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Dynamic loading Fracture Tests of Ferritic Steel using Direct Current Potential Drop Method

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Abstract

To apply Leak-Before-Break (LBB) concept to a nuclear piping, the dynamic strain aging of low alloy steel materials has to be considered. For this goal, the J-R tests are needed over a range of temperatures and loading rates, including rapid dynamic loading conditions. In dynamic J-R tests, the unloading compliance method can not be applied and usually the direct current potential drop (DCPD) method has been used. But. Even the DCPD method is known to have the problem in defining the crack initiation point due to a potential peak arising in early part of loading of ferromagnetic materials. In this study, the characteristics of measured DC potential peaks were investigated for SA106Gr.C piping steels, and the definition of crack initiation point was determined by back tracking from physically measured final crack length. It is proposed that this technique could be applied as an improved DCPD method applicable for dynamic loading J-R test.

Introduction

The leak-before-break (LBB) approach in nuclear power plants utilizes the fracture mechanics technology to demonstrate that a high-energy fluid piping is very unlikely to experience a double-ended guillotine break or its equivalent as longitudinal or diagonal splits. When LBB is demonstrated, it is advantageous that pipe whip restraints or jet impingement shield for the protection of pipings of safety systems and other equipment could be removed and this would result in significant savings in both cost and radiation exposure.[1]

It is well known that materials susceptible to dynamic strain aging (DSA) have tensile and J-R characteristics varying significantly with temperature and loading rate.[2-3] For these materials, tensile and J-R test have to be accomplished at various loading rates ranging over anticipated service conditions, to determine the lower-bound of properties. Also, in Korean Standard Review Plan 3.6.3, and 3.6.3-1 for nuclear power plants, it is specified that dynamic fracture test must be performed for carbon steels to estimate DSA.[4] But, J-R standard test methods which can be applied for rapid loading rate conditions of ferritic steel materials, do not exist yet.

The current J-R testing standard available for ASTM allows the three ways of crack length measurement. They are 1)multi-specimen method [5], 2)unloading compliance method [6], and 3)direct current electric potential drop (DCPD) method [7]. The multi-specimen method employs a number of specimens to construct one J-R curve [12]. With each specimen, a monotonous loading is applied to make certain amount of crack growth and single value of J are determined. In order to construct entire J-R curve, however, many tests are required. As the unloading compliance method is a single-specimen method, it is more economical than the multi-specimen method[12]. But, in this method, the specimen loading is not continuous as specimen must be partially unloaded at frequent intervals during a test for crack length measurement. For this reason, this method can not be applied to the J-R test in continuous dynamic loading. In contrast, DCPD method can be employed for both single-specimen and continuous loading, so the dynamic J-R test can be performed with this method.

But, it is reported that DCPD method has its own when it is applied to a dynamic test of ferromagnetic materials.[8-10] The problem is an abnormal voltage pulse superimposed on the normal DC-electric potential signal[8]. It was reported that no problems were encountered in using the DCPD method in rapid loading tests in the non-magnetic materials such as austenitic stainless steels, and the problem was encountered in the ferritic steel matrials. It is believed that the voltage pulse originates from the ferromagnetic properties of the ferritic steel, probably due to the sudden reorientation of ferromagnetic domains and the generation of electromotive force when stress is applied rapidly.[8]

In spite of the problem like this, DCPD method has been applied to dynamic J-R tests due to the lack of acceptable alternative methods. In this study, potential impact of ferromagnetic noise on the measurement accuracy of dynamic J-R curve is examined for a low alloy steel. DCPD potential peak is measured as a function of input currents and loading rates. The accuracy of the dynamic J-R test for ferritic low alloy steel is verified using alternative method that are free from the ferromagnetic effect. It is attempted to explore alternative methods to improve the accuracy of the fracture mechanics analysis including LBB of nuclear piping.

Direct Current Potential Drop (DCPD) method

Under a constant current flow, the electric potential or voltage difference across the crack plane will increase with increasing crack size due to modification of the electrical field and associated perturbation of the current streamlines. When the constant current is applied and the voltage is measured in the test specimen like Figure 1, the change in voltage can be related to crack size through an analytical model or an experimental calibration curve.

DCPD calibration for a crack length determination was initially proposed by Johnson et al..[8] This method has been employed by the many researchers[9-11], and recently its practice is standardized method in the ASTM E1737-96 Annexes 5 [7]. The relationship between voltage and crack size is taken from Johnson's work[8] as follows:

$$\frac{a}{W} = \frac{2}{p}\cos^{-1}\left[\frac{\cosh\left(\frac{py}{2W}\right)}{\cosh\left[\left(\frac{U}{U_0}\right)\cosh^{-1}\left[\frac{\cosh\left(\frac{py}{2W}\right)}{\cos\left(\frac{pa_0}{2W}\right)}\right]\right]}\right] \quad (1)$$

where U is electric potential signal, U_0 is initial electric potential signal, a is crack length, a_0 is initial crack length, W is specimen width, and y is potential lead wire spacing.

To determine the crack length, a plot of electric potential measured during the test as a function of crack-opening displacement(COD) is constructed as shown in Figure 2. By a linear best-fit of the data over the range from 0.1 to 0.5 P_{max}, U_B of Figure 2 is determined by an intersection of 5% offset line and the measured DCPD curve as the crack initiation point. This procedure is to remove plastic deformation effect for DCPD signals. In short, U_B is the calibration start point, and hence the accuracy in determining U_B is very important for a valid testing. But, in dynamic J-R test of ferritic steel, this procedure to define crack initiation point has the difficulty due to afore mentioned noise. The DCPD problems with dynamic J-R test of ferritic steels are illustrated by the test data shown in Figure 3. Voltage pulses superimposed on the DCPD signal, obscures the crack initiation point U_B.

Experiments

SA106Gr.C low alloy steel material, that is an archival material of main steam line piping in Ulchin nuclear power plant unit 3&4, was used in this study. This has ferrite-pearlite structures and its chemical compositions are shown in Table 1. One inch thickness Compact Tension(1TCT) standard specimens were used in dynamic loading J-R tests. To test in dynamic loading rate condition, a servohydraulic test machine with 25 ton load capacity and high speed data acquisition system was used. Overall test systems are shown in Figure 4.

At first, to examine the loading rate and input current effects for voltage pulses in DCPD signals, the J-R tests were conducted at various loading rates and input currents. Then, the results of DCPD method were compared with multi-specimen method and normalization method to examine the reliability of DCPD method. Each of test methods is explained below.

Multi-specimen method

In multi-specimen method, many tests are conducted for nominally identical specimens in order to construct entire one J-R curve. This method is seldom used in these days due to high cost and material consumption. But this is the only method which can be applied for dynamic loading J-R test of ferritc steel materials.

In ASTM Method E1737-96 A4, plastic J is expressed by following equation.

$$J_{pl} = \frac{\eta A_{pl}}{B_N b_0} \qquad (2)$$

where, η is geometry constant, A_{pl} is area of plastic deformation, B_N is specimen net thickness, and b_0 is initial ligament.

But this equation is not considered as a valid crack growth correction, so it can not be applied for large crack extension. In order to complement this shortcoming, following plastic J equation in ASTM standard E1737-96 A2 was used in this study.

$$J_{pl(i)} = \left[J_{pl(i-1)} + \left(\frac{\eta_{(i-1)}}{b_{(i-1)}} \right) \frac{A_{pl(i)} - A_{pl(i-1)}}{B_N} \right] \left[1 - \gamma_{(i-1)} \frac{a_{(i)} - a_{(i-1)}}{b_{(i-1)}} \right] \qquad (3)$$

$$\eta_{(i-1)} = 2.0 + 0.522 b_{(i-1)} / W, \quad \gamma_{(i-1)} = 1.0 + 0.76 b_{(i-1)} / W$$

where, (i) and (i-1) means the measurement counts. This equation is used in unloading compliance method or DCPD method. But, we used this equation in multi-specimen method using data of entire tested specimens.

Normalization method

Normalization method is a kind of direct method like key-curve method or load ratio method. Direct method means that crack lengths are measured using only load – load line displacement record without resorting to additional crack length measuring apparatus. The normalization method was proposed by Herrera and Landes et al. and has been improved up to the point when LMN function was proposed in 1991.[13] To evaluate a new proposed Annex to ASTM Method E1820, ‘ High rate round robin’ which was to apply normalization method to rapid loading J-R test, was completed in 2000. [14] For this reason, this method is worth to be compared with DCPD method in dynamic loading of ferritic materials.

Normalization method is based on the principle of load separation developed by Ernst et al. well described by the following equation.[15,16]

$$P = G(a/W) H(\nu_{pl}/W) \qquad (4)$$

where P is load, a is crack length, ν_{pl} is plastic displacement and W is specimen width dimension. When the load is divided by the crack length function, G, a normalized load, P_N, is defined which is a function only of plastic displacement.

$$P_N = \frac{P}{G(a/W)} = H(\nu_{pl}/W) \qquad (5)$$

In ASTM Method E1820 draft Annex, G(a/W) and fitting equation of P_N is determined as follows,

$$G(a/W) = WB\left[\frac{W-a}{W}\right]^{h_{pl}} \qquad (6)$$

$$P_N = \left[\frac{L + M\left(v_{pl}/W\right)}{N + \left(v_{pl}/W\right)}\right]\left(\frac{v_{pl}}{W}\right) \qquad (7)$$

where, B is specimen thickness, η_{pl} is geometry factor, L, M, N are fitting constants.

When P_N is determined by data fitting to Equation (7), the crack lengths are known at all points of load – load line displacement curve. In this study, more detail procedure for normalization method was made according to ASTM Method E1820 draft Annex in High Rate Round Robin draft report[14].

Direct Current Potential Drop method

Current input wires and potential output leads are placed according to ASTM Mehtod E1737-96. Current input wires were attached to the top and bottom edges at W/2 from the load line with bolts. By the resistance spot welding, one of the potential leads was near one side and another was near the other side, in an attempt to detect average crack length, as shown in Figure 5. DCPD signal is amplified by 2000 times and then entered into the high speed data acquisition system.

To determine J-R curve, the calibration equation of ASTM E1737-96 was used. But linear fitting and offset method to define crack initiation point, could not be used because of potential peak in ferromagnetic materials. Therefore, the crack initiation points were tracked back from the final crack lengths that were physically measured on fracture surfaces of broken specimens. The procedure for back tracking technique developed in this study is as follows ;

1) Determine final crack length that was physically measured by fracture surface from broken specimen according to ASTM Method E1737.

2) Determine any crack initiation point, and calculate J-R curve according to ASTM Method E1737-96 procedure

3) Compare final crack length in J-R curve with physically measured crack length.

4) Adjust the crack initiation point until final crack length in J-R curve is agreed with physically measured crack length.

5) Determine J-R curve finally using adjusted crack initiation point.

The J-R curve determined by back tracking DCPD method according to this procedure were compared with that determined by multi-specimen method and normalization method.

Results & Discussion

Potential peak characteristic

To characterize the DCPD potential peaks in ferromagnetic material J-R tests in dynamic loading and the effect of them in J-R curve determination, the dynamic loading tests were performed in various input currents and loading rates. The input currents of 50A and 100A, and the loading rates of 500mm/min, 1000mm/min and 2000mm/min are employed. All the tests were accomplished at room temperature condition. In this study, potential peak heights and the noise removal or recovery rates were examined in connection with input currents and loading rates.

To see the potential peak recovery rates, general potential peak shape is shown in Figure 6. The recovery rates were increased with decreasing loading rates, but clear dependence on input currents was not established as shown in Figure 6. The characteristics of potential peak height are shown in Figure 7. The peak height is increased with increasing loading rates, and again their clear tendency was not found. Nevertheless the observed characteristics can be explained by Faraday`s Law in electromagnetic theory. That is,

Loading rate	μ	Deformation rate of magnetic domain in crack tip	μ	Changing rate of Magnetic field intensity (∂B/∂t)	μ	Magnitude of electric field

This explanation is well substantiated by the former supposition[12] that that the voltage pulse originates from the ferromagnetic properties of the ferritic steel, probably due to the instantaneous reorientation of ferromagnetic domains when stress is applied rapidly.

The temperature effect for potential peak was shown in figure 8. The potential peak height changed little, but the potential peak recovery was more rapid in high temperature than in room temperature condition.

J-R curves

To determine the most reliable J-R curve of SA106Gr.C low alloy steel in dynamic loading rate, the multi-specimen method was used. The DCPD signals were measured for the each multi specimens, and J-R curves calculated by back tracking DCPD method and normalization method were compared with the result of multi-specimen method. All the tests were made at the loading rate of 1000 mm/min of and test temperature of 289 °C. These are seismic loading rate region and operating temperature of main steam line piping in Korean Standard Nuclear Power Plant, respectively.

Figure 9(a) shows the load – load line displacement curves of multi-specimens, and this has reproducibility enough to be applied to multi-specimen method. Figure 9(b) shows the most reliable J-R curve determined by multi specimen method. Figure 10 shows the overall J-R curve determined by multi-specimen method, back tracking DCPD method and normalization method. And the J-R curves determined by back tracking DCPD method and normalization method were agree well with that of multi-specimen method.

J_{Ic} and dJ/da in 2.5mm of crack extension of J-R curve determined by DCPD method and normalization method were calculated, and shown in Figure 11 (a) and (b), respectively. J_{Ic}`s determined by DCPD method had the smaller relative error than the normalization method does, and dJ/da`s in 2.5mm of crack extension determined by DCPD method showed the greater relative error than the normalization method does.

Conclusion

From the study of the accuracy of dynamic loading fracture tests of SA106Gr.C ferritic steel using direct current potential drop method, the following conclusions were made.

1) The DC potential peak characteristics is examined for ferritic steel on function of in various input currents, loading rates and temperature. The heights of potential peaks increase with increasing loading rate, and have no relationship with input currents. The recovery rates of potential peaks increase with decreasing loading rates.
2) The reliable J-R curve of SA106Gr.C low alloy steel were obtained in dynamic loading condition by multi-specimen method.
3) The J-R curves determined by the DCPD method with back tracking method are found to be reproducible and agreed well with those determined by multi-specimen method.
4) J_{Ic}`s determined by the back tracking DCPD method leads to the smaller relative error than the case of normalization method, but the dJ/da for 2.5 mm of crack extension shows the greater relative error with the back tracking DCPD method than those by the normalization method.

Acknowledgments

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Table 1. The chemical composition of SA106Gr.C nuclear piping steel

	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	V
Weight Percent %	0.24	0.23	1.08	0.011	0.011	0.11	0.09	0.04	0.09	0.007

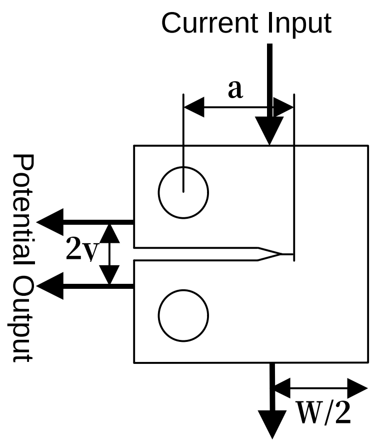


Figure 1. The basic principle of DCPD method

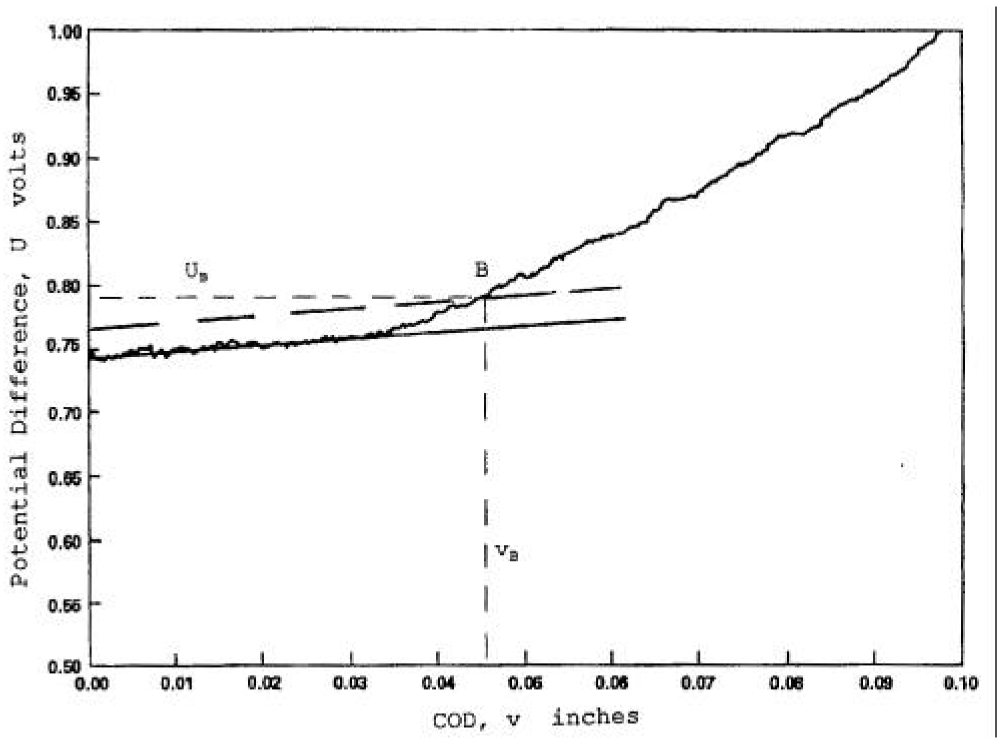


Figure 2. COD – DCPD curve for crack length calibration [7]

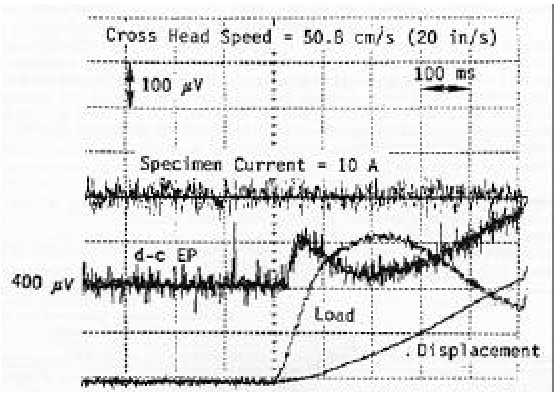


Figure 3. The example of DCPD potential peak of ferritic steel in dynamic loading [12]

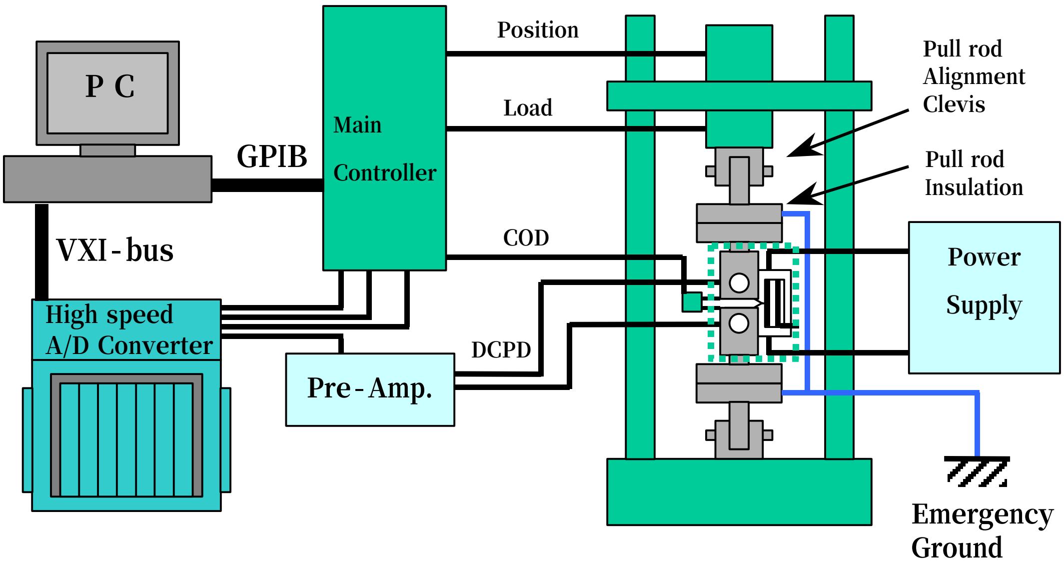


Figure 4. The schematic diagram of dynamic loading fracture testing system.

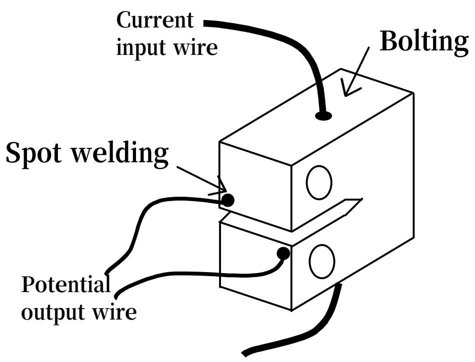


Figure 5. The wire connection for DCPD measurement

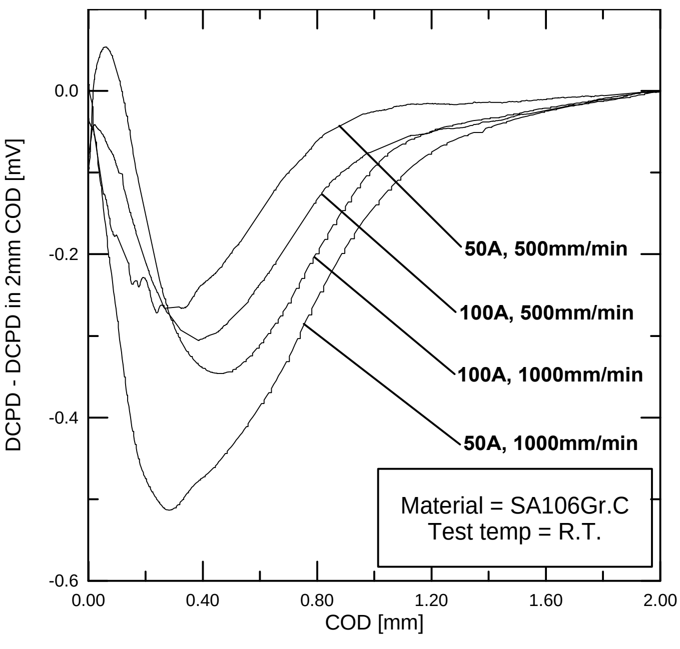
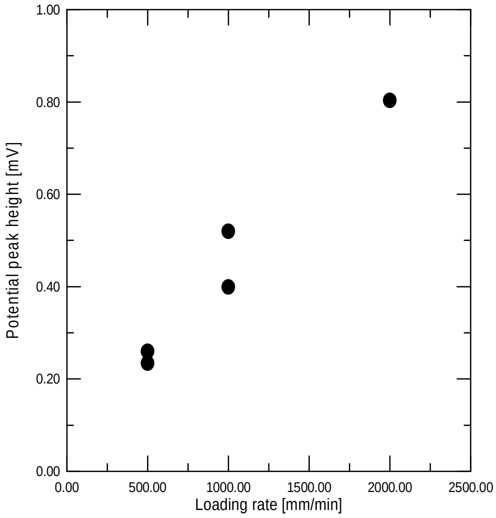
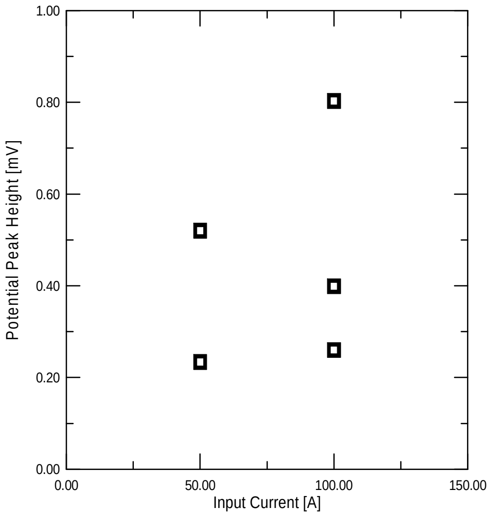


Figure 6. The recovery characteristic of potential peak



(a) Potential peak height versus loading rate



(b) Potential peak height versus input current

Figure 7. Characteristic of the potential peak height

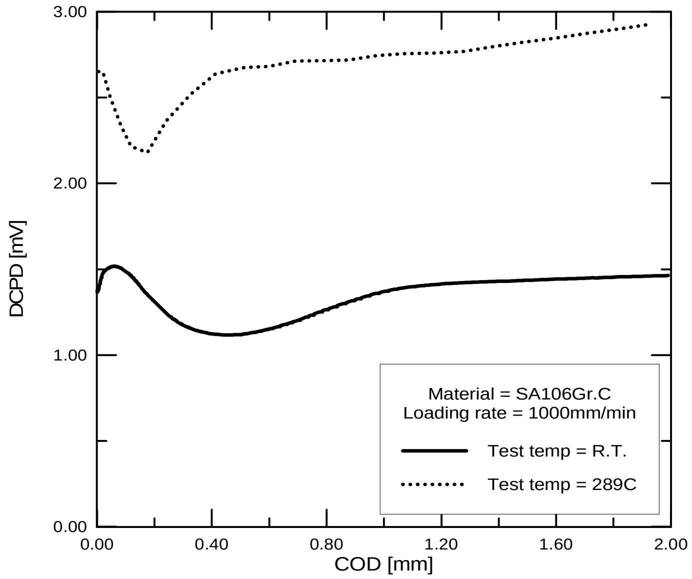
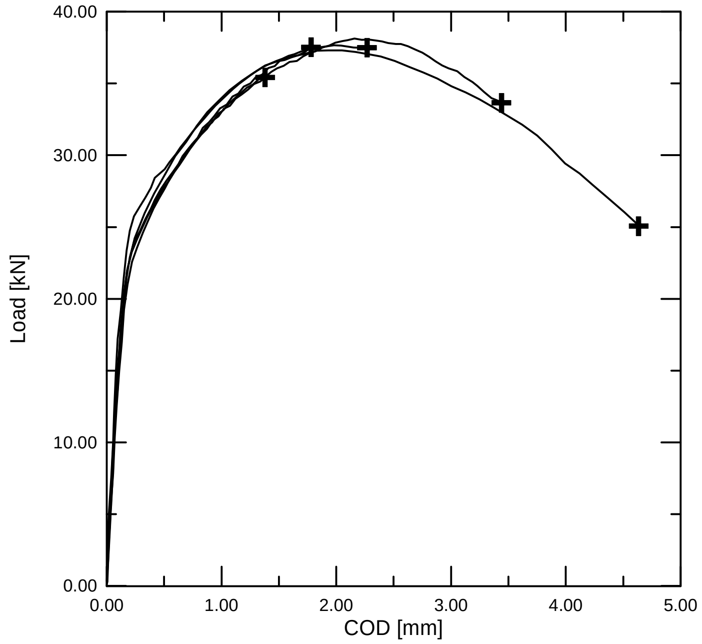
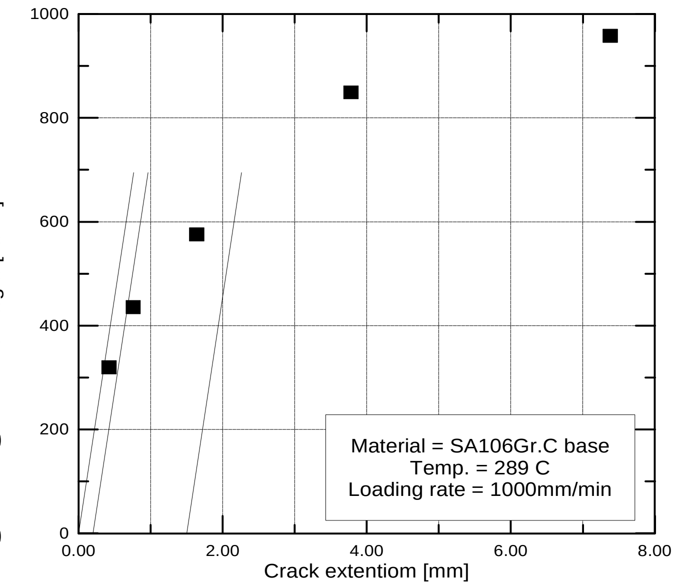


Figure 8. The temperature effect for potential peak



(a) Load – load line displacement curve

(b)
(c)
(d)
(e)



(b) J-R curve

Figure 9. Result of the multi-specimen method

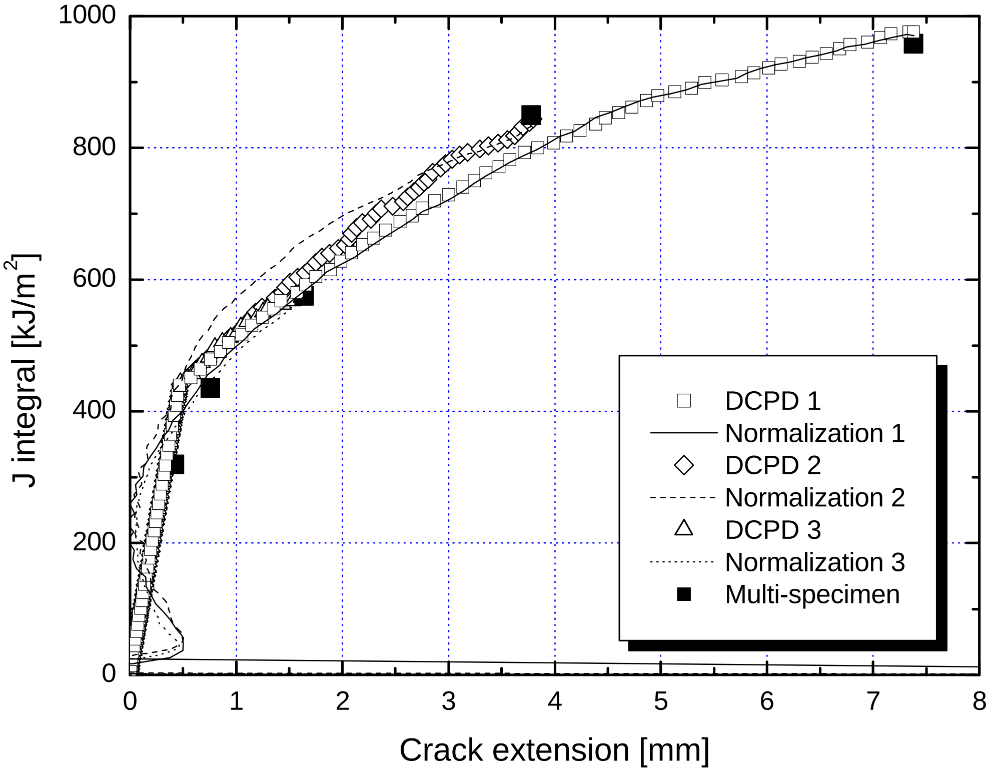
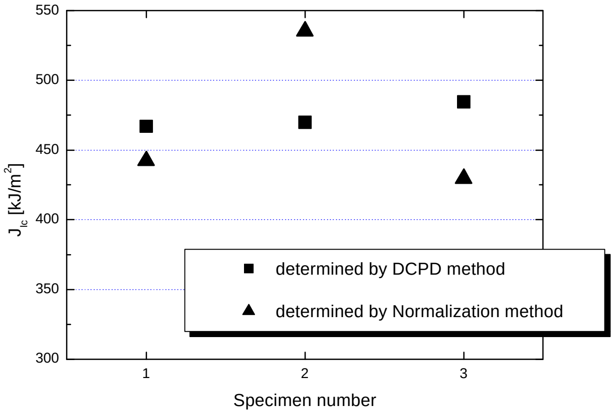
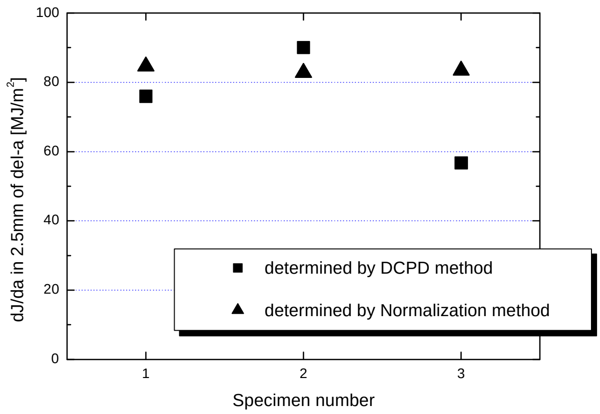


Figure 10. Overall J-R curves



(a) J_{Ic}



(b) dJ/da in 2.5mm of crack extension

Figure 11. J-R characteristics determined by back tracking DCPD method and normalization method.