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Advances in Development of J-Integral Experimental Estimation, Testing and Standardization

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ABSTRACT: The *J*-integral is an important concept in the elastic-plastic fracture mechanics, and serves as a critical material parameter to quantify the toughness or resistance of ductile materials against fracture. The relation between the *J*-integral and crack extension has been widely used as the resistance curve of ductile materials in fracture mechanics design and in structural integrity assessment. Experimental testing and evaluation have played a central role in providing reliable fracture toughness properties to fracture mechanics analysis. Since the *J*-integral concept was proposed, extensive efforts of investigations have been made to develop its experimental estimation method, testing technique and standardization, as evident in the ASTM E1820 - a commonly used fracture toughness testing standard. In recent years, significant progresses of the *J*-integral fracture testing and experimental estimation have been achieved, and a part of them was accepted and updated in ASTM E1820. To better understand and use this fracture testing standard, the present paper gives a brief review of historical efforts and recent advances in the development of the *J*-integral experimental estimation and standard testing.

KEYWORDS: *J*-integral, *J-R* curve, experimental estimation, fracture test, ASTM E1820

INTRODUCTION

Fracture resistance is a measure of fracture toughness to describe the increasing resistance of ductile materials against fracture or crack growth, and is often characterized by the relation between a fracture parameter such as the *J*-integral and crack extension. This fracture resistance property of ductile materials is often simply referred to as a *J-R* curve. The concept of *J*-integral was proposed by Rice [1] in the late 1960s for describing the intensity of singularity of an elastic-plastic crack-tip stress field. In the early 1970s, Begley and Landes [2, 3] conducted the pioneering fracture tests and first measured the *J*-integral using multiple specimens. Since then, the *J*-integral became a measurable material parameter, and has been used to quantify the fracture resistance of metals or other ductile materials. As an important elastic-plastic fracture mechanics parameter, the critical *J*-integral or *J-R* curve has been extensively applied to material selection, material performance evaluation, damage analysis, fitness-for-service analysis and structural integrity assessment for various engineering structures, including nuclear pressure vessels and piping, oil and gas pipelines, and petrochemical storage tanks.

Over the years, to obtain reliable fracture toughness, a large number of experimental investigations have been performed. This includes development of experimental testing technique, test devices and specimens, testing procedures, experimental evaluation and estimation method, and test standardization as well. In recent years, significant progresses of the *J*-integral fracture testing and experimental estimation have been made, as evident in the fracture toughness testing standard ASTM E1820 [4] that is updated annually or regularly. ASTM E1820 is a commonly combined fracture toughness test standard that was developed by ASTM (American Society for Testing and Materials). This standard has been used worldwide for measuring the critical value of *J*-integral at the onset of ductile fracture and *J-R* curves during fracture tearing. To better understand and use this fracture toughness testing standard, this paper will overview the historical efforts and recent advances in the development of the *J*-integral experimental estimation and standard testing.

EARLY EXPERIMENTAL ESTIMATION METHODS

J-integral estimation for stationary cracks

Originally, Rice [1] proposed the *J*-integral as a path independent mechanics parameter based on the deformation theory of plasticity. This parameter was used to measure the intensity of HRR singular crack-tip field (Hutchinson [5], Rice and Rosengren [6]) for elastic-plastic hardening materials. Finite element analysis showed that the *J*-integral can well describe the stresses, strains and other mechanics behaviors at the crack tip for ductile metals. This encouraged the early experimental investigations on the *J*-integral testing to develop a viable test method for evaluating its critical value. Among the pioneers, Begley and Landes [2] and Landes and Begley [3] first successfully measured the *J*-integral and its critical value at the onset of ductile fracture tearing using multiple laboratory-scale specimens in mode-I loading. Since then, the *J*-integral has become a measurable material parameter and obtained extensive applications in characterizing the fracture toughness of ductile materials.

In the earliest experimental evaluation, the *J*-integral was interpreted as a strain energy release rate, or work done to the specimen per unit fracture surface area in a material given by:

$$J = -\frac{dU}{Bda} \tag{1}$$

where U is strain energy, a is crack length and B is specimen thickness. Begley and Landes [2] tested a series of fracture specimens of the same geometry with different crack sizes and instrumented load-displacement data. From the test data, the energy absorbed by each specimen was determined, and then the *J*-integral was calculated using Eq (1). However, this rudimentary approach has obvious disadvantages: multiple specimen tests and complicated experimental analysis in determination of a critical J_c. Therefore, a simple experimental technique was sought for estimating the *J*-integral simply from a single-specimen test.

Among others, Rice *et al.* [7] showed that the *J*-integral can be simply determined directly from a load-displacement curve obtained in a single-specimen test using an approximate evaluation formula. They proposed several simple J evaluation equations for different specimens they considered. However, only the single-edge notched bend (SENB) specimen and compact tension (CT) specimen in mode-I loading are mostly often used, and thus these two specimens are discussed only in the present review. Through further investigations by Landes *et al.* [8] and Merkle and Corten [9], a more general equation for estimating the *J*-integral in a single-specimen fracture test for the SENB and CT specimens was developed as:

$$J = \frac{\eta A}{Bb} \tag{2}$$

where $b=W-a$ with b the ligament, a the crack length and W the specimen width. A is the total area under a load versus load-line displacement (LLD) that represents the work done to the specimen or the energy absorbed by the specimen as a result of the presence of a crack. η is a dimensionless geometry factor that is a function of crack length to specimen width ratio, a/W. Clarke and Landes [10] and Sumpter [11] obtained expressions of the η factor using the limit analysis method, respectively for CT and SENB specimens.

For convenience, a total load-line displacement is often separated into an elastic component and a plastic component. Similarly, the total *J*-integral has been split into elastic and plastic components that are determined separately:

$$J = J_{el} + J_{pl} \tag{3}$$

The objective of the separation in Eq. (3) is to improve the accuracy of *J*-integral estimation, and to obtain the consistent value of *J*-integral when near linear elastic conditions are applied. In Eq. (3), the elastic component J_{el} can be calculated directly and accurately from the stress intensity factor K for a plane strain crack:

$$J_{el} = \frac{K^2(1-\nu^2)}{E} \tag{4}$$

where E is Young's modulus and ν is Poisson's ratio. For a stationary crack, the plastic J_{pl} is determined from Eq. (2) as:

$$J_{pl} = \frac{\eta A_{pl}}{B_N b} \tag{5}$$

where B_N is a net thickness for the specimen with side grooves, η denotes a plastic geometry factor, and A_{pl} is the plastic area under the load-LLD curve obtained in a fracture test. Equations (3)–(5) were adopted in the first ASTM fracture toughness testing standard E813-81 [12], and now are used in the basic procedure of the current version E1820-09 [4] to evaluate the plain strain initiation toughness J_{Ic}, when a crack growth resistance is not desired.

J-integral estimation for growing cracks

The *J*-integral estimation equation (2) or (5) is valid only for stationary cracks in an experimental evaluation of the *J*-integral to obtain its critical value at ductile fracture initiation. However, the earliest *J-R* curves were constructed simply using the *J*-integral values that were calculated by Eq. (2) in terms of the original crack size and crack extension that was measured using an unloading compliance technology proposed by Clark *et al.* [13]. The resulting resistance curve tends to overestimate *J* for a growing crack because the crack growth correction was not taken into account. To allow crack growth, Equation (2) or (5) has been extended in different ways, and several approaches were then developed historically to obtain a crack growth corrected *J* as needed in an accurate *J-R* curve evaluation. Two typical improved equations for considering the crack growth correction are of incremental functions, where test data are spaced at small intervals of crack extension and the *J* is evaluated from the previous step. The first *J*-integral incremental equation was proposed by Garwood *et al.* [14] and improved by Etemad and Turner [15] for a single edge bending specimen with a deep crack. At the n^{th} step of crack growth, the total *J*-integral was estimated by:

$$J_n = J_{n-1}\left(1 + \frac{g(\eta)_n}{(W - a_n)}(a_n - a_{n-1})\right) + \frac{\eta_n \Delta U_{n,(n-1)}}{B(W - a_n)} \tag{6}$$

The second *J*-integral incremental equation was proposed by Ernst *et al.* [16] based on the principle of variable separation. Since the *J*-integral was developed in reference to the deformation theory of plasticity, it was shown that *J* is independent of the loading path leading to the current values of load-line displacement and crack size in the *J*-controlled crack growth conditions. As a result, the deformation theory based *J*-integral is a unique function of two independent variables: load-line displacement and crack length. With these bases, Ernst *et al.* [16] obtained an incremental equation to evaluate the total *J*-integral at the i^{th} step of crack growth in the form of:

$$J_i = \left[J_{i-1} + \frac{\eta_{i-1}}{Bb_{i-1}} A_{i-1,i} \right]\left(1 - \frac{\gamma_{i-1}}{b_{i-1}}(a_i - a_{i-1})\right) \tag{7}$$

where γ is a geometry factor related to the plastic η factor, $A_{i-1,i}$ is the incremental area under an actual load-displacement record from step *i*-1 to *i*. Both incremental equations in Eqs (6) and (7) consider the crack growth correction on the *J*-integral from the last step. Equation (7) also makes the correction on the incremental work done to the specimen, but Eq. (6) does not. Consequently, a larger estimated *J* is likely to be obtained from Eq. (6) than from Eq. (7), as shown by the experimental results in Ernst *et al.* [16]. In general, these two typical incremental formations of the *J*-integral equation are applicable to any specimens, provided that the two geometry factors are known for each specimen.

In the first *J-R* curve testing standard ASTM E1152-87 [17], the *J*-integral was separated into elastic and plastic components as shown in Eq. (3), and determined incrementally at each loading step. The elastic component of *J* is calculated directly from the stress intensity factor using Eq. (4), and the plastic component of *J* is determined from Eq. (7) that was proposed by Ernst et al. [16]:

$$J_{pl(i)} = \left[J_{pl(i-1)} + \frac{\eta_{i-1}}{B_N b_{i-1}} A_{pl}^{i-1,i} \right]\left(1 - \frac{\gamma_{i-1}}{b_{i-1}}(a_i - a_{i-1})\right) \tag{8}$$

where the incremental plastic area $A_{pl}^{i-1,i}$ is calculated by:

$$A_{pl}^{i-1,i} = \frac{1}{2}(P_i + P_{i-1})(\Delta_{pl(i)} - \Delta_{pl(i-1)}) \tag{9}$$

where Δ_{pl} is the plastic component of load-line displacement. Accurate estimation of the plastic component $J_{pl(i)}$ at each loading step using Eq. (8) requires small and uniform crack growth increments. Accordingly, a loading increment between the two loading-unloading cycles must be small, and usually 30 to 60 loading-unloading cycles are sufficient if the elastic compliance method is used. Equally, a crack growth increment is required less than 1% of the crack ligament size. With the calculated values of J_i and the measured values of crack extension (a_i-a_0), where a_0 is an original crack length, a *J-R* curve is obtained by applying Eqs. (3), (4) and (8) to successive increments of crack growth from a single-specimen test.

CMOD-based *J* estimation for stationary cracks

Experiments showed that an accurate measurement of load-line displacement (LLD) is more difficult than that of crack-mouth opening displacement (CMOD) for the SENB specimens in three-point bending, particularly for a shallow crack. Sumpter [11] first used load-CMOD data directly in a *J*-integral evaluation using a bending specimen. Following the basic idea of Sumpter, Kirk and Dodds [18] studied several possible *J*-integral estimation approaches for shallow cracked SENB specimens using detailed elastic-plastic finite element analyses (FEA). They found that the LLD-based *J* estimation equation could give inaccurate results for hardening materials because the LLD-based plastic η factor is very sensitive to the strain hardening exponent for SENB specimens with shallow cracks of a/W<0.3. In contrast, for the same geometry, the CMOD-based plastic η factor is nearly insensitive to the strain hardening exponent, when a similar η-factor equation was used with the plastic area being obtained under a load-CMOD curve. Thus, Kirk and Dodds [18] concluded that the CMOD-based *J* estimation is the most reliable, and suggested use the following equation in a *J*-integral evaluation for SENB specimens:

$$J = \frac{K^2\left(1-\nu^2\right)}{E} + \frac{\eta_{CMOD} A_{CMOD}^{pl}}{Bb} \tag{10}$$

where the CMOD-based plastic geometry factor was obtained in Reference [18] from their FEA results.

ADVANCES OF J EXPERIMENTAL ESTIMATIONS

More accurate J-integral incremental equations

In the experimental evaluation of *J-R* curves, the LLD based *J*-integral incremental equation (8) has been used widely as an "accurate" expression for more than 30 years because it considers crack growth correction and was adopted by ASTM E1820. In contrast, the other incremental equation (6) did not receive much attention until 2008 when two similar equations were proposed by Neimitz [19] and Kroon et al. [20]. However, Zhu and Joyce [21] revealed that the two "new" equations are similar and equivalent to the Garwood-type equation (6). In addition, Tyson and Park [22] proposed a modified ASTM E1820 incremental *J*-integral equation in order to allow larger crack growth increments between any two unloading-reloading cycles in a fracture test using the elastic compliance method. In comparison to Eq. (8), it is seen that their expression is too complicated to be used in practice.

To obtain a more accurate *J*-integral incremental equation for a growing crack, Zhu and Joyce [21] developed different mathematical models and physical models, and obtained the corresponding incremental *J*-integral equations. In which, three physical models were assumed to approximate the integration path of a differential of the *J*-integral along the actual load-displacement curve obtained in a fracture test for a growing crack. For convenience, these physical models are referred to as the upper step line approximation (USLA), the lower step line approximation (LSLA) and the means step line approximation (MSLA). For each physical model, they developed an incremental equation for estimating the *J*-integral with considering the crack growth correction.

For the USLA model, the *J*-integral incremental equation is:

$$J_{pl(i)} = \left[J_{pl(i-1)} + \frac{\eta_{i-1}}{B_N b_{i-1}} A_{pl}^{i-1,i}\right]\left(1-\frac{\gamma_{i-1}}{b_{i-1}}(a_i - a_{i-1})\right) \tag{11}$$

For the LSLA model, the *J*-integral incremental equation is:

$$J_{pl(i)} = J_{pl(i-1)}\left(1-\frac{\gamma_i}{b_i}(a_i - a_{i-1})\right) + \frac{\eta_i}{B_N b_i} A_{pl}^{i-1,i} \tag{12}$$

For the MSLA model, the *J*-integral incremental equation is:

$$\begin{aligned} J_{pl(i)} &= J_{pl(i-1)}\left(1-\frac{1}{2}\left(\frac{\gamma_{i-1}}{b_{i-1}}+\frac{\gamma_i}{b_i}\right)(a_i - a_{i-1})\right) \\ &+ \left[\frac{1}{2B_N}\left(\frac{\eta_{i-1}}{b_{i-1}}+\frac{\eta_i}{b_i}\right)A_{pl}^{i-1,i}\right]\left(1-\frac{1}{4}\left(\frac{\gamma_{i-1}}{b_{i-1}}+\frac{\gamma_i}{b_i}\right)(a_i - a_{i-1})\right) \end{aligned} \tag{13}$$

Comparison of Eq. (11) with Eq. (8) and Eq. (12) with Eq. (6) shows that the *J*-integral incremental equation for the USLA model is the same as the Ernst-type equation, and the incremental equation for the LSLA model is identical to the Garwood-type equation. Equation (13) for the MSLA model is a new incremental equation that is equivalent to the average of Eqs (11) and (12). Furthermore, Zhu and Joyce [21] and Zhu and Leis [23] showed using SENB and CT specimens that the Garwood-type incremental equation (12) could overestimate a theoretical *J-R* curve, the Ernst-type incremental equation (11) always underestimates the theoretical *J-R* curve, and the new equation (13) determines a *J-R* curve that match well the theoretical one with much higher accuracy than the two existing incremental *J*-integral equation.

Normalization method

The two conventional techniques, i.e., the elastic unloading compliance method and the electric potential drop method, are frequently used for instantaneous crack size measurements. It can be difficult or impractical to implement these two test methods under severe test conditions, such as high loading rate, high temperature, or aggressive environments. An alternative approach, i.e., normalization method, was thus developed for directly estimating instantaneous crack lengths from a load versus load-line displacement curve in conjunction with the use of initial and final measurements of physical crack sizes. This method does not require any test devices for online monitoring crack growth, and thus the test costs are reduced.

Herrera and Landes [24] first proposed the concept of the normalization method in determining a *J-R* curve directly from a load-displacement record obtained from a single-specimen test. Basically, the normalization method requires an adequate calibration function to fit the relation between the normalized load versus the normalized plastic displacement. Different calibration functions were investigated, including a power-law function, a combined function of power law and straight line and other functions. A three-parameter LMN function proposed by Landes *et al.* [25] was found to be good. Joyce [26] improved the LMN function as a four parameter normalization function, and the corresponding normalization method was finally accepted by ASTM E1820-01 and its later versions in Annex 15 "Normalization Data Reduction Technique".

Typically, to obtain an adequate normalization function, a blunted crack size is used, and measured loads are normalized:

$$P_{Ni} = \frac{P_i}{WB\left[1 - a_{bi}/W\right]^{\eta}}, \tag{14}$$

where i refers to the i-th loading point, P_{Ni} is a normalized load and a_{bi} is the blunting corrected crack length. In the same time, the measured plastic displacement Δ_{pli} is normalized:

$$\overline{\Delta}_{pli} = \frac{\Delta_{pli}}{W} = \frac{\Delta_i - P_i C_i}{W}, \tag{15}$$

where C_i is the specimen load-line compliance using the blunting corrected crack length a_{bi}. Using Eqs (14) and (15), the measured load and displacement data up to but not including the maximum load are normalized. The final load-displacement pair is normalized using the same equations except for the final crack length which is used without blunting correction. From the final normalized point, a tangent line is drawn to the normalized load-displacement curve to define a tangent point. Using the normalized load-displacement pair (P_{Ni}, $\overline{\Delta}_{pli}$), a normalization function can be fitted using the least squares regression in the form of:

$$P_N = \frac{c_1 + c_2\overline{\Delta}_{pl} + c_3\overline{\Delta}_{pl}^2}{c_4 + \overline{\Delta}_{pl}}, \tag{16}$$

where c_1, c_2, c_3 and c_4 are the fitting coefficients. With this normalization function, an iterative procedure is further used to force all P_{Ni}, $\overline{\Delta}_{pli}$ and a_i data at each loading point to lie on the fitted function expressed in Eq. (16) by adjusting a_i. In this way, crack lengths at all data points can be determined, and then the *J*-integral is calculated from Eqs (3), (4) and (8), and thus a *J-R* curve is obtained.

For the SENB specimens in three-point bending, successful applications of the normalization method were demonstrated by the present author and his coauthors: Zhu and Joyce [27] for HY80 steel, Zhu and Leis [28] for X80 pipeline steel, and Zhu *et al.* [29] for A285 carbon steel. All experimental *J-R* curves obtained using the normalization method were then compared with those obtained using the conventional unloading compliance method or the electrical potential method. Combined with other applications, these comparisons showed that the normalization method is equivalent to the unloading compliance method and the potential drop method in a *J-R* curve evaluation from a single-specimen test.

Modified basic method

To unify the different fracture testing standards developed in Europe and in USA, Wallin and Laukkanen [30] proposed a new evaluation procedure to correct ductile crack growth in a *J-R* curve evaluation. This procedure is regarded as an improved basic method of ASTM E1820, and so is simply referred to as a modified basic method. In this evaluation method, four steps are needed to determine a final crack growth corrected *J-R* curve:

$$J_i(\Delta a) = J_{el(i)}(a_0) + \frac{J_{pl(i)}(a_0)}{1 + \left(\dfrac{\alpha - m}{\alpha + m}\right)\cdot\dfrac{\Delta a}{b_0}} \tag{17}$$

where α=1 for SENB specimens and α=0.9 for CT specimens. m is a curve-fitting parameter from experimental data.

The new correction procedures have been developed for standard CT and SENB specimens, and are generally valid for both LLD-based and CMOD-based *J*-integral calculations. The procedures are applicable to both single-specimen tests and multiple-specimen tests, and have the same or better accuracy as the crack growth correction used in the present ASTM E1820. Therefore, this modified basic method was adopted by ASTM E1820-05 and its later versions in Annex A16 "Evaluation of crack growth corrected *J*-integral values".

CMOD-based J-integral incremental equations

Since CMOD measurements are generally more accurate than LLD measurements, a fracture test using SENB specimen favors CMOD gages for measuring displacement and specimen compliance. Using load-CMOD data, a crack growth corrected *J-R* curve can be determined using the modified basic method outlined above. However, the suggested correction procedure is indirect and involves multiple steps in determining a crack growth corrected *J-R* curve. A direct CMOD method is desired for long time in determination of a crack growth corrected *J-R* curve. To this end, Zhu *et al.* [31] developed a CMOD-based *J*-integral incremental equation similar to ASTM E1820 LLD-based *J*-integral incremental equation:

$$J_{pl(i)} = \left(J_{pl(i-1)} + \frac{\eta^{i-1}_{CMOD}}{b_{i-1}B_N} A^{i-1,i}_{V_{pl}} \right)\left(1 - \frac{\gamma^{i-1}_{CMOD}}{b_{i-1}}(a_i - a_{i-1}) \right) \tag{18}$$

for determining the plastic component of the *J*-integral. In this equation, η_{CMOD} and γ_{CMOD} are two CMOD-based plastic geometry factors, $A^{i-1,i}_{V_{pl}}$ denotes the incremental area under the P-V_{pl} curve (where V_{pl} is plastic CMOD), and is calculated by:

$$A^{i-1,i}_{V_{pl}} = \frac{1}{2}\left(P_i + P_{i-1}\right)\left(V^i_{pl} - V^{i-1}_{pl}\right) \tag{19}$$

The elastic component and total value of the *J*-integral are still calculated by Eqs (3) and (4), respectively. Note that an equation similar to Eq. (18) was recently proposed by Cravero and Ruggieri [32] in a different analysis for a single edge notched tension (SENT) specimen. For a special case with equal LLD and CMOD, such as for compact-type specimens where LLD could be estimated directly from CMOD gages, the two incremental equations (8) and (18) become identical to each other. In general, Equation (18) can be used for any specimen, provided that the corresponding geometry factors η_{CMOD} and γ_{CMOD} are known a priori for that specimen.

Due to the more accurate CMOD data are used in Eqs (18) and (19), this new *J*-integral incremental equation is able to determine more accurate *J-R* curve in a single-specimen test. Moreover, because LLD data are not needed in the CMOD-based *J*-integral estimation, LLD gages are not required. Thus, the test costs are reduced.

Determination of the plastic geometry factors for SENB specimens

In both LLD- and CMOD-based *J*-integral incremental equations (8) and (18), two plastic geometry factors η and γ are involved. Apparently, an accurate *J-R* curve evaluation needs accurate functions of these geometry factors, and thus their determination become greatly important. A brief review of determining these geometry factors were given by Zhu and his coworkers [27, 31]. The slip-line solution and the elastic-plastic finite element calculation have been used to determine these geometry factors for the conventional fracture specimens. However, some inconsistent or inaccurate functions of η and γ were found in the available solutions for the SENB specimens in both LLD- and CMOD-based formulations. More accurate functions of these geometry factors were thus determined by the present author. Zhu and Joyce [27] obtained more accurate functions of LLD-based η and γ factors for SENB specimens with a wide range of crack lengths in pure bending conditions. Zhu et al. [31] obtained more accurate functions of both LLD- and CMOD-based η and γ factors for SENB specimens with deep and shallow cracks in three-point bending conditions. The latter newer functions of the plastic geometry factors have been used in the current version of ASTM E1820-09 [4].

DEVELOPMENT OF J-INTEGRAL BASED FRACTURE TESTING STANDARD

With the development of experimental estimation method and experimental testing technique, many efforts have been contributed to standardize the *J*-integral based fracture testing method. Landes [33] presented an interesting review of historical development of *J*-integral fracture mechanics and experimental testing at ASTM that involved important events, places and people. It is found that the process of ASTM standardization for the first J_{Ic} testing method was very long and about 10 years was taken from drafting to publication. The first fracture toughness testing standard is ASTM E813-81 [12] in which the only experimental result of the critical *J*-integral was accepted as the fracture toughness of materials. This standard became the sample for all subsequent fracture toughness testing standards in ASTM. Similarly, the first *J-R* curve testing standard ASTM E1152-87 [17] also took another 10 year to be developed from drafting to publication. Again, about another 10 years later, ASTM E1737-96 [34] merged E813 for the initiation toughness J_{Ic} testing and E1152 for the *J-R* curve testing. In parallel to this effort, a commonly combined fracture testing standard ASTM E1820-96 [35] was published for measuring the critical values of all three fracture parameters *J*, *K*, and δ (crack-tip opening displacement) as well as *J-R* curve and δ-*R* curve. The latest version of *J*-integral testing standard is ASTM E1820-09 [4] that has incorporated the normalization method, the modified basic method, the CMOD-based simple equation for basic procedure, the CMOD-based incremental equation for the resistance curve procedure and the more accurate functions for the plastic η and γ factors. The different versions of ASTM E1820 overviewed here reflect the improvement and update of this fracture toughness testing standard made by ASTM over the past 40 years.

The experimental testing technique and development for the *J*-integral testing are not described here, but can be found in an ASTM manual by Joyce [36]. A more detailed review of the *J*-integral testing and evaluation was recently given by the present author in Reference [37].

CONCLUSIONS

This paper reviewed the historical efforts and recent advances in development of the *J*-integral based fracture testing, experimental estimation and standardization at ASTM in USA. Traditional *J-R* curve evaluation was LLD-based, and has been used for more than 30 years. A more accurate *J-R* curve estimation method was recently developed by use of CMOD only. In addition, this review described the normalization method, modified basic method, more accurate *J*-integral incremental equations, more accurate functions of the plastic geometry factors, and the progresses of ASTM fracture toughness testing standard E1820. It is anticipated that this review will help users to better understand and use ASTM E1820.

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