LIMITATION OF UNLOADING COMPLIANCE METHOD TO CORRELATE WITH PHYSICAL CRACK SIZE DURING SINGLE SPECIMEN J-INTEGRAL TESTING.

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Abstract

Unloading compliance technique in conjunction with crack opening displacement gage is widely used in fatigue and fracture mechanics testing to estimate crack size / crack length increment. Crack extension estimated by unloading compliance method during single specimen J-integral testing appears to be less compared to physical measurement of crack extension obtained through nine-point averaging of crack front after specimen failure. Experiments were organized to study if the discrepancy is due to inherent problems in unloading compliance method or due to other factors. Compliance estimated crack length correlated better than 99% with physical crack size during constant amplitude fatigue tests that precede J integral testing. However, unloading compliance method provided underestimate of crack size / crack extension during multiple load/unload cycles of single specimen J integral testing. It appears that unloading compliance estimate is influenced by the previous load history-such as an overload. This aspect requires careful study to obtain valid results during fracture mechanics testing.

Introduction

Compliance technique is routinely used in fatigue crack growth testing, plane strain fracture toughness testing and in J-integral testing to obtain on-line estimate of crack length (Faucher and Tyson [1], Garwood [2]). Compact tension specimens are widely used for J integral testing, and usually a crack opening displacement gage either mounted at the specimen edge or at load-line is used to estimate the specimen compliance (Faucher and Tyson [3]) in accordance with ASTM E1820-99 test standard [4]. Compliance calculated from slope of load-crack opening displacement data and corrected for elastic modulus, specimen rotation (which in turn is based on remaining un-cracked ligament) is used to estimate crack length using standard crack length Vs compliance functions [4]. As by definition, J is related to crack extension, it would be appropriate to emphasize the significance of correct measurement of crack length / crack extension during testing to obtain valid J values. Incorrect estimation of crack extension during J-integral testing can lead to non-conservative J1c values [1].

J integral tests are usually carried out by one of the two procedures: Multiple specimen method and single specimen method. In case of multiple specimen method, a pre-cracked specimen is loaded in static tension (as is the case with C(T) samples) up to a maximum load in displacement control mode and the specimen unloaded to zero load thereafter. The area under the load-COD is used for compute J values. In order to distinguish static crack extension, specimens are usually heat tinted or fatigue cycled after static test. Further, load-COD data recorded during unloading segment is normally used to estimate compliance and crack extension during static loading. In case of single specimen test method, crack extension for each COD / LLD increment is estimated by unloading the specimen to a fraction of the maximum load reached in previous loading cycle. In both the test methods (single specimen and multiple specimen method) compliance based crack length estimates are cross-verified with physical crack size measurements obtained from nine-point analysis of fracture surface.

Research on single specimen J integral estimation often reports discrepancies in crack extension obtained through compliance method [1], negative crack extension during first few unloading cycles (Several Authors [5]), and in most of the cases, an underestimate in static crack extension during single specimen J integral testing (Jung et al [6]). However, these results were considered to be acceptable as the deviation between compliance estimated crack extension and physical crack extension is less than 15%. In an attempt to ensure that crack length estimates are not affected by experimental variables, ASTM test standard for J integral estimation [4] provides a check-point for crack length estimation and data acquisition system through estimation of deviation between three consecutive crack length estimates. If the deviation prior to start of J integral test exceeds 0.002 times the specimen width, it is not advisable to proceed with J integral testing. Further, the ASTM test method suggests corrections to Elastic modulus to account for discrepancies at the end of pre-cracking step by correlating compliance estimated crack length with nine-point average crack length. During some of our experiments on single specimen J integral testing of Al-Cu alloys (2014-T6511 equivalent) and Cr-Mo steels (9Cr-1Mo), we observed that in some cases, negative crack extension was observed for first few cycles of load-unload and in almost all tests, final crack extension was observed to be less than the physical estimate.

To understand if this discrepancy is due to compliance method or other factors, experiments were organized to examine: a) accuracy of crack length estimated by unloading compliance method prior to start of J integral test and b) establish crack extension correlation after single specimen J integral test. Results of this experimental investigation are presented in this paper.

Fatigue Crack Growth Experiments

Experiments were carried out on compact tension C(T) specimens made out of an Al-Cu alloy 2014-T6511 oriented along TL direction. First set of experiments were aimed at establishing a correlation between compliance based crack length estimate and post-failure examined fatigue crack length estimates. In order to verify this over the entire range of crack length as well as to enable easy identification of crack front on fracture surface after specimen failure, programmed block loading was applied on C(T) specimen with constant monitoring of crack length using compliance method. The nominal dimensions of C(T) specimen are: W=40 mm and thickness=10 mm and clevis pin hole of 10 mm diameter loading pin of 6 mm diameter. Fatigue crack growth experiments were carried out on a 50 kN servo-hydraulic test system at BiSS Research. Crack mouth opening displacement was monitored on-line during testing using a BiSS COD gage with a gage length of 10 mm and travel of 4 mm.

Fatigue crack growth test was programmed to consist of ten blocks of loading – alternating blocks of stress ratio (R) 0.1 and 0.7 were applied on the test specimen. Stress ratio of 0.1 introduces a relatively dark band on the fracture surface compared to the loading block with a stress ratio of 0.7. Thus post failure, one could identify the different bands, their starting and end points and compare compliance estimated crack length at beginning and end of each block of loading. To enable easy identification of light and dark bands, test sequence was programmed for a switch over from R=0.1 constant amplitude loading after a crack increment of 1.5 mm, while switch over was programmed after a crack increment of 3.0 mm for stress ratio of 0.7. Further, to ensure that a single specimen could cover maximum possible crack length, tests were carried out under K_{max} constant and varying stress ratio conditions. The exponent for varying stress ratio was assigned a zero value and as a consequence, tests were carried out at each block of loading at a constant stress ratio – of either 0.1 or 0.7. K_{max} value at the end of previous step was used as reference K_{max} for next step. Compliance constants corresponding to crack mouth condition (a/W = -0.25) provided in ASTM E-647 standard [4] was used to estimate crack length. Elastic modulus corresponding to plane stress condition (E = 72000 MPa) was used for compliance-crack length estimation.

Figure 1 presents macro view of the fracture surface post-failure. Table 1 presents visually examined surface (front and back) crack length and corresponding compliance estimate of crack length. A linear regression of crack length estimated by compliance method Vs average surface crack length provided a correlation of the order of 96%.

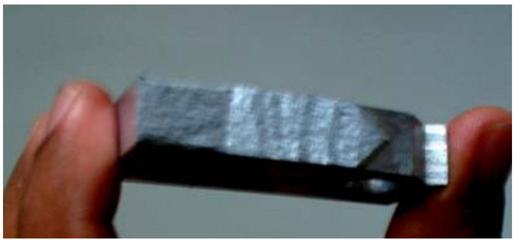

FIGURE 1 - Macro-photograph of fatigue surface. Dark bands correspond to stress ratio (R) of 0.1 and light bands correspond to stress ratio (R) of 0.7.

Table 1. Comparison of surface crack length measurement with compliance estimated crack length.

Step No.	Crack Length (Estimated)	Crack Length, Front, mm	Crack Length, Rear, mm	Average Crack Length, mm
1	7.586	7.9	7.25	7.575
2	10.712	10.93	9.75	10.34
3	12.284	12	11.08	11.54
4	15.232	15.38	14.14	14.76
5	16.86	16.69	15.34	16.015
6	19.811	18.25	19.3	18.775
7	21.376	19.81	21.1	20.455
8	22.348	20.79	22	21.395
9	23.876	22.15	23.24	22.695
10	27.361	27.8	26.17	26.985

Crack length was measured at nine points across specimen thickness for each distinguishable crack front on the fracture surface. Table 2 presents the results of nine point average crack length Vs compliance estimate. Linear fit of crack length obtained through nine point average method and compliance based estimate indicated a correlation better than 99%.

Table 2. Comparison of compliance estimated crack length with physical crack size estimated by nine point average method after specimen failure.

Step	R	C.L. Front mm	Sec. 1	Sec. 2	Sec. 3	Sec. 4	Sec. 5	Sec. 6	Sec. 7	Sec. 8	Sec. 9	C.L. Back mm	9-pt. avg CL, mm	Cmpl. Est. mm
1	0.1	7.9	7.75	7.7	7.74	7.55	7.72	7.39	7.45	7.3	7.37	7.25	7.56	7.586
2	0.7	10.93	10.6	10.5	10.08	10.5	10.66	10.35	10.4	10	9.8	9.75	10.3	10.71
3	0.1	12	12.15	12.26	12.29	11.85	12.33	12.36	12.1	11.3	10.8	11.08	11.9	12.28
4	0.7	15.38	14	15.28	14.74	15.04	15.11	15.15	14.8	14.4	14.3	14.14	14.8	15.23
5	0.1	16.69	17.1	16.21	16.84	16.9	17.43	17.06	16.6	15.8	15.7	15.34	16.5	16.86
6	0.7	18.25	18.5	18.28	18.63	19.4	19.65	19.66	19.6	18.9	19.1	19.3	19	19.81
7	0.1	19.81	20.25	20.24	20.67	20.85	21.35	21.6	21.3	21.4	21.3	21.1	20.9	21.38
8	0.7	20.79	21.25	21.4	21.74	21.84	22.2	22.25	22.1	22.3	22.3	22	21.8	22.35
9	0.1	22.15	22.58	23.5	23.39	23.36	23.95	24.15	24	24	24.1	23.24	23.5	23.88
10	0.7	27.8	27.5	27.3	27.59	27.35	27.4	27.05	26.9	26.7	27.1	26.17	27.2	27.36

The above study suggests that compliance based estimates are in close conformity with physical crack size and compliance method provides an average crack length even in the presence of thumbnail crack front. Surface crack length measurements present a less accurate picture of crack length compared to compliance based estimation. One could expect higher difference between surface crack length and compliance estimated crack length in case of thicker specimens, as the thumbnail crack front is predominant in thicker specimens. Plane stress elastic modulus in the compliance-crack length equation presents a correct estimate of physical crack length even in 10 mm thick specimen, where the mid-thickness region is predominantly under plane strain condition.

Single specimen J-integral testing

Single specimen J integral test was conducted on C(T) specimen of same material, orientation and dimension. A 6 mm diameter clevis pin was used for specimen loading to avoid possible influence of pin-hole clearance on unloading compliance. Previous experiments suggested that use of pins with adequate pin-hole clearance provide an accurate estimate of crack length (Raghu Prakash [7]). Pins with close tolerances can result in crack length underestimate up to 1 mm in case of 40 mm wide specimens [7].

The specimen was pre-cracked to crack length corresponding to (a/W) of ~0.5 by K-decreasing method under constant amplitude load cycling. Crack mouth opening displacement was monitored on-line during testing. The specimen was tested for J integral estimation using single specimen test method – ASTM E 1820-99a [4]. Plane stress elastic modulus of 72000 MPa was used for compliance-crack length estimation. Small amplitude, high frequency cycling was applied on the specimen at the start of testing to enable settling of

COD gage with respect to specimen knife edge. Repeat measurement of crack length was carried out to assess deviation of a/W between three measurements. Estimated deviation in crack length estimate between repeat measurements was less than 0.002W (80 microns), thus indicating the consistency in crack length measurement on the test system, and conformity of testing as per ASTM E 1820-99 test standard. Single specimen J-integral test was conducted in stroke control with LLD (crack mouth opening displacement) increment as feedback for test control. Load, crack opening displacement data was continuously logged through super-average mode of data acquisition on MTL-Windows 6 software. Test parameters specified: COD increment of 0.05 mm after each peak load at a loading rate of 0.5 mm/min and unloading to 50% of peak load over a 15 sec time period under load control.

Figure 2 presents the load-COD trace obtained during J integral testing. Total area under load-COD curve was computed on-line and elastic and plastic components delineated. Test was continued till maximum crack extension of approx. 5 mm was achieved. This crack extension during multiple loading and unloading would ensure that there are enough valid data points on 1.5 mm exclusion line. Final crack increment as reported by application software prior to test stop condition was approx. 5.8 mm.

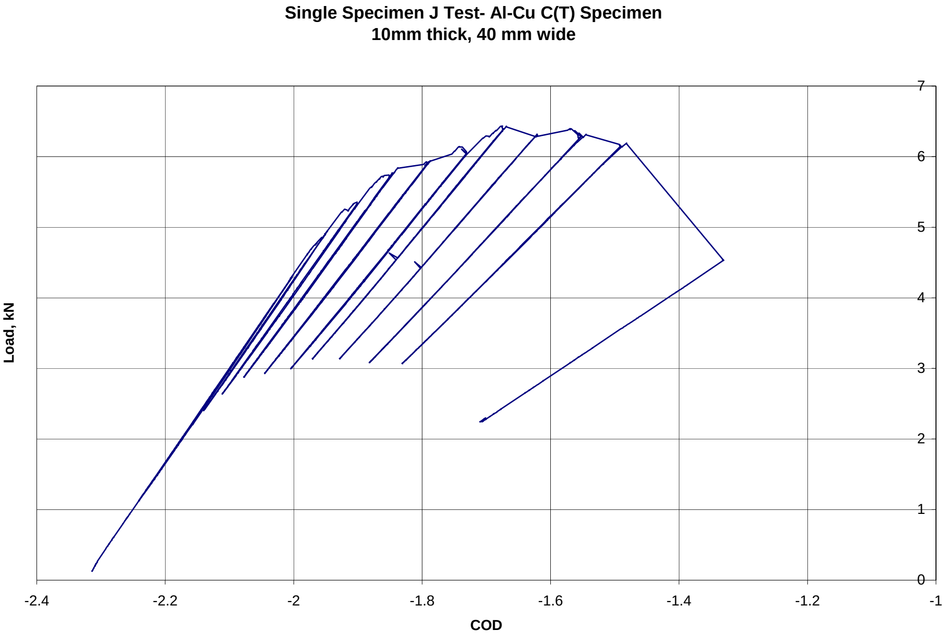

FIGURE 2 Load-COD trace obtained during single specimen J integral test on Al-Cu alloy C(T) specimen of 10 mm thick, 40 mm.

Test specimen was cycled under constant amplitude fatigue to introduce distinguishing static stretch region for J-integral test prior to static pull-out of test specimen. The specimen failed during fatigue loading. Fracture surface of specimen was examined under an optical microscope for crack length estimation at start and stop of J integral testing to estimate crack increment during single specimen J integral testing.

Figure 3 presents macro-view of the fracture surface. Fatigue and static crack extension regions are clearly identified through contrast on fracture surface – fatigue region identified by bright band / region and static crack extension through dark region. A small segment of post-J integral test fatigue region can be seen as bright band on the fracture surface.

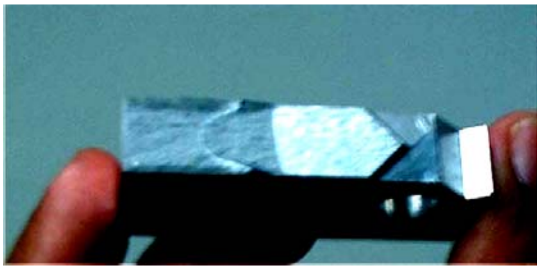

FIGURE 3 - Mac e. Crack growth is from right to left. First bright region from Chevron notch indicates fatigue pre-crack. Static extension during J integral test is seen as region in between fatigue pre-crack and post-J test fatigue region.

Crack length was estimated post-failure using nine-point average method using an optical microscope. Tables 3 and 4 present the results of crack length estimate obtained prior to start of J integral test and after completion of J integral test respectively.

Table 3 – Comparison of crack length estimate obtained through compliance method Vs physical measurement by nine-point average method – At start of J integral test.

Section	1	2	3	4	5	6	7	8	9	Avg. Crack length mm	Cmpl. Estimate, mm
Crack Length	19	19.1	19.5	20.2	20.5	20.5	20.5	20	20	19.92	20.05

Table 4 – Comparison of crack length estimate obtained through compliance method Vs physical crack size measurement by nine-point average method - After completion of J integral test.

Section	1	2	3	4	5	6	7	8	9	Avg. Crack Length, mm (A)	Cmpl. Estimate, mm (B)	Difference, mm (A-B)
Crack Length	21	23	24.5	29	29.5	29	28.3	28	24.5	26.31	25.986	0.324

Discussion

Crack length estimate obtained during pre-cracking is in close conformity with the physical crack size obtained through nine point average method after specimen failure. Crack extension obtained during single specimen J-Integral testing by compliance method is 5.936 mm (difference between 25.986 mm and 20.05 mm). Physical crack extension estimated from fracture surface analysis by optical microscopy and nine-point average method is 6.39 mm (difference between 26.31 and 19.92 mm). Thus, there is a difference of approx. 0.454 mm between the compliance estimate of crack length and physical crack size. This is approx. 7.1% of physical crack extension of 6.39 mm.

In an attempt to assess if the test is valid as per ASTM E1820-99 reference standard, elastic modulus was corrected based on physical crack size at end of pre-crack. Corrected modulus of elasticity was estimated as 70.2511 GPa (less by 2.4% from original modulus of 72 GPa). ASTM standard E1820-99 permits deviation upto 10% on corrected elastic modulus. Thus the test is valid as per the ASTM test standard E 1820-99.

It may be noted that elastic modulus is one of the variables that is used in the compliance – crack length equation and is likely to affect crack length estimate for a given v/P value. Interestingly, previous ASTM test standard E-1820-97 recommends use of plane strain elastic modulus for compliance – crack length estimation. Table 5 presents crack length as computed using plane stress elastic modulus and plane strain elastic modulus. Thus, for a given v/P, use of plane strain elastic modulus results in higher crack length compared to estimates obtained using plane stress elastic modulus.

Table 5. Comparison of crack length estimates based on plane stress elastic modulus and plane strain elastic modulus.

Sl.No	v/P, mm/kN	Crack length estimate	Crack length estimate
		E Pl.Stress (72 GPa)	E Pl.Strain (79.12 GPa)
1	0.07560	19.944	20.781
2	0.07488	19.856	20.697
3	0.07472	19.837	20.678
4	0.07548	19.929	20.767
5	0.07775	20.195	21.024
6	0.07988	20.435	21.256
7	0.08509	20.989	21.790
8	0.08941	21.412	22.198
9	0.09141	21.600	22.379
10	0.09678	22.074	22.835
11	0.10287	22.571	23.313
12	0.11044	23.132	23.852
13	0.16383	25.954	26.558

Use of plane strain elastic modulus in compliance-crack length estimate improves post-failure crack length (difference of 0.248 mm). However, it affects correlation with pre-crack size by as much as 0.7 mm. It is interesting to note that plane stress elastic modulus provides a consistent estimate during fatigue cycling, but fails to provide good correlation during static testing. On the other-hand plane strain elastic modulus provides a better correlation at the end of J-integral testing.

If one were to use elastic modulus of 70.25 GPa for crack length estimate, terminal crack length estimate would be 25.79 mm, thus increasing the disparity between physical crack size and compliance based estimate of crack size (~0.52 mm underestimate by compliance method).

Disparity observed between physical crack extension and compliance estimated crack length requires study. It appears that the disparity is more prevalent in C(T) specimens compared to bend specimens [8] in view of rotation constraints in C(T) specimens apart from other experimental variables like pin-hole friction, load-line alignment of test system. While it may appear that one can overcome the such discrepancies by carrying out tests on bend specimens, it would be important to investigate why the correlation fails in case of C(T) specimens. Exploratory experiments carried out to verify if compliance is influenced by previous load history appear to suggest that compliance values are influenced by previous load history – i.e. overload affects the compliance and as a consequence crack length estimate in subsequent cycles. Such an effect could be more pronounced in case of thick specimens, compared to thin specimens due to plane strain constraint effect. It is proposed to carry out additional experiments on C(T) specimens made out of different materials to better understand the crack length correlation with physical crack size estimates during J integral testing.

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