Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division II

Application of Direct Current Potential Drop for Fracture Toughness Measurement

Xiang Chen[1], Randy K. Nanstad[2], and Mikhail A. Sokolov[3]

[1] Postdoctoral Research Associate, Oak Ridge National Laboratory, Oak Ridge, TN (chenx@ornl.gov)
[2] Group Leader, Oak Ridge National Laboratory, Oak Ridge, TN
[3] Senior R&D Staff, Oak Ridge National Laboratory, Oak Ridge, TN

ABSTRACT

Material fracture toughness based on *J-integral* versus crack-extension relationship (J-R curve) is investigated with direct current potential drop (DCPD) technique and compared with results from elastic unloading compliance (EUC) or normalization technique. The test matrix covered four different materials, half inch thickness and one inch thickness compact tension (C(T))specimens, and temperatures ranging from 24 °C to 600 °C. The original J-R curves from DCPD yielded much smaller Jq value than EUC or normalization results due to the influence of plastic deformation on potential drop. To counter this effect, two new methods for adjusting DCPD data have been proposed. After adjustment, the average difference in Jq between DCPD and EUC or normalization results is only about 8% whereas the difference in tearing modulus is about 17%. The promising results prove the applicability of DCPD for J-R curve determination for C(T) specimens especially in extreme environments, such as elevated temperatures, where conventional EUC method faces considerable challenges.

INTRODUCTION

To improve thermal efficiency, next generation nuclear reactors aim at operating at more severe environment, such as elevated temperatures and higher stress levels, than current reactors. Therefore, characterization of mechanical properties of structural materials for next generation nuclear reactors in extreme environments becomes vitally important from both engineering design and safety management point of view (Zhu et al. 2009). Among different mechanical properties of materials, fracture toughness and resistance curve (J-R curve) is a useful tool for evaluating material structural integrity in the presence of pre-existing defects. Extensive efforts have been continuously devoted to develop simplified and reliable methods for determining material J-R curve. A widely accepted practice for conducting ductile fracture toughness testing is ASTM standard E1820-11 (ASTM 2011). In ASTM E1820-11, the elastic unloading compliance (EUC) method is recommended for online crack length measurement. However, the EUC method becomes impractical in elevated temperature testing due to stress relaxation of the material and enhanced interference between the specimen, pin and clevis due to friction. To address this, ASTM E1820-11 Annex 15 also introduces the normalization method as an alternative J-R curve measurement method. In contrast to the EUC, the normalization method only requires initial crack length, final crack length, and load-displacement record to derive the J-R curve, although the crack length is based on the fitting of a normalization function without online experimental measurement.

Despite the advantage of the normalization method, it is necessary to develop a J-R curve test method with reliable online crack length measurement in elevated temperature testing. To fulfill this goal, direct current potential drop (DCPD) technique is investigated in this study. DCPD relies on the passage of a constant direct current through a specimen and the subsequent measurement of the voltage generated across an area in the specimen. As the crack propagates in the specimen, less area is available for the passage of the current, resulting in increase of electrical resistance and potential drop. Hence DCPD has a correlation with crack length and can be applied for online crack length measurement (Hicks and Pickard 1981, Lowes and Fearnehough 1971, McGowan and Nanstad 1981, Ritchie and Bathe 1978, Tong 2001). Previously, DCPD has been applied for J-R curve measurement although uncertainties existed especially in differentiating potential drop due to stable crack growth and material deformation (Lowes and Fearnehough 1971). In current investigation, two new methods for adjusting DCPD measurement to determine J-R curve is proposed. Validation of the adjustment methods are achieved by the comparison with results from the EUC or normalization method if EUC method is not able to yield valid J-R curve measurement.

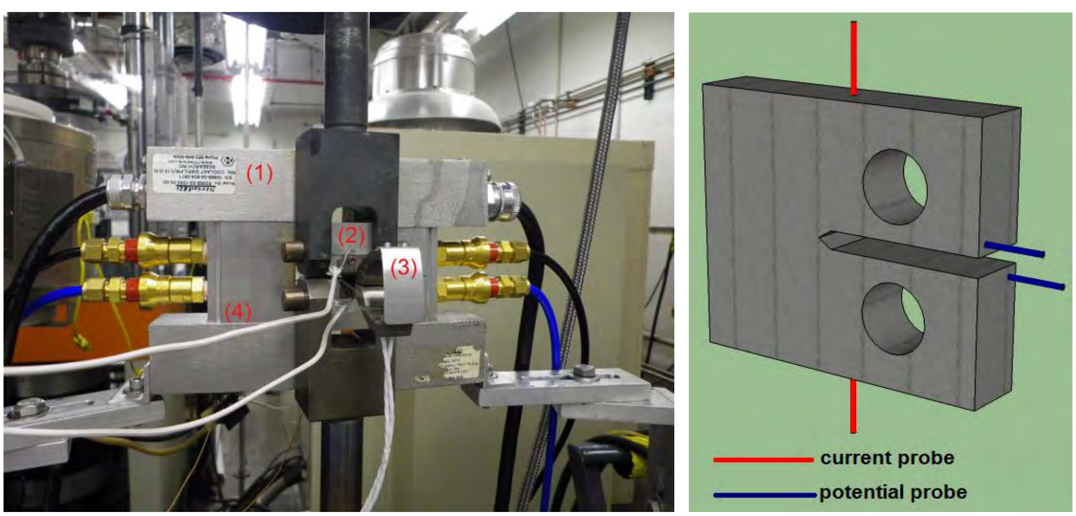
EXPERIMENTAL

Materials

Four different materials, covering broad categories of metallic materials including low alloy steel weld (MatA), low alloy steel heat affect zone (MatB), a Ni-based superalloy (MatC), and an advanced ferritic-martensitic steel (MatD), are tested in the current study to evaluate the applicability of DCPD technique for the J-R curve determination for different materials.

Specimen Configuration and Test Conditions

Standard half inch thickness (0.5T) and one inch thickness (1T) compact tension (C(T)) specimens machined from raw materials were used for J-R curve characterization. The C(T) specimens were firstly fatigue precracked to an initial crack length equaling one half of the specimen width and then side-grooved to remove 10% of specimen thickness on each side of the specimens. A servo-hydraulic test frame with infrared heating was employed for fracture toughness testing (Figure 1(a)). The front face crack mouth opening displacement of the specimen was measured by a displacement gage during the test. For the DCPD measurement, current probes and potential probes were spot welded to the specimen as shown in Figure 1(b). The current probes were spot welded midway between the back face of the specimen and the center line of pin holes. The potential probes were spot welded diagonally across the starter notch to average measurements of non-uniform crack fronts if applicable (ASTM 2011). The detailed test conditions are summarized in Table 1. For each test, load-displacement (including EUC if EUC was used for the analysis) and DCPD signal are recorded from the same specimen so that comparison between DCPD results and EUC or normalization results is made on the same specimen to avoid any influence due to different specimens.



(a) (b)

Figure 1. (a) Fracture toughness testing setup: (1) infrared heating, (2) C(T) specimen, (3) displacement gage, (4) potential probes; (b) location of current and potential probes for DCPD acquisition.

Table 1: Summary of test conditions

Material	Specimen type	Temperature (°C)
Low alloy steel weld (MatA)	1T C(T)	150, 371, 421
Low alloy steel HAZ (MatB)	1T C(T)	371, 538, 593
Ni-based superalloy (MatC)	0.5T C(T)	24, 100, 250, 600
Advanced ferritic-martensitic steel (MatD)	0.5T C(T)	24, 300, 500, 600

RESULTS & DISCUSSION

J-R Curves Based on Original DCPD Results

J-R curves based on original DCPD results are compared with results from EUC or normalization method. The online crack length of the DCPD test is calculated using Johnson's equation (Johnson 1965, Schwalbe and Hellmann 1981):

$$a = \frac{2W}{\pi}\cos^{-1}\frac{\cosh(\pi y/2W)}{\cosh\{(U/U_0)\cosh^{-1}[\cosh(\pi y/2W)/\cos(\pi a_0/2W)]\}} \tag{1}$$

where a is the crack length corresponding to potential drop U, W is specimen width, y is one half of the potential gage span, and a_0 and U_0 are initial crack length and potential drop, respectively. J-R curves of EUC and normalization method are obtained per ASTM standard E1820-11 with special requirements from Annex 2 and Annex 15. Initial assessment of J-R curves based on original DCPD results and J-R curves from EUC or normalization method indicates that J-R curves from original DCPD results yield much lower Jq values compared with other two methods (e.g. Figure 2). Moreover, the final crack extension from original DCPD results is much larger than prediction from the other two methods and optical measurement. As noted in the work of Bakker (Bakker 1985), material potential drop can also result from deformation, crack blunting, and void growth in the process zone ahead of the crack. If the influences of these factors are not accounted in the crack length prediction of DCPD, DCPD method would over-predict the actual crack growth resulting in much lower Jq value. Therefore adjustment on original DCPD results is needed.

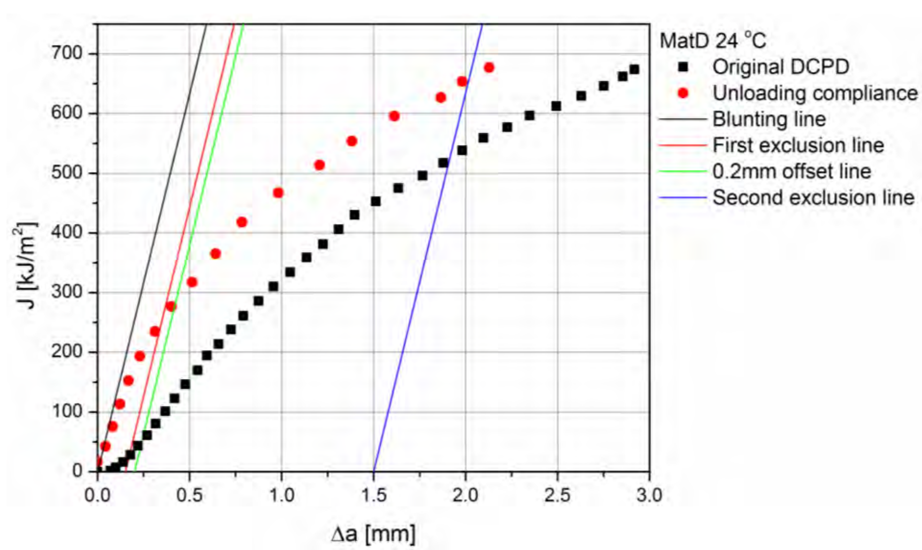


Figure 2. Comparison of J-R curves of original DCPD result and EUC for MatD at 24 °C.

DCPD Adjustment Methods

Two different methods for adjusting original DCPD J-R curves are proposed in this section. The first method applies to materials with regular crack growth behavior (MatC and MatD in this study), namely in-plane fracture surface and straight crack growth front line, whereas the second method applies to materials with irregular crack growth behavior (MatA and MatB in this study), i.e. curved fracture surface and non-straight crack growth front line.

The first DCPD adjustment method is shown in Figure 3(a) using the J-R curve of MatD tested at 24 °C as an example. The final crack extension of the original J-R curve is longer than the actual measured one. If the crack length prediction form DCPD is correct, the final crack extension of the DCPD J-R curve should match the actual measured one. Hence all the crack extension values of the original DCPD J-R curve are reduced with the amount equal to the difference between the actual measured crack extension and the original DCPD prediction value, which yields the DCPD first adjustment curve in Figure 3(a). Since in most ductile fracture toughness tests, the initial J-R curve follows the blunting line, for the DCPD first adjustment curve data points on the left side of the blunting line are shifted right on top of the blunting line whereas data points on the right side of the blunting line are unchanged resulting in the DCPD second adjustment. For each data point on the DCPD second adjustment curve, the crack extension value has been updated from the original DCPD curve and correspondingly the *J-integral* value needs to be updated since *J-integral* has dependence on the crack extension value. Procedures in ASTM E1820-11 are followed to recalculate the updated *J-integral* value to obtain the final post-adjustment DCPD J-R curve. The first DCPD adjustment method is firstly developed in this work and has not been reported elsewhere.

The first DCPD adjustment method described above is not suitable for adjusting DCPD results of MatA and MatB which is likely due to the irregular crack growth behavior in those two materials during testing. Therefore a second DCPD adjustment method shown in Figure 3(b) is introduced for adjusting DCPD results of MatA and MatB. Staring from the original DCPD J-R curve, excluding the first few transitional data points, the following data points of the original DCPD J-R curve fall on one straight line. Then the first data point deviates from the straight line is counted as the slope change point. All the data points prior to the slope change point are shifted left to the blunting line. The slope change point and data points after it are also shifted left with the same crack extension reduction as the data point right before the slope change point. After the first adjustment, the *J-integral* value of each data point would be recalculated as in the first DCPD adjustment method. The second DCPD adjustment method is an improvement over previous DCPD adjustment method (Dufresne et al. 1979). In the previous method, a slope change point is identified in displacement-potential drop curve and is counted as the critical point for the onset of slow stable crack growth. Occasionally the slope change point in displacement-potential drop curve of a test is not clearly defined and the selection of the critical point tends to be arbitrary and hence the repeatability of the analysis results is poor. However the slope change point in the original DCPD J-R curve is more clearly defined and hence the repeatability of the analysis results should be improved.

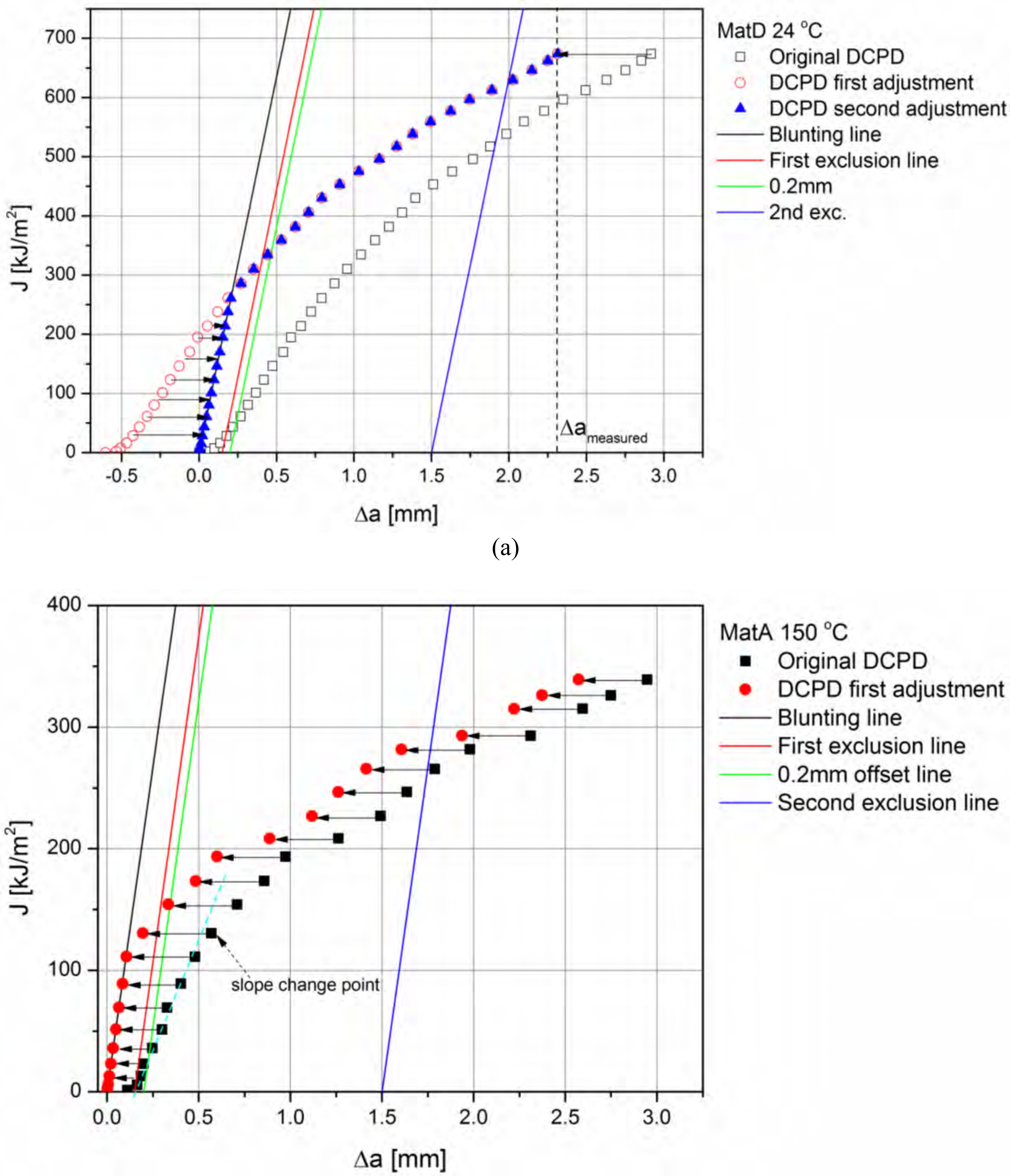
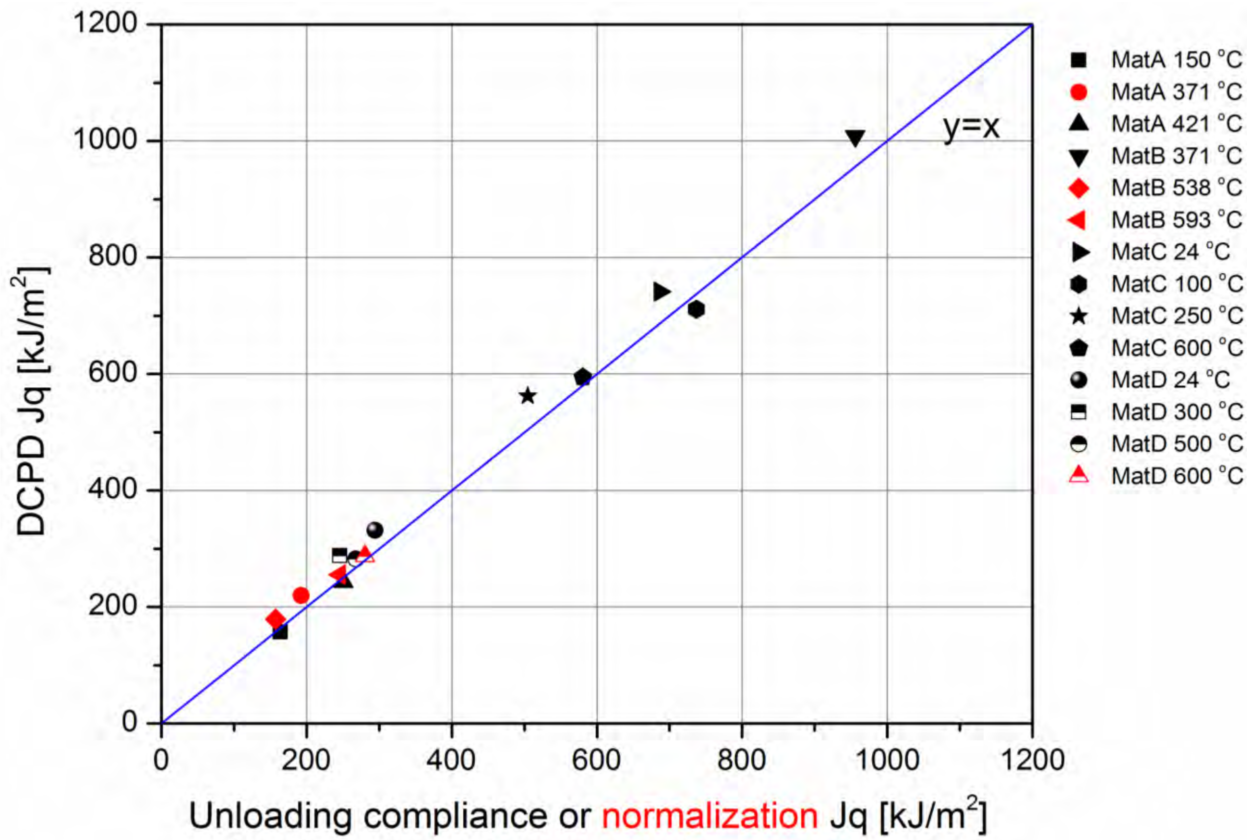


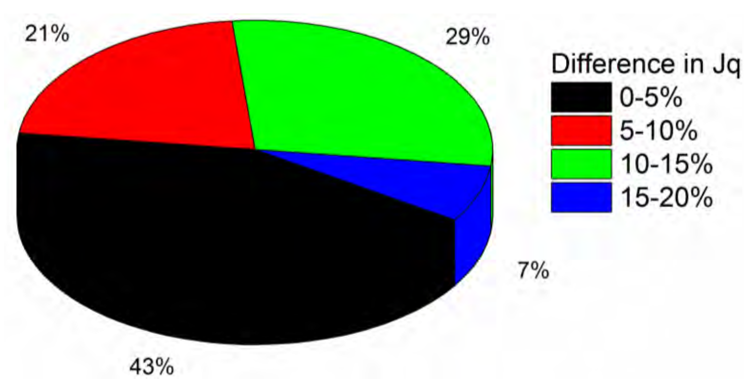
Figure 3. (a) DCPD adjustment method one for materials with regular crack growth; (b) DCPD adjustment method two for materials with irregular crack growth.

DCPD Results after Adjustment

The Jq and tearing modulus determined from post-adjustment DCPD J-R curves are compared with results from EUC or normalization method in Figure 4 and Figure 5, respectively. The black data points in both figures compare the DCPD results with EUC results and red data points compare the DCPD results with normalization results. Regardless of the DCPD adjustment method used, test temperatures, and type of materials tested, the comparison reveals excellent agreement between post-adjustment DCPD results and EUC or normalization results in terms of Jq with an average difference of 8%. The comparison of tearing modulus also indicates satisfactory result with a slightly larger average difference of 17%. Additional tests incorporating higher testing temperatures, more different materials, and different specimen geometries, such as single edge notched bend specimens and disk-shaped compact tension specimens, are needed to verify the applicability of the DCPD adjustment method developed in this study for more board category of testing.

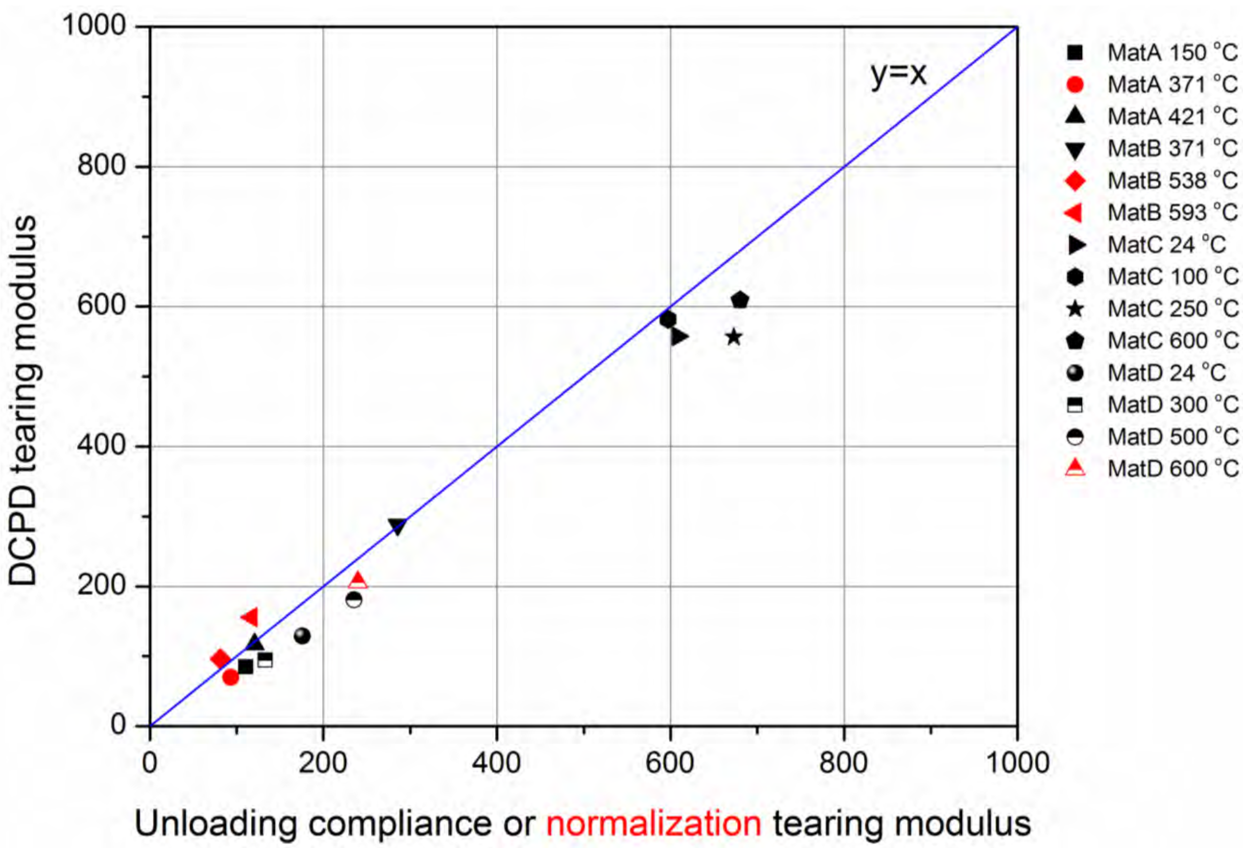


(a)

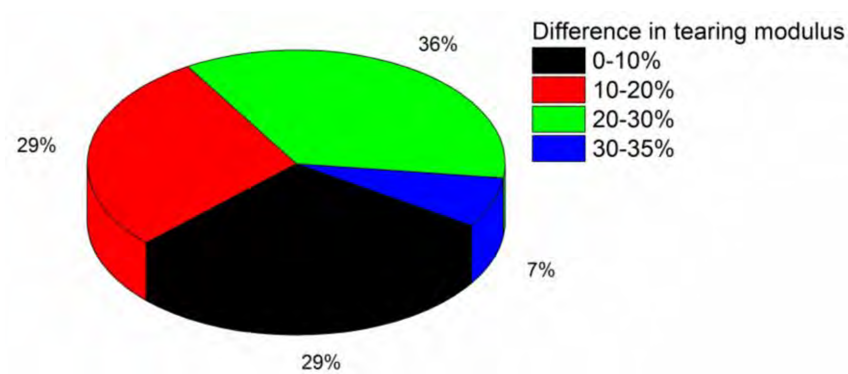


(b)

Figure 4. (a) Comparison of post-adjustment DCPD Jq with EUC or normalization Jq; (b) statistical analysis of the difference in Jq between post-adjustment DCPD results and EUC or normalization results.



(a)



(b)

Figure 5. (a) Comparison of post-adjustment DCPD tearing modulus with EUC or normalization tearing modulus; (b) statistical analysis of the difference in tearing modulus between post-adjustment DCPD results and EUC or normalization results.

CONCLUSION

Two new DCPD adjustment methods are proposed in this study to counter the influence of deformation on material potential drop. After incorporating the adjustment, Jq and tearing modulus derived from DCPD J-R curves are in excellent agreement with their counterparts based on EUC or normalization method for 0.5T and 1T C(T) specimens made from four different metallic materials with testing temperatures ranging from 24 °C to 600 °C. The promising results prove the applicability of

DCPD for J-R curve determination for C(T) specimens especially in extreme environments, such as elevated temperatures, where conventional EUC method faces considerable challenges.

REFERENCES

ASTM (2011). “Standard Test Method for Measurement of Fracture Toughness,” E1820-11, ASTM International, West Conshohocken, PA.

ASTM (2011). “Standard Test Method for Measurement of Fatigue Crack Growth Rates,” E647-11e1, ASTM International, West Conshohocken, PA.

Bakker, A. D. (1985). “A DC Potential Drop Procedure for Crack Initiation and R-Curve Measurements During Euctile Fracture Tests,” *ASTM STP*, 856, 394-410.

Dufresne, J., Henry, B., and Larsson, H. (1979). "Fracture Toughness of Irradiated AISI 304 and 316L Stainless Steels," *ASTM STP,* 683, 511-528.

Hicks, M. A. and Pickard, A. C. (1981). “A Comparison of Theoretical and Experimental Methods of Calibrating the Electrical Potential Drop Technique for Crack Length Determination,” *International Journal of Fracture,* 20, 91-101.

Johnson, H. H. (1965). “Calibrating the Electrical Potential Method for Studying Slow Crack Growth,” *Materials Research and Standards,* 5(9), 442-445.

Lowes, J. M. and Fearnehough, G. D. (1971). “The Detection of Slow Crack Growth in Crack Opening Displacement Specimens Using an Electrical Potential Method,” *Engineering Fracture Mechanics,* 3, 103-108.

McGowan, J. J. and Nanstad, R. K. (1984). “Direct Comparison of Unloading Compliance and Potential Drop Techniques in J-integral Testing,” *Fall conference of the Society for Experimental Mechanics, Milwaukee, WI,* CONF-8411104-1.

Ritchie, R. O. and Bathe, K. J. (1979). “On the Calibration of the Electrical Potential Technique for Monitoring Crack Growth Using Finite Element Methods,” *International Journal of Fracture,* 15(1), 47-55.

Schwalbe, K. H. and Hellmann, D. (1981). “Application of the Electrical Potential Method to Crack Length Measurements Using Johnson’s Formula,” *Journal of Testing and Evaluation,* 9(3), 218-221.

Tong, J. (2001). “Notes on Direct Current Potential Drop Calibration for Crack Growth in Compact Tension Specimens,” *Journal of Testing and Evaluation,* 29(4), 402-406.

Zhu, X. K., Lam, P. S., and Chao, Y. J. (2009). “Application of Normalization Method to Fracture Resistance Testing for Storage Tank A285 Carbon Steel,” *International Journal of Pressure Vessels and Piping,* 86, 669-676.