Double Clip-on Gauge Compliance Method for Determining J_{IC}^*

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Synopsis

As one of the candidates for single specimen method to determine J_{IC} value, a Double Clip-on Gauge Compliance (DCGC) method was developed, by which J_{IC} value could be determined using only two clip-on gauges on a compact specimen. To examine the usefulness of the DCGC method, J_{IC} values of several kinds of steel which were determined by the DCGC method were compared with J_{IC} values determined by the multiple specimen method specified in the JSME standard. The relationship between J_{IC} values determined by the DCGC method and those by the JSME method was discussed. The correlation of J_{IC} value with the Charpy upper shelf impact energy was studied.

I. Introduction

J_{IC} is one of the typical criteria to evaluate the initiation of ductile crack. Though R -curve method and Stretched Zone Width (SZW) method are used as typical multiple specimen methods for determining J_{IC} value, they need not only complicated works such as measurement of the ductile crack length and/or stretched zone width *etc.*, but also more than 4~6 specimens. On the other hand, lots of single specimen methods to determine J_{IC} value have been proposed. They include unloading compliance method, acoustic emission method, ultrasonic method and electro-potential method. They also have some defects such as deterioration effect of unloading on J_{IC} value, elevation of temperature at the crack tip due to electric current, and so on.

The present paper introduces Double Clip-on Gauge Compliance (DCGC) method to determine J_{IC} value, which needs only two clip-on gauges mounted on a single specimen without any expensive equipment. The advantages of this method are also discussed. Furthermore, the correlation between J_{IC} value and Charpy upper shelf impact energy is studied.

II. DCGC Method

Firstly suppose that the crack surfaces maintain to be planar during the loading as shown in Fig. 1. Let a_0 be the initial crack length, θ be the angle between the crack surfaces, and V_1 and V_2 be the distance between crack surfaces at the loading line, and at the middle point between the loading line and the crack tip, respectively. Then the following equations are derived:

$$V_1 = (a_0 + a)\theta \dots\dots\dots(1)$$

$$V_2 = (1/2a_0 + a)\theta \dots\dots\dots(2)$$

$$\frac{dV_2}{dV_1} = \frac{(1/2a_0 + a)d\theta + \theta da}{(a_0 + a)d\theta + \theta da} \dots\dots\dots(3)$$

where, a : the length between the initial crack tip and the margining point of the crack planes.

Secondly suppose that the crack grows in the following way (see Fig. 2):

- (i) In the first stage, the crack does not blunt and the angle θ continues to increase. In this stage, therefore, the value of a is always zero.
- (ii) In the second stage, the crack blunts and both θ and a increase simultaneously.
- (iii) In the third stage, the ductile crack propagates. In this stage, only a continues to increase, while the angle θ remains constant.

Since the value of a is always zero in the first stage, Eq. (3) is rewritten as follows:

$$dV_2/dV_1 = (1/2a_0 d\theta)/a_0 d\theta = 1/2 \dots\dots\dots(4)$$

In the third stage, as the value of θ is constant, the following equation is drawn from Eq. (3).

$$dV_2/dV_1 = \theta da/\theta da = 1 \dots\dots\dots(5)$$

In the second stage, the value of dV_2/dV_1 increases monotonously from 1/2 to 1. If the above assumptions (i) to (iii) were valid, therefore, the ductile crack starts to propagate when the value of dV_2/dV_1 becomes constant, and the J value at this instant is J_{IC} .

III. Experimental Procedures

Material examined were eight types of steel whose chemical compositions and mechanical properties are listed in Tables 1 and 2, respectively. Figure 3 shows the specimen geometry. The specimen thickness was 25.4 mm except for that of Steel 2 whose thickness

Fig. 1. Assumed crack configuration.

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Table 1. Chemical compositions. (wt%)

Steel No.	C	Si	Mn	P	S	Cu	Cr	Mo	V	Ni	B	Nb
1	0.12	0.25	0.90	0.018	0.018	—	—	—	—	—	—	—
2	0.10	0.24	1.22	0.019	0.007	—	—	—	—	—	—	—
3	0.14	0.25	1.30	0.024	0.004	0.13	—	0.03	0.040	—	—	—
4	0.11	0.32	1.61	0.014	0.008	—	0.19	—	0.075	0.02	—	0.029
5	0.10	0.27	0.86	0.012	0.005	0.18	0.63	0.32	0.040	—	0.0016	—
6	0.07	0.17	0.45	0.010	0.005	—	—	—	—	9.01	—	—
7	0.06	0.26	0.44	0.002	0.001	—	—	—	—	9.20	—	—
8	0.04	0.22	0.45	0.009	0.003	—	—	—	—	9.17	—	—

Table 2. Mechanical properties.

Steel No.	Y. S. (kgf/mm ²)	T. S. (kgf/mm ²)	El. (%)	$\sqrt{E_s^*}$ (kgf·m)
1	27.2	44.1	30.4	9.6
2	38.5	51.5	37.8	16.0
3	46.0	60.1	27.0	19.4
4	47.5	60.9	25.0	11.0
4 (L-T)	45.8	58.5	28.0	—
5	72.1	80.1	16.3	13.7
6	63.9	77.7	25.2	13.0
7	68.0	73.0	31.0	25.0
8	74.0	77.0	42.0	20.0

* $\sqrt{E_s}$: Charpy upper shelf impact energy

Fig. 2. Assumed three stages of crack growth.

Fig. 3. Specimen geometry.

was 20 mm. Specimens were machined as the T-L specimen described in ASTM E399.¹⁾ In the case of Steel 4, L-T specimens were also prepared, which are distinguished as Steel 4(L-T) from Steel 4(T-L) in Tables 2 and 3. Furthermore, in order to make the ductile crack front straight, specimens with side grooves were prepared whose depth was 10 % of the thickness, in the cases of Steels 1, 2, 4, 7 and 8.

The experiment was carried out at room temperature in a 20 tf screw driven type testing machine. The rate of loading line displacement was kept constant, that is, 0.5 mm/min. During the test, the displacements V_1 and V_2 and load P were measured. The V_1 and V_2 were measured by two clip-on gauges set as shown in Photo. 1, and P was measured by a load-cell. These data were fed to a pen recorder to draw $P-V_1$ curves and V_2-V_1 curves, whose examples are shown in Fig. 4.

Figure 5 shows examples of $J-V_1$ and dV_2/dV_1-V_1

Photo. 1. Setting method of two clip-on gauges on a specimen.

curves calculated from $P-V_1$ and V_2-V_1 curves by means of a personal computer system. J values were calculated according to Eq. (6) as described in JSME S-001²⁾ for the compact specimen.

$J = (A/Bb)f(a_0/W) \dots\dots\dots(6)$

where, *A*: the area under the load *vs.* load line displacement record in energy unit
B: the specimen thickness
b: the initial ligament
W: the specimen width
*a*₀: the original crack length.

For the calculation of *J* value on specimens with side grooves, the breadth at the minimum cross section was used for the convenience sake. According to the present model, the *J* value corresponding to the inflexion point of the *dV*₂/*dV*₁–*V*₁ curve is the *J*_{IC}. Thus the *J*_{IC} value can be determined by carrying out the treatment as shown by a broken line in Fig. 5.

Fig. 4. Examples of *P*–*V*₁ and *V*₂–*V*₁ curves.

Fig. 5. Examples of *J*–*V*₁ and *dV*₂/*dV*₁–*V*₁ curves.

The *J*_{IC} values were also determined on the same specimens by the *R*-curve method according to JSME S-001.²⁾ In this method, the ductile crack length is measured as an average value of those at 3/8, 4/8 and 5/8 thickness of the specimen. Furthermore, the blunting line is drawn using the experimental data and the *R*-curve is also drawn using data measured on the specimens whose ductile crack lengths are in the range of 0.1 to 1.0 mm.

IV. Experimental Results and Discussion

All *J*_{IC} values determined by the DCGC method are listed in Table 3, in which the *J*_{IC} values for specimens with side grooves are distinguished by the symbol (SG) from those for the standard specimens. These values of each material scatter in a relatively small range, and the standard deviations are within 2.0 kgf/mm except for a few materials. So, this method seems to have a well reproducible feature to determine the *J*_{IC} values.

Table 3. *J*_{IC} values by the DCGC method.

Steel No.	<i>J</i> _{IC} values by the DCGC method	Average	Standard deviation
1	4.1, 4.7, 4.7, 4.9	4.6	0.35
1 (SG)	2.1, 2.7, 2.9, 2.9, 3.3, 3.6, 3.7, 5.1, 6.0	3.6	1.2
2 (SG)	12.0, 13.5, 13.9, 14.3, 14.4, 14.5, 15.1, 15.9	14.2	1.2
3	14.0, 14.9, 15.2	14.7	0.62
4	9.2, 10.5, 11.1, 11.8, 12.1	10.9	1.7
4 (SG)	9.2, 10.0, 10.5, 13.2	10.7	1.7
4 (L-T)	14.7, 16.3	15.5	1.1
5	18.0, 19.7, 21.9	19.9	2.0
6	17.4, 20.1, 20.1	19.2	1.6
7	14.6, 15.4	15.0	0.57
7 (SG)	14.3, 17.9, 22.3	18.2	4.0
8	15.2, 18.9	17.1	2.6

Fig. 6. Comparison between *J*_{IC} value obtained by the DCGC method and that by the JSME method.

Fig. 7.
Relation between J_{IC} value and Charpy upper shelf impact energy.

Photo. 2. Examples of fractured surfaces.

Figure 6 shows the comparison between the J_{IC} values by the JSME method and the average of J_{IC} values by the DCGC method. The J_{IC} values by both methods coincide well with each other within an error of $\pm 40\%$. Therefore, the DCGC method is considered to have enough accuracy to determine the J_{IC} value.

As can be seen in Photo. 2, the ductile crack front is fairly uniform in the side-grooved CT specimen, if it is compared with that of the specimen without side-groove. Nevertheless, J_{IC} values for side grooved specimens and those for specimens without side-groove coincide well with each other within an error of $\pm 10\%$. Thus it seems that the shape of ductile crack front only slightly affects the J_{IC} value obtained by the DCGC method.

The relation between the J_{IC} value and the Charpy impact energy in the upper shelf region is shown in Fig. 7. In the case of steels whose Charpy impact energy is greater than about 15 kgf·m, the J_{IC} value

obtained by the DCGC method tends to be smaller than that by the JSME method. Some experimental results which have been reported indicate that the J_{IC} value increases almost linearly with the increase in the Charpy impact energy.^{3,4)} In the present study, however, the J_{IC} values obtained by both methods tend to be almost constant if the Charpy impact energy is greater than 15~20 kgf·m.

V. Conclusions

A DCGC method was developed to determine the J_{IC} value. Some of the advantages of this method was discussed. The main results obtained are as follows.

- (1) The J_{IC} values of each material obtained by the DCGC method scattered in a relatively small range and the standard deviation was almost within 2.0 kgf/mm.
- (2) The J_{IC} value obtained by the DCGC method and that by the JSME method coincided well with each other within an error of $\pm 40\%$ for many steels which showed a wide range of tensile strength.
- (3) The shape of ductile crack front did not affect the J_{IC} values obtained by the DCGC method significantly.
- (4) The DCGC method needs only two clip-on gauges mounted on a single specimen, so that this method is considered to be a useful method to determine the J_{IC} value in an industrial sense.

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