment procedure, ductile fracture toughness near the initiation of stable crack growth (\( J_q \)) from DCPD is in excellent agreement with results from EUC and normalization, whereas only small deviations are observed in tearing modulus (\( T_R \)) results.

**Summary**

This article presents the experimental setup and three different techniques—EUC, normalization, and DCPD—for evaluating ductile fracture toughness in metals using the J-R curve. The \( J \)-Integral calculation is the same in all three methods, with differences primarily involving crack size measurements. EUC relies on material compliance to derive the real-time crack size, while for the normalization method, initial and final crack lengths are measured and intermediate crack sizes are determined based on the normalization function. For DCPD, the correlation between potential drop and crack size is exploited to assess crack size. All three methods are applicable for testing in the normal temperature range. However, for elevated temperature tests, the material relaxation behavior and increased friction between the loading clevises and pins degrade the accuracy of the elastic compliance measurements for the EUC method, so normalization or DCPD should be used. In addition, the original J-R curve based on DCPD requires adjustment to account for the deformation-induced potential drop.

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