REVIEW OF DYNAMIC LOADING J-R TEST METHOD FOR LEAK BEFORE BREAK OF NUCLEAR PIPING

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In order to apply the leak before break (LBB) concept to nuclear piping systems, the dynamic strain aging effect of low carbon steel materials has to be taken into account, in compliance with the requirements of the Korean Standard Review Guide (KSRG) 3.6.3-1. For this goal, J-R tests are needed for a range of various temperatures and loading rates, including dynamic loading conditions. In the dynamic loading J-R test, the unloading compliance method can not be applied to measure the crack growth and direct current potential drop (DCPD) method; this method also has a problem defining the crack initiation point. The normalization method is known as a very useful method to determine the J-R curve under dynamic loading because it does not need additional equipment or complicated loading sequences such as electric current or unloading. This method was accepted by the American Society for Testing and Materials (ASTM) as a standard test method E1820 A15 in 2001. However, it has not yet been clearly verified yet if the normalization method is sufficiently reliable to be applied to LBB. In this study, the basic background of the J-integral, LBB and dynamic loading J-R test are explained, and the current status for dynamic loading J-R test methods are reviewed from the view point of LBB for nuclear piping. In particular, the theoretical and historical background of the normalization method which has received attention recently, is summarized. Recent studies for this method are introduced and future works are suggested that may improve the reliability of LBB for nuclear piping.

KEYWORDS : Leak Before Break, Dynamic Loading Normalization Method, J-R Curve, Blunt Notch, Modified Test Method

1. J-R TEST AND LEAK BEFORE BREAK OF NUCLEAR PIPING

The integrity of piping in a nuclear power plant is important for nuclear safety. Therefore, all nuclear power plants are required to be designed to assure a safe shutdown in the event of a double-ended guillotine break (DEGB) in the high energy piping system [1]. However, in the 1980's, several experimental and analytical evaluations showed that the probability of the hypothetical DEGB is extremely low, leading to the establishment of the leak before break (LBB) concept [2,3].

On the basis of these studies, the LBB concept has been applied to the design of high energy piping in nuclear power plants, as illustrated in Fig. 1. When the LBB is shown to be acceptable in a piping system, pipe whip restraints (PWR) and jet impingement shields (JIS) for the protection of piping in safety systems, as well as other equipment, should be removed, which results in significant cost savings and reduced man-Ram exposure [4]. Under some conditions, the DEGB hypothesis has been overridden for some small piping provided that the LBB concept can be demonstrated.

In order to apply the LBB concept to any piping system, it is mandatory to show that the crack length which allows leakage of a fluid to be detectable is stable in the piping system. Fig. 2 shows a schematic diagram of a nuclear LBB analysis procedure [5,6]. First, attention should be drawn to the fact that the piping has the an extremely low probability of DEGB considering the screening criteria described in Fig. 2. Second, the crack size allowing for the detectable leakage amount should be determined considering the normal operating loads, tensile properties and leakage sensing ability. Finally, whether or not the determined leak size crack is stable under the harshest loading conditions of the piping system should be confirmed. If the crack is not stable and can experience an unstable fracture, LBB is not acceptable for the piping system.

The J-integral concept, based on elastic-plastic fracture mechanics (EPFM), has been widely used for crack instability analyses. J-integral was first proposed by Rice in 1968 [7] as a path-independent line integral in the crack tip. This parameter describes crack tip conditions in the elastic-plastic strain field and can be used to predict fracture behaviors. Hutchinson [8], and Rice and Rosengren [9]

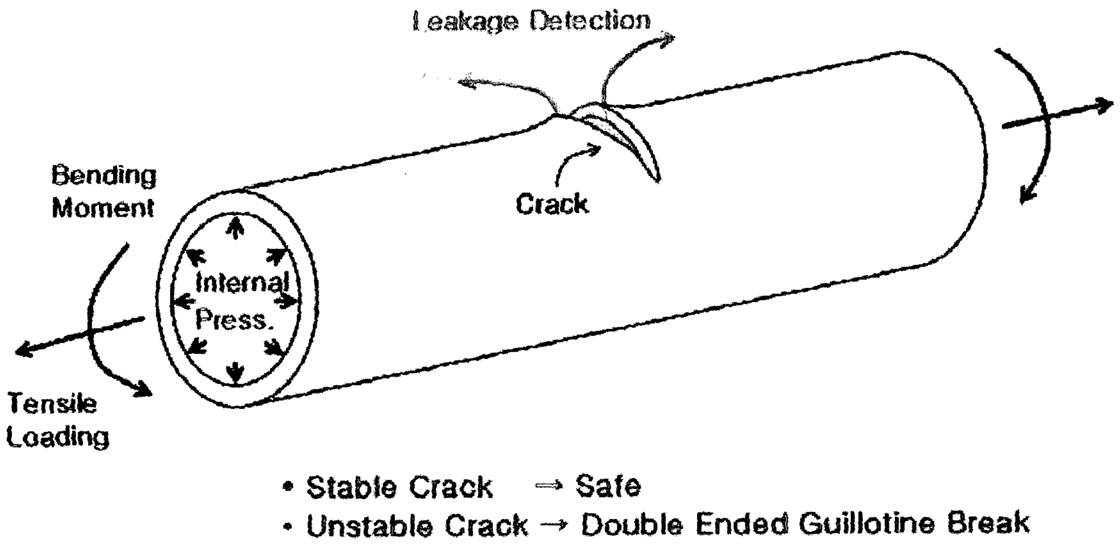


Fig. 1. Schematics for the Leak-before-break Concept

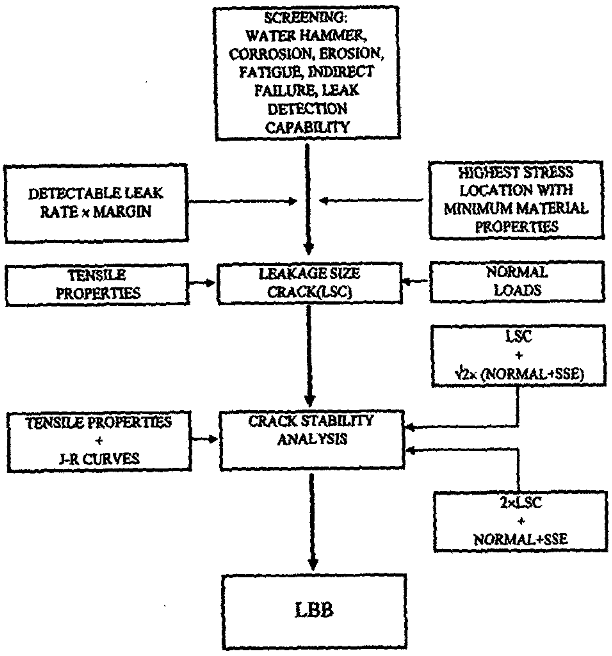


Fig. 2. Overall Procedure of a Nuclear LBB Analysis [5,6]

independently showed that J characterizes the crack tip stress field (HRR field) in a nonlinear elastic material, indicating that J represents the stress intensity parameter in a crack tip of a power-law hardening material. Subsequent to these findings, a laboratory measurement method of J-integral using a single specimen was developed, and its validity has been confirmed by many researchers [19,20].

Based on J-integral theory, the J-resistance (J-R) curve can be measured using a cracked specimen. The J-R curve shows the amount of crack extension according to the applied J-integral in the material. Fig. 3 [10] shows a typical shape of a J-R curve. During the initial stage of deformation, the curve rises steeply and a small amount of apparent crack growth due to crack tip blunting occurs. As J increases, the material at the crack tip reinitiates a crack locally and stable growth ensues. The J value at the crack reinitiation point is called JIc as shown in Fig. 3.

Consequently, it is acceptable for LBB when the applied J value under the given applied load and leak size crack is smaller than the J_{Ic} value of the piping material. However, the J_{Ic} value is not a crack instability point but only a starting point of stable crack growth. Instability occurs when the driving force curve meets the J-R curve in tangency, as illustrated in Fig. 4 [10]. Therefore, the crack for a given size is stable when the dJ/da value in J-R curve is larger than the applied dJ/da in the piping, where dJ/da is the slope of J-integral on the crack extension.

A reliable estimation of crack instability is very important for the LBB assessment. Crack instability estimations can be guaranteed by a reliable calculation of the applied J values and a reliable measurement of the J-R curve. This study focuses on the methodology for a reliable J-R curve measurement.

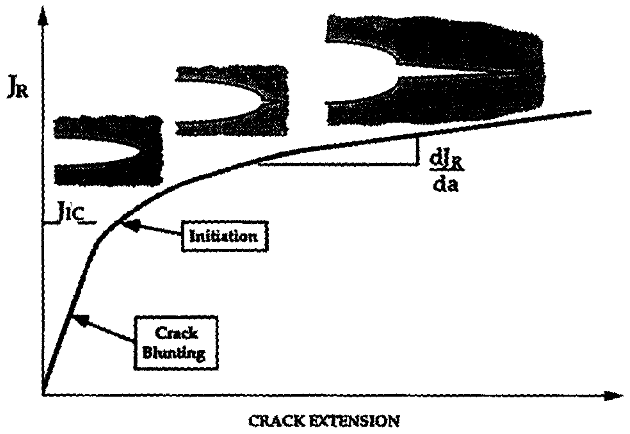


Fig. 3. Schematic J-R Curve for a Ductile Material [10]

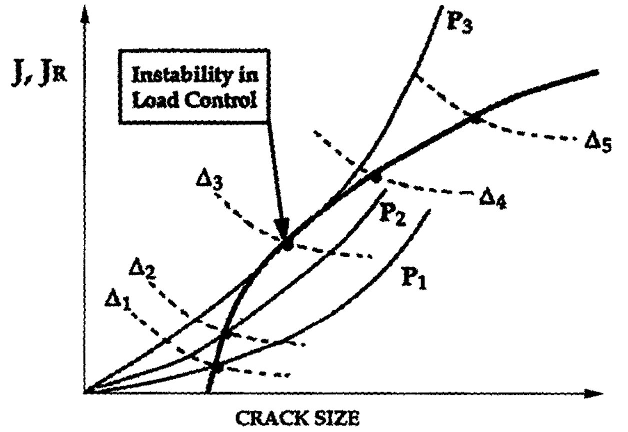


Fig. 4. Schematics of the J Driving Force - J-R Curve Diagram [10]

2. DYNAMIC LOADING J-R TEST IN LEAK BEFORE BREAK

Typically, the material properties used for the LBB analysis are obtained under quasi-static and at specified temperature conditions [4]. However, the piping systems are operated at elevated temperatures and are subjected to various loading conditions, such as normal operating loading and seismic loading.

It is well known that ferritic steel may exhibit lower toughness due to the Dynamic Strain Aging (DSA) phenomenon under a specific range of loading rate and temperature conditions. Experimental evidence from both a full-scale pipe and laboratory tests conducted by several investigators indicates that nuclear ferritic steel pipe material, susceptible to DSA, does display increased strength and decreased fracture resistance at normal operating temperatures [11~17].

Therefore, especially for materials susceptible to DSA, it can not be assured that material properties obtained under conventional testing conditions correspond with conservative results. Based on this research, it is stipulated in the Korean Standard Review Guide (KSRG) Section 3.6.3-1 [18] that a dynamic loading fracture test must be performed for carbon steels in order to be applied to a LBB analysis.

In order to determine the J-R curve, the load-displacement curve should be measured by the loading of a pre-cracked specimen. In addition, the crack lengths in each load-displacement step should be quantified. The unloading compliance method has been most widely used for crack length measurements in J-R tests.

As illustrated in Fig. 5 [10], the crack length is computed at a regular interval during the test by partially unloading the specimen and measuring the compliance. As the crack grows, the specimen becomes more compliant and less stiff [19,20]. Although it is the most widely used method, it can not be applied to a dynamic loading J-R test, as unloading is not acceptable during testing.

An alternative method for crack length measurement in a dynamic J-R test is the direct current potential drop (DCPD) method. As shown in Fig. 6 [10], crack growth is monitored through a change in electrical resistance which accompanies a loss in the cross sectional area. Therefore, the electric potential is increased as the crack length increases when a constant current is applied to the specimen.

Given that the DCPD method allows monotonic loading, this method has been used in dynamic loading J-R tests by many researchers [15,17,21~27]. However, it has been reported that the DCPD method has its own shortcoming when it is applied to a dynamic test of ferromagnetic materials. The problem stems from an abnormal voltage pulse superimposed on the normal dc-electric potential signal [21~26]. This abnormal voltage pulse is known to originate from the sudden reorientation of ferromagnetic domains and from the generation of an electromotive force when plastic strain occurs rapidly [23].

A number of researchers have tried several modified DCPD techniques in an effort to determine the crack initiation point; however, reliability issues or applicability limits under high temperature tests [25,26] were noted in most cases. In 1999, the American Society of Testing and Materials (ASTM) excluded the DCPD method from Standard Method E1820 based on arguments concerning the calibration methodology and the measuring uncertainty in the J_{Ic} region [28,29]. In 2001, the normalization method was accepted as the standard methodology of the ASTM for high loading rates, high temperatures or other aggressive environmental applications [28].

The normalization method has been developed and

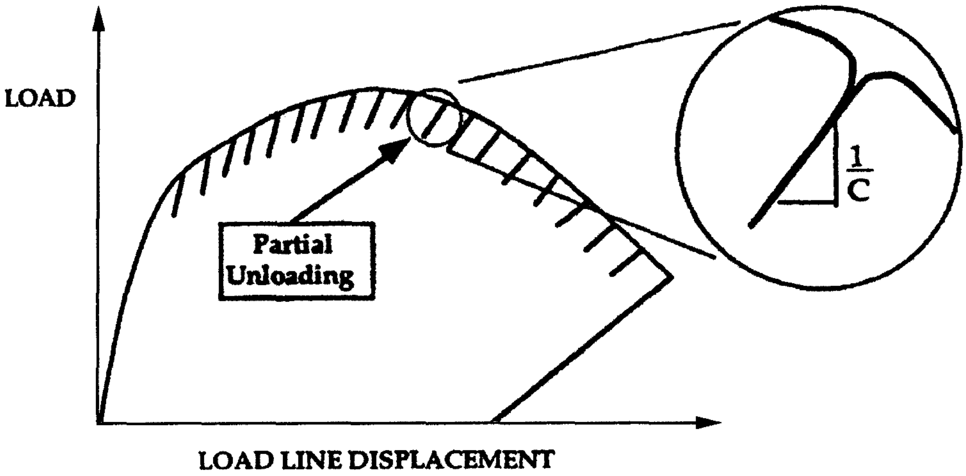


Fig. 5. Unloading Compliance Method for Measuring Crack Extension [10]

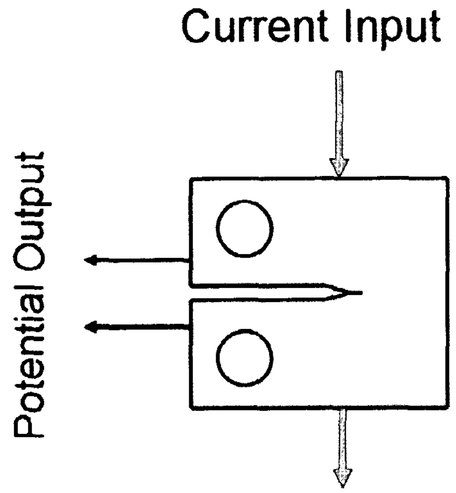


Fig. 6. Direct Current Potential Drop Method for Measuring Crack Extension

modified by Landes et al. since the 1980's [30~34] as an uninstrumented J-R test method that uses only the load-displacement curve without additional measurements of crack length during testing, such as unloading or an electric current. This method, evolved from the key-curve method [35,36], which uses the principle of load separation [37,38] and assumes a four parameter deformation function to determine a calibration equation for each specimen under testing. Although the normalization method is most convenient, especially for the dynamic loading J-R test, it has not shown adequate reliability for application to nuclear LBB estimations.

3. NORMALIZATION METHOD FOR J-R TEST

Even though the unloading compliance method is reliable and most widely used for static loading J-R tests, it is not applicable to the dynamic loading J-R test. The DCPD method is applicable to dynamic testing; however, it has severe shortcomings in terms of its reliability. In addition, it has been excluded from the ASTM Standard Method for J-R tests.

The normalization method has no fundamental shortcoming in its application to dynamic loading J-R tests given that only load and load line displacement need to be measured in order to determine J-R curves. At the workshop of ASTM Subcommittee E08.08.02 held in November 1998, positive experiences with the method were extensively reported [39], culminating in the High Rate Round Robin testing campaign conducted under the E08.08.02 subcommittee from 1998 to 2000 with the coordination of Joyce [40].

The efforts helped resolve issues related to the suitability of this method as an ASTM method for elastic-plastic fracture test under the dynamic or impact loading conditions highly demanded for ferritic steel evaluations. In the High Rate Round Robin, however, the results of the normalization method could not be compared with any other well-established methods as suitable method was available as a reference.

3.1 Load Separation Principle [35,37]

The normalization method [30~34] was initially proposed by J. D. Landes et. al. in 1988, and is based on the load separation principle and the key curve method [35,36].

The load separation principle states that the load on a cracked body can be represented by a combination of two separable forms: a specimen geometry function and a material hardening function, as shown by the following equation;

$$P = G(a/W) \cdot H(v_{pl}/W) \quad (1)$$

where P is the load, G is the geometry function, H is the material hardening function, a is the crack length, W is the specimen width, and v_{pl} is the plastic displacement for the specimen, as defined in Fig. 7, respectively.

The load separation principle provides a theoretical basis for the measurement of J-integral using a single specimen. The concept of load separation was introduced as early as that of J itself; in 1971, Rice et. al. [41]. proposed that the load-displacement relationship for deeply cracked bend specimens can be represented as:

$$\theta = F\left(M/b^2\right) \quad (2)$$

where M is the bending moment, b is uncracked ligament, and θ is rotation due to crack opening. Eq. (2) can be rewritten as:

$$M = G(b) \cdot f(\theta) \quad (3)$$

where G(b) and f(θ) can be defined as geometry and deformation functions, respectively. This separable form of Eq. (3) yielded the first specimen deformation form for J-integral, as follows:

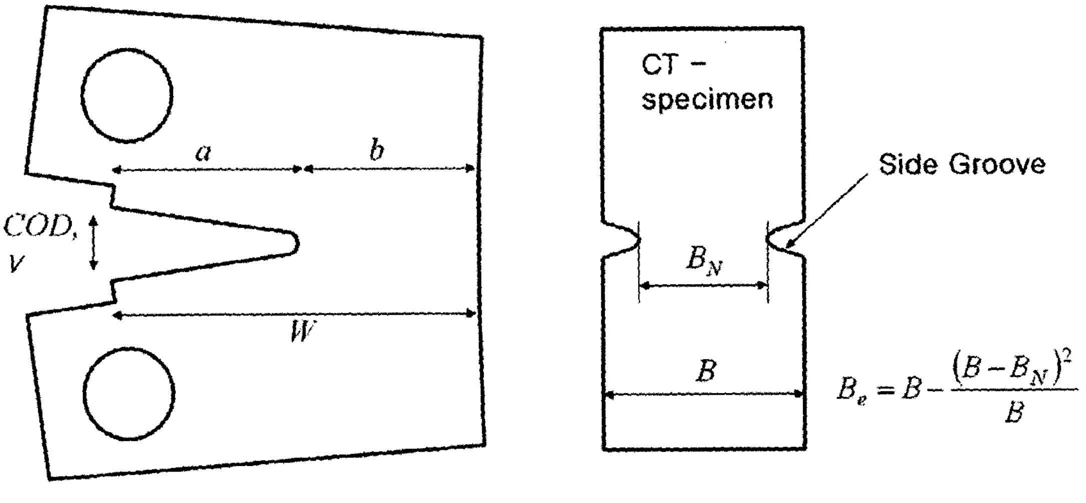
$$J = 2\frac{A}{b} \quad (4)$$

where A is the area under a test record M-θ. This form allowed for the evaluation of J from a single bend specimen test record.

Merkle and Corten [42] developed a separable form to represent the load in compact geometry using a limit load analysis. Their approach yielded a single specimen J form, as in:

$$J = \frac{2(1+\alpha)}{1+\alpha^2}\frac{A}{b}, \quad where$$
$$\alpha = \left[\left(\frac{2a}{b}\right)^2 + 2\left(\frac{2a}{b}\right) + 2\right]^{1/2} - \left(\frac{2a}{b} + 1\right) \quad (5)$$

where a is crack length and α is Merkle and Corten's expression in relation to η-factor. Landes et. al. [43] found a reasonable agreement between the experimental results for the energy rate interpretation of J using their multi-specimen technique and the single specimen J value obtained via the method of Merkle and Corten. This established an experi-



< ASTM E1820 >

Fig. 7. The Definition of the CT Specimen Geometry

mental validation for the load separation principle and the single specimen J form.

Based on further studies, J was found to be more rigorously represented as the sum of two parts; J_{el} and J_{pl}, in which J_{el} can be obtained from linear elastic fracture parameters, and J_{pl} can be evaluated using the single specimen form of:

$$J_{pl} = \eta_{pl}\left(A_{pl} / b\right) \tag{6}$$

where A_{pl} is the area under the load per unit thickness versus the plastic displacement record and η_{pl} is a factor that can be written as :

$$\eta_{pl} = 2 \quad \ldots\ldots \textit{ for the bend specimen} \tag{7}$$

$$\eta_{pl} = 2 + 0.522b/W \ldots\ldots \textit{ for the compact tension specimen}$$

The η_{pl} expression for a compact tension specimen is a linear fit approximation made by Clarke and Landes [44]. It is interesting to compare η_{pl} with Merkle and Corten's η-expression, as given in Eq. (5). Ernst et. al. has proved that η-factor exists only if the load can be represented by a separable form [35,36].

In 1991 and 1993, Sharobeam and Landes verified load separability by experiments using blunt-notch specimens [37] as well as fatigue pre-cracked specimens [38]. In the load separable form, Sharobeam and Landes became convinced that G-function in the following form is the appropriate load separable form [37,38] ;

$$G(a/W) = WB\left[\frac{W-a}{W}\right]^{\eta_{pl}} \tag{8}$$

where η_{pl} is the plastic η-factor and B is the specimen thickness. Their investigations are applicable for load separation and the calculation of G-function, and provide the foundation for the normalization method.

3.2 Theories of Normalization Method

The normalization method is based on the principle of load separation as shown in Eq. (1). In the normalization method, a normalized load, P_N is defined by the following equation;

$$P_N = \frac{P}{G(a/W)} = H\left(v_{pl,N}\right), \qquad v_{pl,N} = v_{pl}/W \tag{9}$$

where $v_{pl,N}$ is normalized plastic displacement, with G(a/W) as previously given by Eq. (8).

The normalized load, P_N can be calculated by Eq. (9) provided that the instantaneous crack length is measured. However, the crack length normally cannot be determined at this step. The standard normalization method uses a curve fitting technique in order to predict the normalization curve (the normalized load as a function of the normalized displacement). The curve fitting utilizes the only data in the crack tip blunting region where the crack length is known, as well as that at the final data point. After the test, it is possible to optically measure the final crack length from the broken halves of a specimen.

The power-law type fitting function based on the Ramberg-Osgood equation was proposed in the first version of normalization method [30,31], despite the fact that the equation is not accurate for certain ductile materials including ferritic steels.

$$P_N = \left(\frac{v_{pl,N}}{\beta}\right)^{\frac{1}{n}} \tag{10}$$

< Power-law type function [30] >

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n \tag{11}$$

< Ramberg-Osgood equation [30] >

where P_N is the normalized load, $v_{pl,N}$ is the normalized plastic displacement, σ is the stress, σ_0 is a reference stress which is typically used by the yield strength, ε is the strain, ε_0 is a reference stain typically used by the yield strain, and α, β, and n, are the fitting constants, respectively.

In 1991, based on experiences with the J-R test for ductile metals, the normalization curves were shown to follow a power-law type function in the early region of loading and a linear function in the final region. In order to make a better overall fitting to this characteristics, Landes et. al. [33] proposed the so-called LMN function for the normalization curve fitting, as in the following equation.

$$P_N = \frac{Lv_{pl,N} + Mv_{pl,N}^2}{N + v_{pl,N}} \tag{12}$$

< LMN function [17] >

where L, M and N are fitting constants, respectively. Donoso et. al. [45] attempted to apply this LMN function to tensile stress-strain curve fitting, as in the following equation;

$$\sigma = \frac{L'\varepsilon + M'\varepsilon}{N' + \varepsilon} \tag{13}$$

< LMN function for tensile curve [27] >

where L', M' and N' are fitting constants, respectively. Fig. 8 shows a typical shape of this fitting equation. The constants L and M are the intercept point of the y-axis and the linear slope of the asymptotic line, respectively. The constant N affects the curvature in the early region of loading.

While the LMN function is expected to pass through the origin on the x-y plane, most experimental data did not follow the rule due to small but non-negligible experimental errors. Joyce et. al. proposed a modified four-parameter function in order to reconcile the shortcoming of the LMN function, as follows [39];

$$P_N = \frac{a + bv_{pl,N} + cv_{pl,N}^2}{d + v_{pl,N}} \tag{14}$$

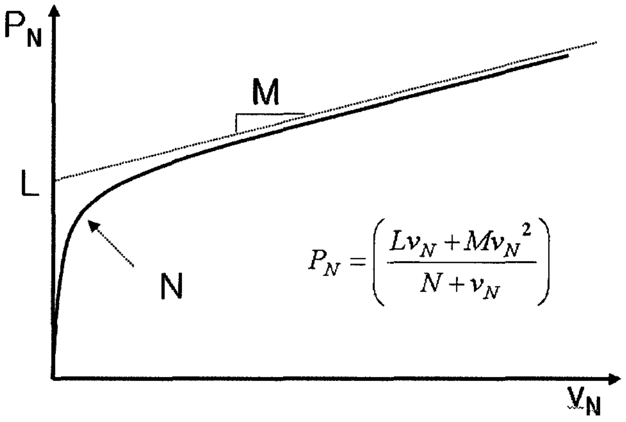


Fig. 8. The Typical Shape of the LMN Function

where a, b, c and d are fitting constants, respectively. Fig. 9 shows that the four-parameter function creates a J-R curve with a better shape [11].

3.3 Current Standard Procedure of Normalization Method [28]

The standard procedure for the normalization method is explained briefly here, according to ASTM Method E1820-

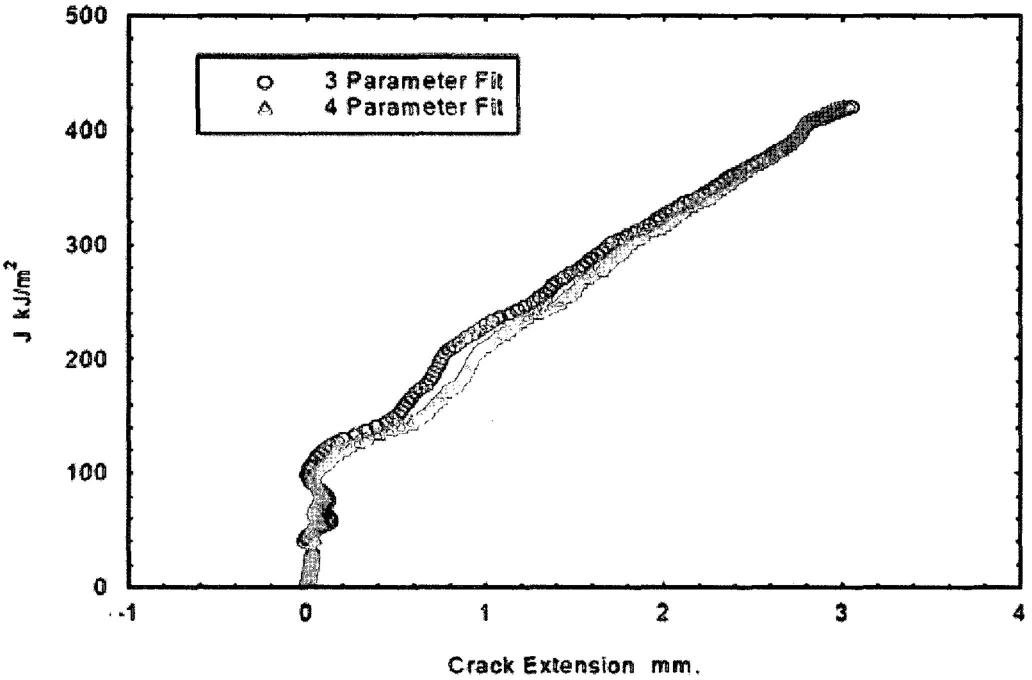


Fig. 9. Normalization Fitting Equation Effect on the J-R Curve [11]

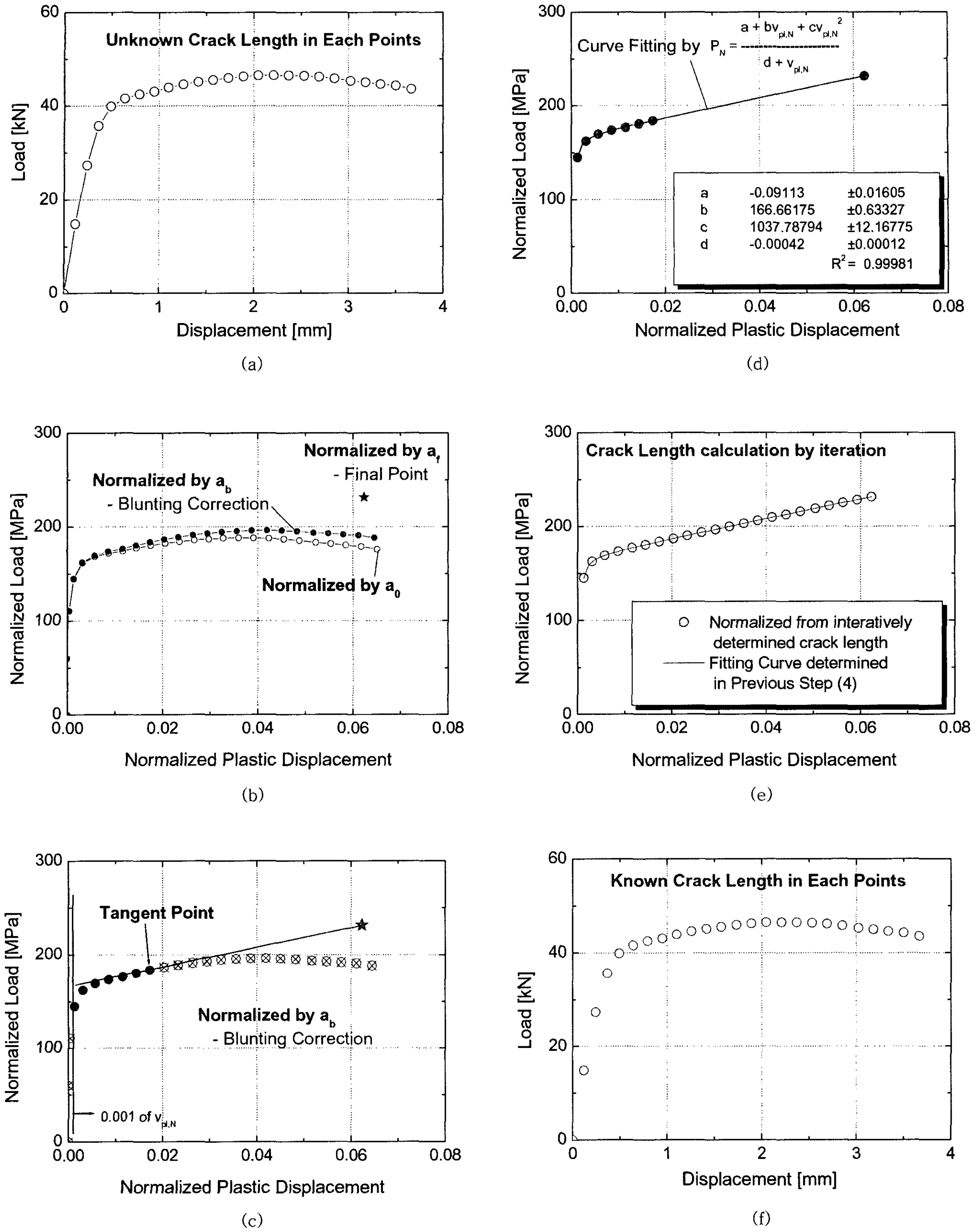


Fig. 10. Schematics of the ASTM Standard Procedure for Normalization Method

01 “A15. Normalization Data Reduction Technique” [28]. Figs. 10 (a)~(f) show the schematics of the crack length determination procedure, as follows:

(a) Unlike the unloading compliance method, the crack length is unknown at each load-displacement data point directly after specimen loading.

(b) The blunting corrected normalization curve is calculated from the load-displacement data using the following equation:

$$P_{N,i} = \frac{P_i}{WB\left[\frac{W - a_{b,i}}{W}\right]^{\eta_{pl,a_{b,i}}}},$$
$$v_{pl,N,i} = \frac{v_{pl,i}}{W} = \frac{v_i - P_i C_{b,i}}{W} \qquad (15)$$

where P_N,i is the normalized load, P_i is the load measured in the test specimen, $a_{b,i}$ is the blunting corrected crack length, $\eta_{pl,abi}$ is the plastic η-factor for $a_{b,i}$, $v_{pl,N,i}$ is the normalized plastic displacement, $v_{pl,i}$ is the plastic displacement, and v_i is the displacement measured in the test specimen at the i-th data point, respectively. $C_{b,i}$ is the specimen compliance for the blunting corrected crack length, as defined for each type of specimen in ASTM E1820.

$a_{b,i}$ can be calculated via the following equation for the blunting line;

$$a_{b,i} = a_0 + \frac{J_{i,0}}{2\sigma_Y} \qquad (16)$$

where a_0 is the initial crack length, σ_Y is the material flow stress and $J_{i,0}$ is the J-integral calculated for the initial crack length. The final point of the load-displacement curve is then converted to a corresponding normalized load-displacement point using the following equation;

$$P_{N,final} = \frac{P_{final}}{WB\left[\frac{W - a_f}{W}\right]^{\eta_{pl,f}}},$$
$$v_{pl,N,final} = \frac{v_{pl,final}}{W} = \frac{v_{final} - P_{final} C_f}{W} \qquad (17)$$

where a_f is the final crack length measured from the broken halves of a specimen, $\eta_{pl,f}$ is the plastic η-factor at the final crack length and C_f is the specimen compliance for the final crack length, respectively.

(c) A line is drawn from the final point such that it creates a tangent with the remaining data set. All data on the right of this tangent point as well as data with $v_{pl,N} \leq 0.001$ is then excluded from the normalization function fit.

(d) Following this, the least-square fitting to Eq. (14) is made using the selected data in Step (c) and the final point data.

(e) Using the least-square fitted normalized load and displacement curve, the individual crack length data is computed iteratively as a function of displacement with the equation;

$$P_{N,i} = \frac{P_i}{WB\left[\frac{W - a_i}{W}\right]^{\eta_{pl,i}}},$$
$$v_{pl,N,i} = \frac{v_{pl,i}}{W} = \frac{v_i - P_i C_i}{W}, \qquad (18)$$
$$P_{N,i} = \frac{a + bv_{pl,N,i} + cv_{pl,N,i}^2}{d + v_{pl,N,i}}$$

where ai is the estimated crack length at the i-th data point, $\eta_{pl,i}$ is the eta-factor for a_i, C_i is the specimen compliance for a_i and a, b, c and d are fitting constants determined in the Step (d) above.

(f) Using the estimated crack lengths at each load-displacement data point, the J-R curve can be constructed by the standard procedure for J-R curve calculation. In each step from (a) to (e), ASTM Method E1820-01 [28] A15 provides the data qualification criteria.

4. EVOLVING J-R TEST METHOD WITHOUT CRACK LENGTH MEASUREMENT

The normalization method uses only the load-displacement curve and final crack extension to determine the J-R curve, without the need for additional information to measure the crack length. This type of J-R test method is called by direct method. In this section, several direct methods for the J-R test are explained.

The load ratio method was proposed by Hu, Albrecht and Joyce in 1992, and focused on high-rate loading test applications [46]. It was developed from the observation that the elastic portion of the total load-line displacement remains constant during crack extension beyond the maximum load in elastic perfect plastic (not strain-hardened) materials. It was improved in 1995 by taking into account strain hardening behavior [47]. Subsequently, in 2001 and

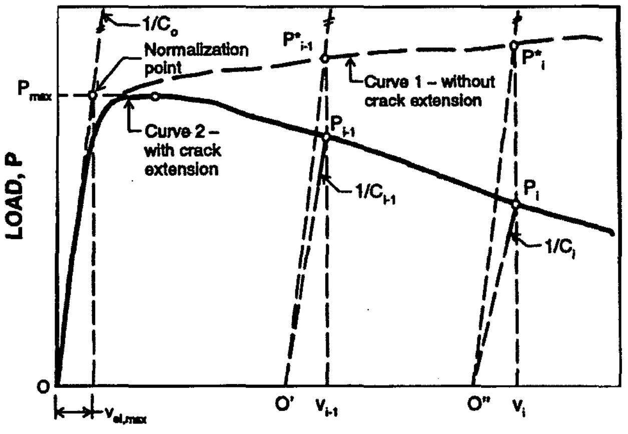


Fig. 11. Schematics for the Load Ratio Method for J-R Test [48]

2002 attempts were made to determine a type of normalization curve, named as reference curve or key curve, experimentally for various materials [48,49]. Lee et. al. [50] attempted to determine a reference curve using a linear tangent line comparable to that in the standard normalization procedure in Step (c) described in the previous section.

As shown in "Curve 1" of Fig. 11 [48], the reference load-displacement curve is a virtual deformation curve without crack extension, similar to the normalization curve in the normalization method. Based on the theory of deformation plasticity and the key curve [35,36], the magnitude of the plastic deformation is assumed to be identical regardless of crack extension. When there is no crack extension, the compliance remains constant in all displacement values. On the other hand, the compliance values for a crack-extended specimen can be determined as shown in Fig. 11, if the reference curve without crack extension can be determined. As explained earlier, attempts have been made to determine an effective and accurate method for determining a reference curve or key curve since the 1990's; this is a key issue in the load ratio method.

Byun et al. proposed an iteration method for J-R curve calculation [51]. They combined the calculation of the crack length and the calculation of J-integral, using an energy release rate formulation as follows:

$$J = -\frac{1}{B}\frac{\partial U}{\partial a}\bigg|_{v=const.} \cong -\frac{1}{B}\frac{\Delta U}{\Delta a}\bigg|_{v=const.}$$

$$\Rightarrow \quad \Delta a = \frac{\Delta U}{BJ}\bigg|_{v=const.} \qquad (19)$$

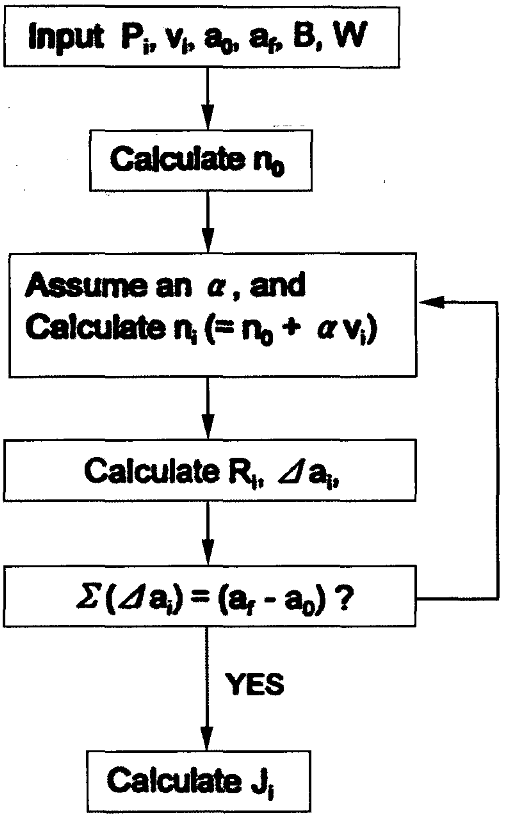


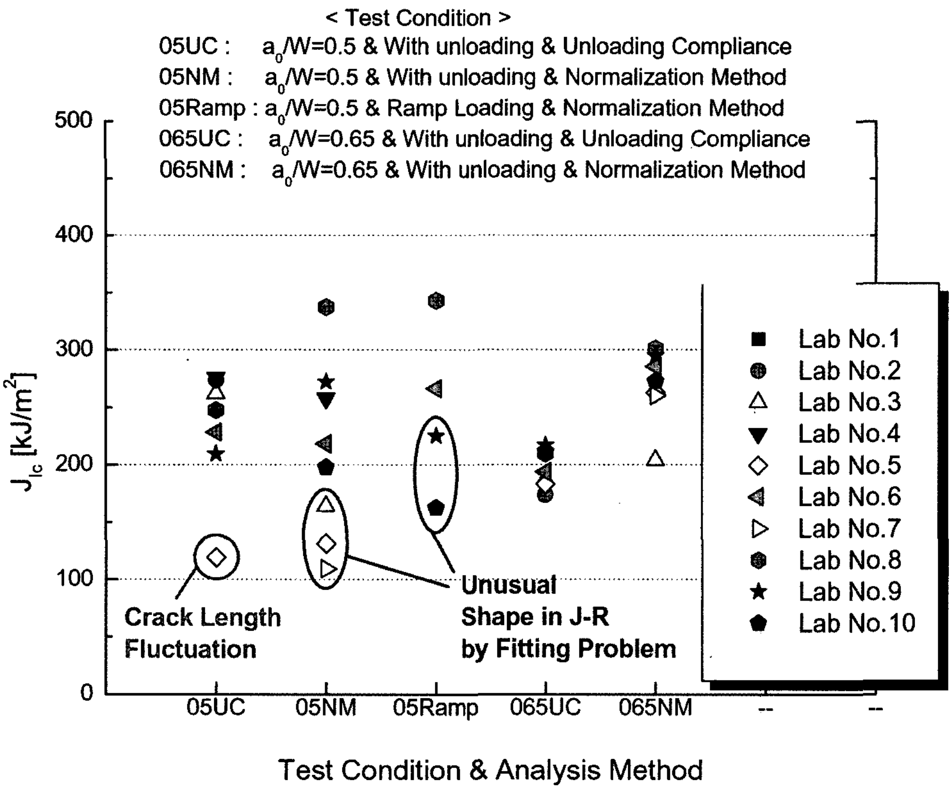
Fig. 12. Schematic Flow Chart for the Iteration Method [49]

where B is the specimen thickness, a is the crack length, v is the load line displacement and U is the elastic-plastic energy measured as the area under the hardening curve.

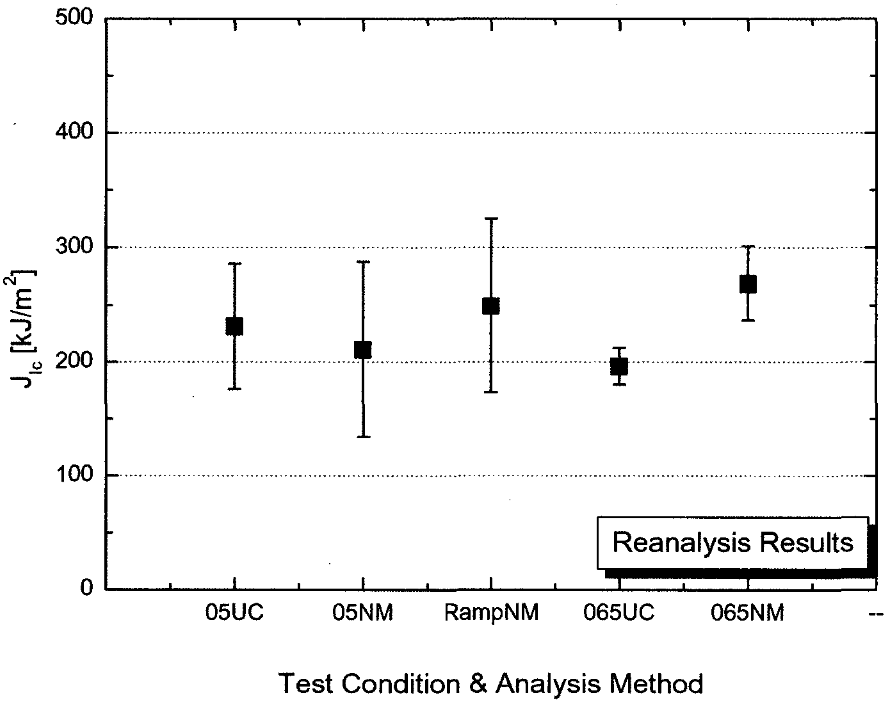
In order to calculate U, load-displacement functions are needed at a given crack length. In the iteration method, a power-law function was used for the load-displacement curve, with hardening exponent varying linearly with deformation, as follows:

$$P(v, a_i) = P_i\left(\frac{v}{v_i}\right)^{n_i}, \quad n_i = n_0 + \alpha v_i \qquad (20)$$

where P is the load, P_i is the i-th load value in the specimen with a growing crack, v is the load line displacement in the hardening curve, v_i is the i-th displacement value in the specimen with a growing crack, n_i is hardening exponent in i-th point, n_0 is initial hardening exponent and α is a constant determined iteratively. Based on these formulae,



(a) All J_{Ic} values



(b) Mean values and standard deviations

Fig. 13. The Measured J_{Ic} in Normalization Round Robin under Static Loading Conditions [55]

the iterative procedure was applied, as shown in Fig. 12.

The iteration method uses a new approach in which the energy release rate formulation of J-integral is utilized. It also, however, assumes a particular shape of hardening curve. Similar practices for varying hardening exponents are employed with the normalization curve in the normalization method and with the reference curve in the load ratio method. For its application to ductile steels, the iteration method uses a linear relationship between a hardening exponent and a load-line displacement. This approach shares common ground with the LMN function that was derived from a power-law function in the early stage of the development of the normalization method.

Wainstein et. al. proposed the use of the load separability parameter, S_{pb} for measuring the crack length in 2003 [52~54]. The load separability parameter was initially defined by Sharobeam and Landes [37] in order to verify the load separation principle, as follows:

$$S_{pb} = \left.\frac{P_p(a_p, v_{pl})}{P_b(a_b, v_{pl})}\right|_{v_{pl}} = \left.\frac{G_p(a_p/W)\cdot H(v_{pl}/W)}{G_b(a_b/W)\cdot H(v_{pl}/W)}\right|_{v_{pl}} \tag{21}$$

where P_p is the applied load to the pre-cracked specimen and a_p is its corresponding crack length, P_b is the applied load to the blunt notched specimen and a_b is its corresponding crack length, v_{pl} is the plastic displacement, and W is the specimen width.

Based on the experiments for a load separability test by Sharobeam and Landes [37,38], the crack length is represented by the following equation:

$$a_p = a_b\left(S_{pb}\Big|_{v_{pl}}\right)^{1/m} = a_b\left(\left.\frac{P_p}{P_b}\right|_{v_{pl}}\right)^{1/m} \tag{22}$$

where m is an exponent for the G function. Sharobeam et. al.'s work found it to be identical to the η_{pl} factor.

Wainstein et. al. also proposed a procedure for determining parameter 'm', using a pre-cracked specimen as well as a blunt-notch specimen. Resultantly, it is a procedure for determining the η_{pl} factor that does not use its standard form. This work used a blunt-notch specimen instead of a theoretical approach. Hence, it is nearly identical to the normalization method. This methodology was applied to several types of steels and polymers but did not show sufficient reliability for the measurement of J-R curves [53,54].

In summary, three types of direct uninstrumented methods were explored for J-R curve measurements. All of them are based on deformation theories or on certain types of deformation curves without crack extension. The prediction of a deformation curve is shown to be a key issue for each of the three types of the direct method as well as for the normalization method.

5. RECENT STUDIES FOR NORMALIZATION METHOD

5.1 Normalization Round Robin

At the workshop of ASTM subcommittee E08.08.02 held in November 1998, positive experiences with the method were extensively reported. From 1998 to 2000, a High Rate Round Robin testing campaign was conducted under the E08.08.02 subcommittee with the coordination of J.A. Joyce [40]. The efforts helped resolve issues with the suitability of this method as an ASTM method for elastic-plastic fracture test under dynamic or impact loading conditions.

In the High Rate Round Robin tests [40], however, the results of the normalization method could not be compared with any other well-established methods as no suitable method was available as a reference due to the aforementioned difficulties. With the new Annex A15 developed for its implementation and added into the ASTM Method E1820-01, the need for systematic validation regarding the consistency of the normalization method with a well-established standard method became apparent.

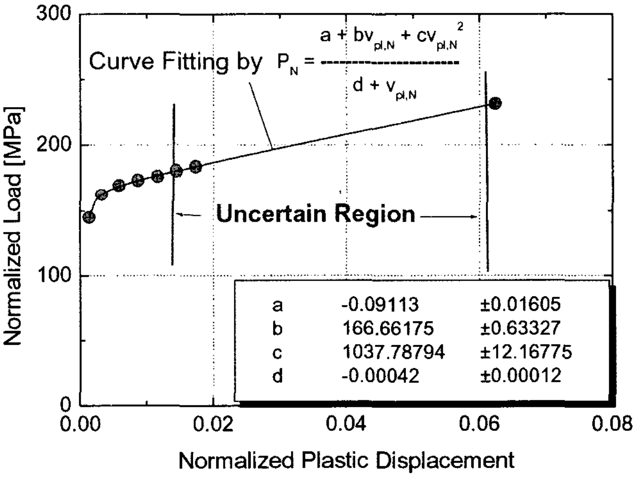
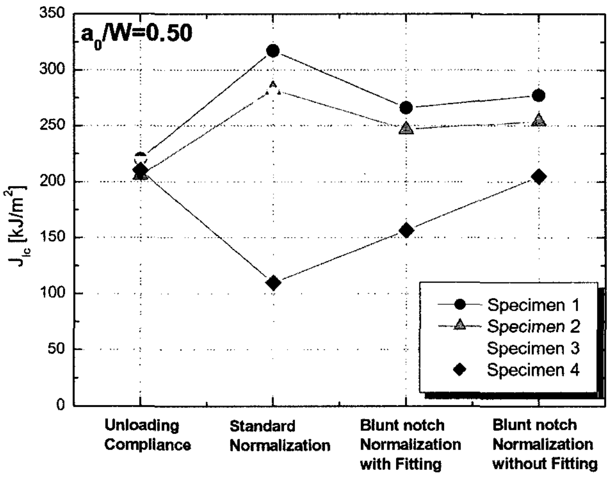


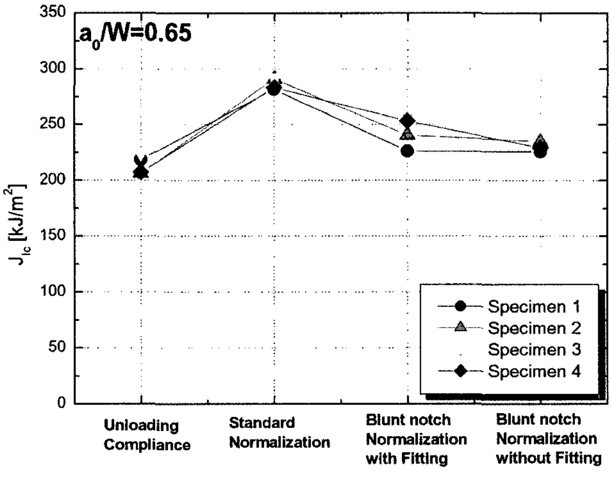
Fig. 14. Uncertainty of the Normalization Curve Determination

For this reason, a 'Normalization Round Robin under Static Loading Condition' was conducted by ASTM subcommittee E08.08.02 and Seoul National University [55]. In this round robin involving 10 laboratories in four countries, the normalization method exhibited relatively large maximum deviation among the data for tests at $a_0/W=0.5$, and displayed systematical differences in the average J_{Ic} value compared to those of unloading compliance method at $a_0/W=0.65$, as shown in Fig. 13. In order to decrease the J_{Ic} deviations several alternative techniques were applied, which were alternative data selection techniques for the curve fitting. However, they also failed to improve the agreement with the unloading compliance method.

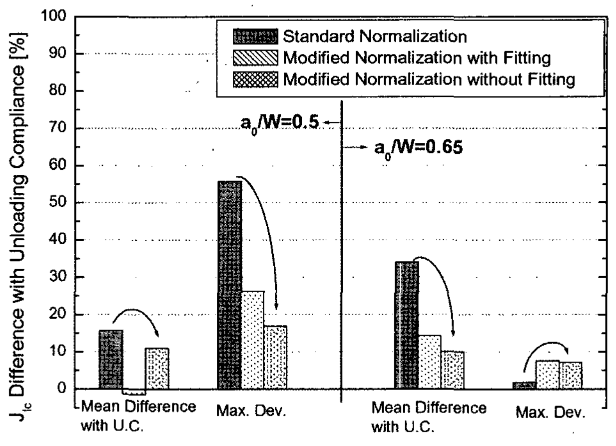
As shown in Fig. 14, the fitting data selection depends mainly on the tangent point that is determined by a linear projection from the final point. This procedure has evolved from extensive experimental experiences with various types of materials and/or test conditions. Nevertheless, from the point of view of fracture mechanics, there is no significant basis for the assumption that the stable crack growth starts at the tangent point.



(a) J_{Ic} values in $a_0/W=0.5$



(b) J_{Ic} values in $a_0/W=0.65$



(c) Mean difference in J_{Ic} between the unloading compliance method and normalization method.

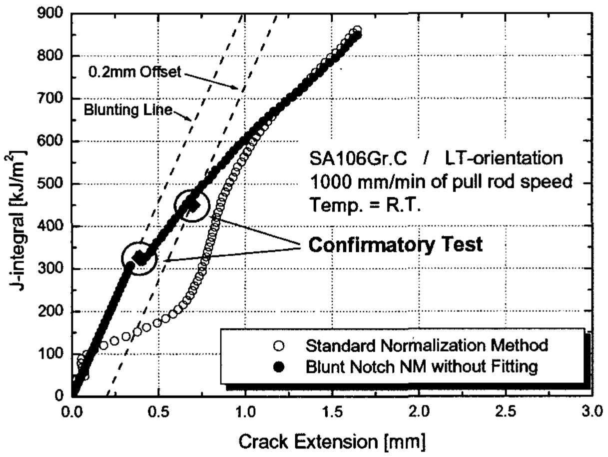
Fig. 15. J_{Ic} Values for the Standard Normalization Method and the Modified Normalization Method under Static Loading Conditions [56]

The static loading round robin for the normalization method indeed showed that the tangent points can be found at various locations even for the same material under nominally identical test conditions even with a small deviation of the measured load data. Nonetheless, the location of the tangent point deeply affects the J_{Ic} values, especially due to the lack of data at large displacement region. As shown in Fig. 14, it is conceivable that the compromised reproducibility and agreements originated from the variability of the fitting data selection in addition to the lack of data in the end part of the normalization curve.

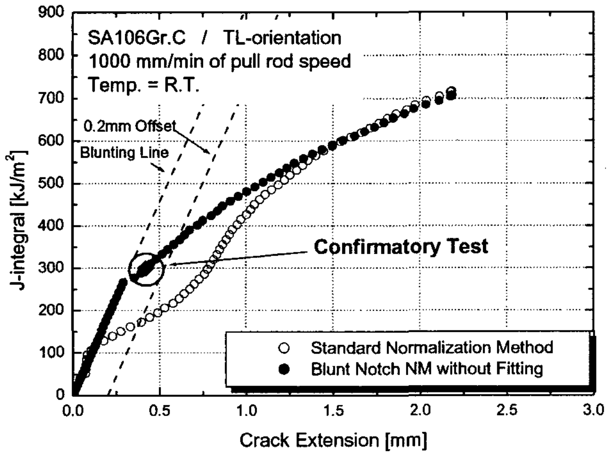
5.2 Modified Normalization Method Using Blunt Notch Specimen [56]

Based on the normalization round robin and the basic study of the deformation behavior of a CT specimen, Oh et. al. proposed a modified normalization method using an additional blunt notch specimen [56]. In his thesis, a deformation analysis for the CT specimen was conducted using an analytic engineering approximation and finite element analysis. Resultantly, the analytical engineering approximation approaches were not applicable to the normalization method. A 3-D FEA showed a normalization curve that agreed with the experiments when it was corrected by the final point of the experimental data. However, this requires extensive and an exceedingly high level of work as well as time for application to normalization method.

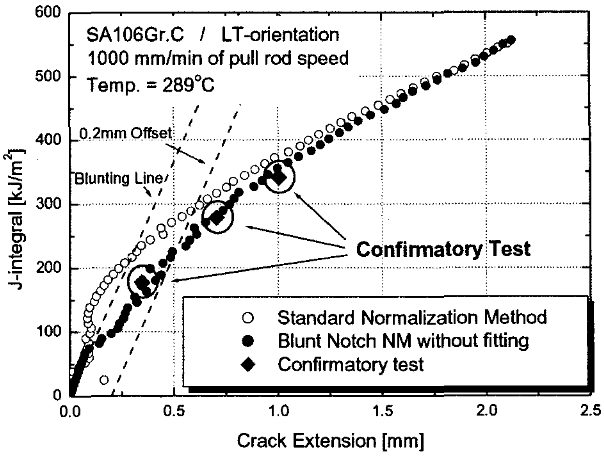
For this reason, Oh et al. conducted an experimental approach in order to obtain reliable normalization curves using the blunt-notch specimen, as shown in Fig. 6-1. Specimens machined with a blunt-notch have been used by other researchers [37,49,52~54], as an experimental technique to intentionally suppress the crack extension. Joyce et. al. [48] used blunt-notch specimens in order to determine the reference curve of the load ratio method. Wainstein et. al. [53] also used blunt-notch specimens while developing the load separation method, but the method did not produce the higher reliability, as mentioned earlier.



(a) LT orientation at room temperature



(b) TL orientation at room temperature



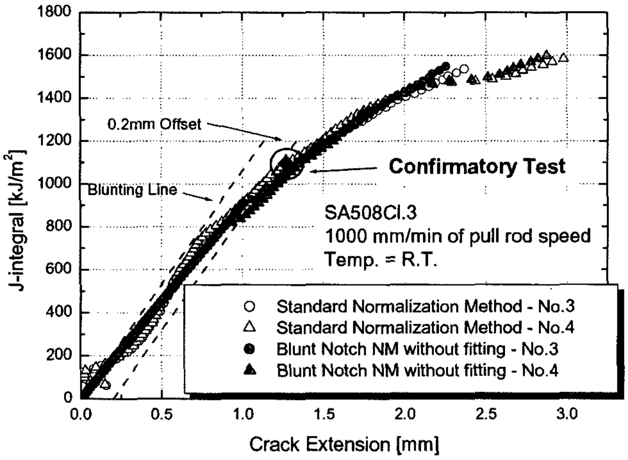
(c) LT orientation at an operating temperature of 289°C

Fig. 16. J-R Curves of SA106 Gr.C Determined by the Standard Normalization Method and the Modified Normalization Method under Dynamic Loading Conditions [56]

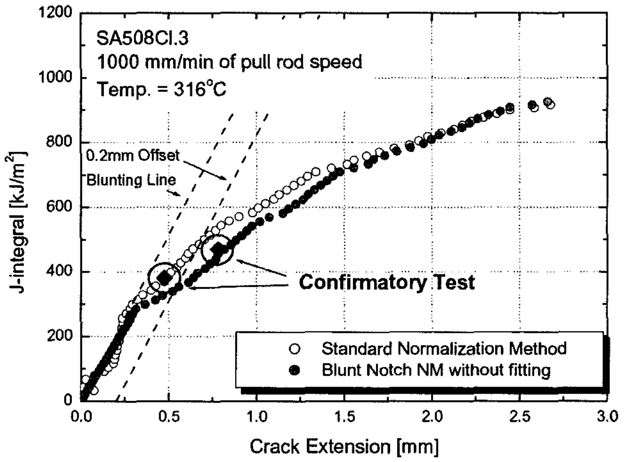
The modified procedure for the normalization method using a blunt-notch specimen has been developed and was initially applied to SA106 Gr.C low carbon steel under a static loading condition. Application results show that the proposed modified method produces J_{Ic} values with much better agreement with unloading compliance methods, as shown in Fig. 15.

Additionally, this modified normalization method was applied to three types of nuclear piping or pressure vessel materials under dynamic loading conditions of 1 m/min of load point displacement rate. Figs. 16~18 show the J-R curves determined by standard normalization method and modified normalization method.

Results with SA106 Gr.C at room temperature show that the standard normalization method overestimates the crack lengths in the J_{Ic} region and leads to a J-R curve with an unusual sigmoidal shape, as shown in Figs. 16 (a) and (b). This relates to the tangent point location in the early part of the normalization curve due to the large effects of the yield point elongation highlighted in its tensile test curve. With this exception, the standard normalization method predicts the larger crack lengths in the J_{Ic} region leading to the higher J_{Ic} values compared with the modified method. These observed tendencies for the standard normalization method and the modified method are in exact agreement with both the static loading application results and the

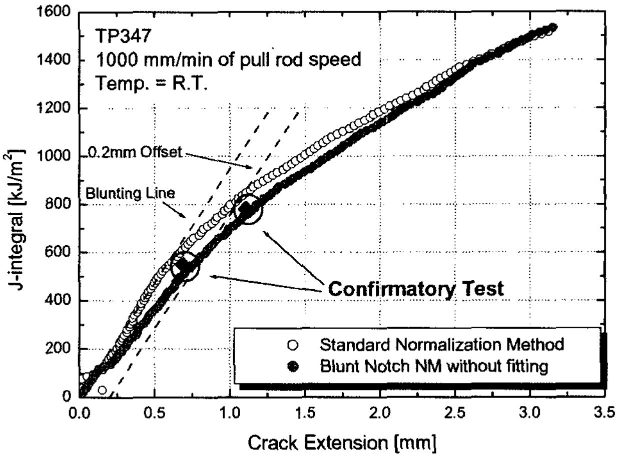


(a) Room temperature

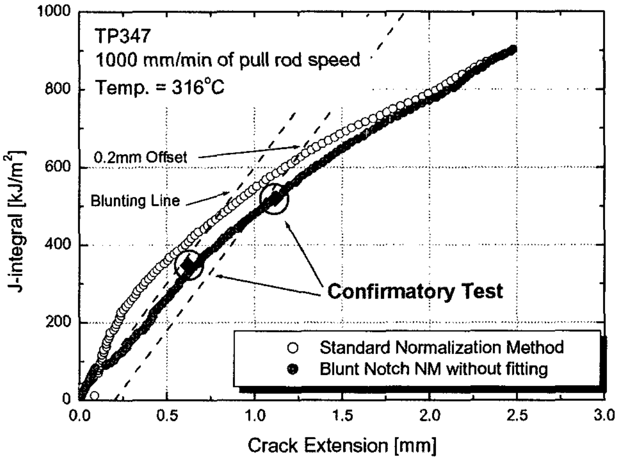


(b) Operating temperature of 316°C

Fig. 17. J-R Curves of SA508 Cl.3 Determined by the Standard Normalization Method and the Modified Normalization Method under Dynamic Loading Conditions [56]



(a) Room temperature



(b) Operating temperature of 316°C

Fig. 18. J-R Curves of TP347 Determined by the Standard Normalization Method and the Modified Normalization Method under Dynamic Loading Conditions [56]

normalization round robin results. Exceptional results for SA106 Gr.C at room temperature are consistent with the unusual J-R curve.

For each of these materials, confirmatory tests were conducted using more than one specimen. For SA508 Cl.3 heavy section forged steel, the confirmatory tests could not verify the modified normalization method on account of the significant specimen-to-specimen variation due to material inhomogeneity. For two other materials including SA106 Gr.C and TP347, confirmatory tests served as good verification for the reliability of the modified normalization method, as shown in Figs. 16 and 18.

With a smaller tip radius of a blunt notch specimen, cracking is easier to initiate during loading. As the measured data after crack initiation can not be used in J-R curve construction, it is not possible to determine a J-R curve for an intended crack extension. In contrast, a blunt notch specimen with an excessively large tip radius makes significantly different deformation curve from the sharp cracked specimen. Therefore, it is not possible to determine a reliable J-R curve with a blunt-notch specimen unless it has the appropriate notch radius.

Oh et. al. used blunt notch specimens with a 1 mm tip radius. This value of 1 mm was selected as an appropriate value based on experimental grounds and 3-D FEA results. Nevertheless, they could not propose any type of procedure for determining an appropriate tip radius of a blunt notch specimen. Future work is needed regarding this subject.

6. SUMMARY

In this article, test methodologies were reviewed for dynamic loading J-R test from the viewpoint of the leak before break (LBB) of nuclear piping. The unloading compliance method, which is known to be the most reliable and is widely used, is can not be applied to dynamic loading J-R tests. The direct current potential drop method is acceptable for dynamic loading tests but causes a noise problem during the rapid loading of carbon steel materials.

Several types of direct methods that do not use additional measuring crack extensions, have been developed. Although the normalization method was added to ASTM standard test method E1820-01 in 2001, it showed a relatively large amount of deviation among the data or displayed systematical differences compared to the unloading compliance method in a normalization round robin program. In 2006, a modified normalization method was proposed using additional blunt notch specimens, in order to improve the reliability of the normalization method under dynamic loading conditions. In order to improve the reliability of a leak before break for nuclear piping, further studies are needed as regards the modified normalization method.

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REFERENCES

[1] Code of Federal Regulations 10CFR Part 50, Appendix A, United States Government, Nov. 1998.

[2] Harris, D.O., Lim E.Y. and Dedhia, D.D., NUREG/CR-2189, Vol.5, US Nuclear Regulatory Commission, 1981.

[3] US Nuclear Regulatory Commission, NUREG-0609, Jan. 1981

[4] US Nuclear Regulatory Commission, "Evaluation of potential for pipe break", NUREG-1061, Vol.3, Oct. 1984.

[5] US Nuclear Regulatory Commission, Draft Standard Review Plan 3.6.3 "Leak-Before-Break Evaluation Procedure", Mar. 1987.

[6] Mukherjee, S.K., SzySlowSki, J.J., Chexal, V., Norris, D.M., Goldstein, N.A., Beaudoin, B.F., Quinones, D.F. and Server, W.L., "Rupture hardware minimization in pressurized water reactor piping", Journal of Pressure Vessel Technology, Vol. 111, 1989, pp. 64~71.

[7] Rice, J.R., "A path independent integral and the approximate analysis of strain concentration by notches and cracks." Journal of Applied Mechanics, Vol. 35, 1968, pp. 379~386.

[8] Hutchinson, J.W., "Singular behavior at the end of a tensile crack tip in a hardening material.", Journal of the Mechanics and Physics of Solids, Vol. 16, 1968, pp. 13~31.

[9] Rice, J.R. and Rosengren, G.F., "Plane strain deformation near a crack tip in a power-law hardening material." Journal of the Mechanics and Physics of Solids, Vol. 16, 1968, pp. 1~12.

[10] Anderson, T.L., "Fracture mechanics : Fundamentals and applications, Second edition," CRC Press, 1995.

[11] Lepik, O.E. and Mukherjee, B., "Ductile fracture properties for assessing Leak-Before-Break issues in ferritic weldments", International Journal of Pressure Vessel and Piping, Vol. 43, 1990, pp. 285~300.

[12] Mukherjee, B., "J-resistance curve leak-before-break test program on material for the darlington nuclear generating station", International Journal of Pressure Vessel and Piping, Vol. 31, 1988, pp. 363~385.

[13] Mukherjee, B., "Observations on the effect of post-weld heat treatment on J-resistance curves of SA-106B seamless piping welds", Nuclear Engineering and Design, Vol. 111, 1989, pp. 63~75.

[14] Marschall, C.W., Wilkowski, G.M., Krishnaswamy, P. and Mohan, R., "Effect of dynamic strain aging on the strength and toughness of nuclear ferritic piping at LWR temperatures", NUREG/CR-6226, 1994.

[15] Marschall, C.W., Landow, M.P. and Wilkowski, G.M., "Loading rate effects on strength and fracture toughness of pipe steels used in Task 1 of the IPIRG program", NUREG/CR-6098, 1993.

[16] Dahl, W. and Kalwa, C., "Investigations on strength and ductility of base metals and welded joints of steels for power plants at elevated temperatures", Nuclear Engineering and Design, Vol.137, 1992, pp. 335~341.

[17] Kim, J.W., "Effect of Dynamic Strain Aging on the Leak-Before-Break Assessment in SA106 Gr.C Piping Steel", Ph.D. Thesis, Korea Advanced Institute of Technology, 1997.

[18] Korean Institute of Nuclear Safty, "Korean Standard Review Guide 3.6.3-1 (Draft)".

[19] Clarke, G.A., Andrews, W.R., Paris, P.C. and Schmidt, D.W., "Single Specimen Tests for J_{Ic} Determination," in Mechanics of Crack Growth, ASTM STP590, American Society for Testing and Materials, Philadelphia, 1976, pp. 24~42.

[20] Joyce, J.A. and Gudas, J.P., "Computer Interactive JIc Testing of Navy Alloys," in Elastic-Plastic Fracture, ASTM STP668, J.D. Landes, J.A. Begley and G.A. Clarke, Eds., American Society for Testing and Materials, Philadelphia, 1979, pp. 451~468.

[21] Vassilaros, M.G. and Hackett, E.M., "J-integral R-Curve Testing of High Strength Steels Utilizing the Direct-Current Potential Drop Method", Fracture Mechanics : Fifteenth Symposium, ASTM STP 833, R.J. Sanford, Ed., ASTM International, West Conshohocken, PA, 1984, pp. 535~552.

[22] Wilkowski, G.M., Wambaugh, J.O. and Probhat, K., "Single Specimen J-Resistance Curve Evaluations Using the Direct Current Potential Method and a Computerized Data Acquisition System", Fracture Mechanics : Fifteenth Symposium, ASTM STP 833, R.J. Sanford, Ed., ASTM International, West Conshohocken, PA, 1984, pp. 553~576.

[23] Landow, M.P. and Marschall, C.W., "Experience in Using

Direct Current Electric Potential to Monitor Crack Growth in Ductile Metals", Elastic-Plastic Fracture Test Methods : The User's Experience (Second Volume), ASTM STP 1114, 1991, pp. 163~117.

[24] Yoon, J.H., Lee, B.S., Oh, Y.J. and Hong, J.H., "Effects of Loading Rate and Temperature on J-R Fracture Resistance of an SA516-Gr.70 Steel for Nuclear Piping", International Journal of Pressure Vessels and Piping, Vol.76, 1999, pp. 663~670.

[25] Oh, Y.J., Kim, J.H. and Hwang, I.S., "Dynamic Loading Fracture Tests of Ferritic Steel Using the Direct Current Potential Drop Method", Journal of Testing and Evaluation, Vol.30, No.3, 2002, pp. 221~227.

[26] Kang, K.J., Kim, S.Y., Kim, H.J. and Jeong, D.Y., "Effect of loading rate upon fracture behavior of ferritic steel under large scale yielding", Nuclear Engineering and Design, Vol. 219, 2003, pp. 11~18.

[27] Kim, K.C., Kim, J.T., Suk, J.I., Sung, U.H. and Kwon, H.K. "Influences of the Dynamic Strain Aging on the J-R Fracture Characteristics of the Ferritic Steels for Reactor Coolant Piping System", Nuclear Engineering and Design, Vol. 228, 2004, pp. 151~159.

[28] American Society for Testing and Materials, "Standard Test Method for Measurement of Fracture Toughness, ASTM Method E1820-01", Annual Book of ASTM Standards, Vol. 03.01.

[29] Private communication with Prof. J.A. Joyce, Department of Mechanical Engineering, US Naval Academy in March 2006.

[30] Landes, J.D. and Herrera, R., "A New Look at J-R Curve Analysis," International Journal of Fracture, Vol. 36, 1988, pp. R9~R14.

[31] Herrera, R. and Landes, J.D., "Direct J-R Curve Analysis of Fracture Toughness Tests," Journal of Testing and Evaluation, Vol. 16, No. 5, Sept. 1988, pp. 427~449.

[32] Herrera, R. and Landes, J.D., "Direct J-R Curve Analysis: A Guide to the Methodology," in Fracture Mechanics: Twenty-First Symposium, ASTM STP 1074, J.P. Gudas, J.A. Joyce and E.M. Hackett, Eds., American Society for Testing and Materials, Philadelpia, 1990, pp. 24~43.

[33] Landes, J.D., Zhou, Z., Lee, K. and Herrera, R., "Normalization Method for Developing J-R Curves with the LMN Function," Journal of Testing and Evaluation, JTEVA, Vol. 19, No. 4, July 1991, pp. 305~311.

[34] Lee, K. "Elastic-Plastic Fracture Toughness Determination under Some Difficult Conditions", Ph.D. Thesis, The university of Tennessee, Knoxville, 1995.

[35] Ernst, Hugo, Paris, P.C., Rossow, Mark and Hutchinson, J. W., "Analysis of Load-Displacement Relationships to Determine J-R Curve and Tearing Instability Material Properties", Fracture Mechanics, ASTM STP677, C. W. Smith, Ed., American Society for Testing and Materials, 1979, pp. 581~599.

[36] Ernst, H.A., Paris, P.C. and Landes, J.D., "Estimation on J-Integral and Tearing Modulus T from a Single Specimen Test Record," Fracture Mechanics: Thirteenth Conference, ASTM STP 743, Richard Roberts, Ed., American Society for Testing and Materials, 1981, pp. 476~502.

[37] Sharobeam, M.H. and Landes, J.D., "The Load Separation Criterion and Methodology in Ductile Fracture Mechanics", International Journal of Fracture, Vol. 47, 1991, pp. 81~104.

[38] Sharobeam, M.H. and Landes, J.D., "The Load Separation and η_{pl} Development in Precracked Specimen Test Records", International Journal of Fracture, Vol. 59, 1993, pp. 213~226.

[39] Joyce, J.A., et al. "ASTM E08.08.02 Workshop on Normalization", Presentation materials, November 4, 1998.

[40] Joyce, J.A., "Analysis of the E08.08.02 High Rate Round Robin Based on Proposed Annexes to ASTM Method E 1820", Journal of Testing and Evaluations, Vol. 29, No. 4, July 2001, pp. 329~351.

[41] Rice, J.R., Paris, P.C. and Merkle, J.G., Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, 1973, pp. 231-345.

[42] Merkle, J.G. and Coten, H.T., "A J-integral Analysis for the Compact Specimen, Considering Axial Force as Well as Bending Effects", ASME Paper No. 74-PVP-33, 1974.

[43] Landes, J.D., Walker, H. and Clarke, G.A., Elastic-Plastic Fracture, ASTM STP 668, 1979, pp. 266~287.

[44] Clarke, G.A. and Landes, J.D., "Evaluation of the J integral for the Compact Specimen", Journal of Testing and Evaluation, Vol.7, No.5, 1979, pp. 264~269.

[45] Donoso, J.R. and Landes, J.D., "The Common Format Equation Approach for Developing Calibration Functions for Two-Dimensional Fracture Specimens from Tensile Data", Engineering Fracture Mechanics, Vol. 54, No. 4, 1996, pp. 499~512.

[46] Hu, J.M., Albrecht, P. and Joyce, J.A., "Load Ratio Method for Estimating Crack Extension", Fracture Mechanics: Twenty-Second Symposium (Volume I), ASTM STP 1131, H.A. Ernst, A. Savena and D.L. McDowell, Eds., ASTM, Philadelphia, 1992, pp. 880~903.

[47] Chen, X.G., Albrecht, P., Wright, W.J. and Joyce, J.A., "Improved Load Ratio Method for Predicting Crack Length", Special Applications and Advanced Techniques for Crack Size Determination, ASTM STP 1251, ASTM, Philadelphia, 1995, pp. 83~103.

[48] Joyce, J.A., Albrecht, P., Tjiang, H.C. and Wright, W.J., "Compliance ratio method of estimating crack length in dynamic fracture toughness tests", ASTM STP 1406, 2001, pp. 139~157.

[49] Candra, H., Wright W.J. and Albrecht, P., "Experimentally Determined Key Curves for Fracture Specimens", International Journal of Fracture, Vol. 117, 2002, pp. 247~267.

[50] Lee, B.S., Yoon, J.H. and Hong, J.H., "A Modified Load Ratio Method for Characterizing J-R Curves of CT Specimens", Proceedings of the KSME 1997 Fall Annual Meeting A, Korean Society of Mechanical Engineers, 1997, pp. 990~995.

[51] Byun, Thak-Sang, Lee, Bong-Sang, Yoon, Ji-Hyun and Hong, Jun-Hwa, "An Iteration Method for Directly Determining J-Resistance Curves of Nuclear Structural Steels", Journal of Materials Science, Vol. 34, 1999, pp. 2039~2047.

[52] Cassanelli, A.N., Cocco, R. and de Vedia, L.A., "Separability Property and η_{pl} factor in ASTM A387-Gr22 Steel Plate", Engineering Fracture Mechanics, Vol. 70, 2003, pp. 1131~1142.

[53] Wainstein, J., de Vedia, L.A. and Cassanelli, A.N., "A Study to Estimate Crack Length using the Separability Parameter Spb in Steels", Engineering Fracture Mechanics, Vol. 70, 2003, pp. 2489~2496.

[54] Wainstein, J., Frontini, P.M. and Cassanelli, A.N., "J-R Curve Determination using the Load Separation Parameter

Spb Method for Ductile Polymers", Polymer Testing Vol. 23, 2004, pp. 591~598.

[55] Oh, Young Jin, Hwang, Il Soon and Joyce, J. A., "Round Robin Test on Normalization Method under Static Loading Condition", will be published in Journal of Testing and Evaluations, November 2006.

[56] Oh, Young Jin, "Development of Modified Normalization Method using Blunt-Notch Specimen for J-R Test of Nuclear Piping Materials", Ph.D. Thesis, Seoul National University, 2006.