Development of J_{Ic} Test in Transition Temperature Region

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Summary

The objective of the J_{IC} test is to determine the value of J_{IC} at initiation of crack extension by small specimens. However, existing two standards on J_{IC} test, JSME S001-1981 and ASTM E813-81, can not be applied to cleavage fracture of steels in transition temperature region. The limitation is based on the experimental results which show that fast cleavage fracture occurs prior to the onset of ductile crack extension from an original crack at the temperature and that the cleavage fracture toughness is affected by the thickness of specimens. The onset of crack extension, however, is not necessarily determined microscopically.

In this study, modified J_{IC} test method was proposed and the test was conducted on ASTM A204 Gr.A (C-1/2Mo) steel and ASTM A387 Gr.22 Cl.2 (2-1/4Cr-1Mo) steel in the transition temperature region. The test method defines J_{IC} as a toughness at the initiation of effective microscopic ductile tearing fracture preceding cleavage fracture at midsection of the specimen where plain-strain exists. J versus ductile crack extension (Δa) curve (R-curve) can be used to determine the value of J_{IC} corresponding to the separating point of the R-curve from a blunting line. The R-curve should not be approximated as a straight line in the range of small value of Δa. When the R-curve method cannot be applied, the maximum length of isolated ductile tearing regions, ℓ_{max}, or the density of the length, $\sum_i \ell i$, along the tip of the stretched zone is substituted for Δa. The value of K converted from the J_{IC} was independent on the thickness of the specimen and corresponded to K_{IC} which was obtained by heavy section specimen. This proves the applicability of the modified J_{IC} test even in the transition temperature.

1. Introduction

The J_{IC} test has the considerable advantage in estimating the plain strain fracture toughness K_{IC} by small specimens[1]. The objective of the test is to determine the value of J at initiation of crack growth. However, existing two standard test methods, JSME S001-1981[2] and ASTM E813-81[3], can not be applied to cleavage fracture of steels in transition temperature. The limitation prevents a wide application of useful J_{IC} test for many of the steels used in the temperature region. This is based on the experimental results which show that fast cleavage fracture occurs prior to the onset of ductile crack extension in the temperature and that the cleavage fracture toughness is affected by the thickness of specimens [4-7]. The onset of crack extension, however, is not necessarily determined microscopically.

In this study, a modified J_{IC} test procedure was proposed and the test was conducted on compact tension specimens of two kinds of steel in the transition temperature. Fractographic examination of microscopic ductile tearing at crack front was made on the fracture surfaces by a scanning electron microscope.

2. Experimental Procedure

The steels examined are ASTM A204 Gr.A (C-1/2Mo) steel used for several years and ASTM A387 Gr.22 Cl.2 (2-1/4Cr-1Mo) steel which was normalized (930°C-2.7 Hr) and tempered (690°C-3.8 Hr). The chemical compositions and mechanical properties of these steels are given in Table 1 and Table 2, respectively. The Chapry V transition curves for these steels are shown in Fig. 1 and Fig. 2 and the fracture appearance transition temperatures, vTrs, are listed in Table 2. Fig. 3 shows the configuration of compact tension (CT) specimens and Table 3 and Table 4 summarize the geometries and fracture toughness test conditions of the specimens.

The modified J_{IC} test procedure is as follows: Several CT specimens are loaded up to different levels at a constant displacement velocity and unloaded. Then, the specimens are broken open by overloading at liquid nitrogen temperature or by subsequent fatigue cracking. The fractographic examination of the amount of microscopic ductile tearing fracture ahead of precrack is performed by a scanning electron microscope at the midsection of the specimen where plain-strain condition exists. Physical crack growth, Δa, which is the total of the stretched zone width, SZW, and an actual slow crack growth is determined as shown in Fig. 4. In this study, length of isolated ductile regions, ℓ, along the tip of the stretched zone is also examined. J of each of the specimens is calculated by the following equation.

$$J = (A/Bbo)[2(1+\alpha)/(1+\alpha^2)]$$
$$\alpha = [(2ao/bo)^2+2(2ao/bo)+2]^{1/2}-[(2ao/bo)+1] \qquad (1)$$

where A = area under load versus load-line displacement record, B = specimen thickness, bo = initial uncracked ligament, W-ao, W = specimen width, and ao = original crack size, including fatigue precrack. In the case of the 1-mm thick specimen of C-1/2Mo steel, supporting plates and oil coated acrylic plates are vised on the specimen to avoid buckling during loading as shown in Photo 1. J_{IC} is determined as the value of J at the separating point of J-Δa relation from a blunting line or as the corresponding J value to an effective length of ductile region ℓ.

K_{IC} test in accordance with ASTM E399-81 was conducted on some of the specimens to compare with the results of J_{IC} test.

3. Results and Discussion

3.1 A204 Gr.A (C-1/2Mo) Steel

(1) Deformation Curves

The deformation of the specimens for A204 Gr.A (C-1/2Mo) steel in terms of load-line deflection, V, versus load, P, is summarized in Fig. 5 using normalized x-y relation[8]. The upper broken curve for a 1-mm thick specimen in the figure shows considerable difference from others due to a friction error between the anti-buckling plates and the specimen. The friction force was measured as shown in Fig. 5 on a couple of broken specimens on which anti-buckling plates were vised. Subtracting the friction force from the original x-y relation, the middle broken curve which differs a little from those of the thicker specimens was obtained. This proves that there is little necessity of considering the influence of the thickness of specimens on the V-P relation which is used in calculating the value of J by eq.(1).

(2) Results of Modified R-Curve Method

Photo 2 indicates an example of fracture surface of A204 Gr.A (C-1/2Mo) steel. The J versus crack extension (Δa) fracture resistance curve (R-curve) obtained by modified J_{IC} test on the C-1/2Mo steel at room temperature (20-25°C) is shown in Fig. 6. The figure indicates that the R-curve is not affected by the thickness of the specimen. This will be due to the following two reasons; (1) the fractographic examination was performed on the midsection of the specimen where a plain-strain condition exists, and (2) the thickness of the specimen has little influence on the calculation of J as mentioned above. From Fig. 6 the length of isolated ductile regions, ℓ, along the stretched zone increases rapidly as the R-curve falls apart from the experimentally determined blunting line. The corresponding J_{IC} at the separating point of the R-curve was determined as 32N/mm which is independent on the thickness of the specimen. The J_{IC} value was converted to K_{IC} by the following equation.

$$K_{IC} = \sqrt{J \cdot E/(1-\nu^2)} \qquad (2)$$

where E and ν is modulus of elasticity and Posson's ratio, respectively. The calculated value of K_{IC} is 86 MPa$\sqrt{m}$ and is close to K_Q of 84 MPa$\sqrt{m}$ which was obtained by the 75-mm thick CT specimen under nearly valid K_{IC} conditions. The impact transition temperature, vTrs, of the C-1/2Mo steel is 67°C as shown in Table 2 and some of the CT specimens failed by cleavage fracture as shown in X mark in Fig. 6. These facts prove that the material tested is in the transition temperature region at test room temperature. That is, the modified J_{IC} test method can be applied in the transition temperature region, provided microscopic ductile tearing fracture is examined tractographically at the midsection of the specimen. In this method, attention should be paid to the fact that the R-curve determined by the smaller values of Δa than those in the standards [2,3]is to be used and can not be approximated as a straight line as shown in Fig. 6.

3.2 A387 Gr.22 Cl.2 (2-1/4 Cr-1Mo) Steel

(1) Results of R-curve Method

Cleavage fracture toughness, K_c, of A387 Gr.22 Cl.2 (2-1/4Cr-1Mo) steel at several temperatures is shown in Fig. 7. The K_c value was converted by eq. (2) in terms of area under load, load-line displacement record as in J_{IC} test. The solid symbols in the figure satisfy the valid K_{IC} conditions.

At 0°C which is obviously in the transition temperature as shown in Fig. 7, the modified J_{IC} test was conducted on the same material but on different specimens from those used in K_c test. Fig. 8, the R-curve of the material, indicates that the actual ductile crack extension is so small that the R-curve is very close to the blunting line and that it is difficult to determine J_{IC} as the separating point of the R-curve from the blunting line. In spite of the difficulty, Fig. 8 indicates that the value of J at which the length of dimple region, ℓ, begins increasing is close to the value corresponding to K_{IC}. An example of fracture appearance is shown in Photo 3.

(2) Results of J versus ℓ_{max} or $\sum_{i}\ell i$ Curve

The maximum length of isolated ductile tearing regions, ℓ_{max}, along the tip of the stretched zone and density of ductile regions, $\sum_{i}\ell i$ which is the ratio of the summation of the length of the ductile regions per 1mm distance along the stretched zone were taken as the abscissa instead of physical crack extension, Δa, as shown in Fig. 9 and Fig. 10, respectively. These figures show that microscopic ductile tearing fracture initiates at a considerably lower value of J compared with the J_{IC} at the upper shelf temperature ($J_{IC(u.s)}$>52 N/mm from Fig. 7) and that ℓ_{max} and $\sum_{i}\ell i$ begin to increase at about the position of an arrow which corresponds to the value of K_{IC} at 0°C. This suggests that J_{IC} or K_{IC} may be determined by the J versus ℓ_{max} or $\sum_{i}\ell i$ curve.

Presently the temperature dependence of the J versus ℓ_{max} or $\sum_{i}\ell i$ curve is not yet evident. Although the data points are not sufficient, comparison of the open symbols on the data at -20°C in Fig. 9 with the previous solid symbols at 0°C suggests the insignificant temperature dependence of the curve. Assuming the temperature independency of the curve, the effective length of ductile tearing, $(\ell_{max})_{eff.}$ and $(\sum_{i}\ell i)_{eff.}$ vary with temperature as shown in Fig. 11 as an example. The abscissa of the figure is the excess temperature, T_{EXCESS}, which is the difference between the test temperature, T_{TEST}, and the impact transition temperature, vTrs. J_{IC} at various temperatures including the upper shelf temperature may be determined by these figures. Quantitative relations of the J versus ℓ_{max} or $\sum_{i}\ell i$ curve should be clarified in future.

In order to determine the detail extent of ductile tearing fracture,it is desirable to separate the specimen by fatigue cracking as in 2-1/4Cr-1Mo steel rather than by cleavage fracture as in C-1/2Mo steel so as to prevent the possibility of additional ductile fracture during the process of specimen separation.

3.3 The Meaning of the Modified J_{IC} Test Method

ASTM E399 specifies that K_{IC} is calculated from the value of load corresponding to a 2% apparent increment of crack extension. Although a contribution of plastic deformation is deducted from the apparent extension, it is considered that the standard recognizes the existance of a small amount of actual stable crack growth even in the transition temperature region. The modified J_{IC} test method proposed in this paper is interpreted as the procedure to determine the initiation of effective microscopic ductile tearing fracture directly by fractographic observation along the tip of the stretched zone ahead of original crack of the specimen.

Although there is little discussion on the quantitative effect of the ductile tearing fracture on the cleavâge fracture, it is considered that the initiation of ductile fracture satisfies the stress condition on cleavage fracture and the tearing fracture acts as a starter of fast fracture[9].

When cleavage fracture occurs during loading of a specimen, combination of the proposed J_{IC} test with the statistic J_{IC} procedure using a large number of specimens[7] will be useful in improving the accuracy of the results.

4. Conclusions

Modified J_{IC} test procedure was proposed in this paper and the test was conducted on C-1/2Mo steel and 2-1/4Cr-1Mo steel in the transition temperature region. The test method defines J_{IC} as a toughness at the initiation of effective microscopic ductile tearing fracture preceding cleavage fracture at midsection of the specimen where plain-strain exists.

When J versus ductile crack extension (Δa) fracture resistance curve (R-curve) is used in determining the initiation of the ductile tearing, the R-curve should not be approximated as a straight line in the range of small value of Δa. In case of difficulty in applying the R-curve method, the maximum length of isolated ductile tearing regions, ℓ_{max}, or the density of the length, $\sum_i \ell i$ along the stretched zone is substituted for Δa. The value of K converted from J_{IC} which was determined by a relatively small number of specimens was independent on the thickness of specimen and coincided well with K_{IC} which was obtained by heavy section specimen. The quantitative evaluation of effective length of ℓ_{max} or $\sum_i \ell i$ at which the crack is considered to begin arising and the temperature dependence of the J versus ℓ_{max} or $\sum_i \ell i$ curve should be clarified by accumulation of data.

References

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[2] "Standard Method of Test for Elastic-Plastic Fracture Toughness J_{IC}", The Japan Society of Mechanical Engineers, S001-1981 (October, 1981).

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Table 1 Chemical compositions of materials.

Steel	C	Si	Mn	P	S	Cr	Mo
A204 Gr.A (C-1/2Mo)	0.20	0.18	0.70	0.013	0.015	—	0.50
A387 Gr.22 Cl.2 (2-1/4Cr-1Mo)	0.14	0.13	0.50	0.010	0.002	2.35	0.94

Table 2 Mechanical properties of materials.

Steel	Test Temperature (°C)	0.2% Offset Yield Strength $\sigma_{0.2}$ (MPa)	Ultimate Tensile Strength σ_B (MPa)	Elongation δ(%)	Reduction of Area ϕ(%)	Impact Transition Temperature vTrs(°C)
A204 Gr.A (C-1/2Mo)	25	341	534	26.5	58.7	67
A387 Gr.22 Cl.2 (1-1/4Cr-1Mo)	0	545	678	20.0	79.0	26
	-20	561	697	21.6	78.3	

Table 3 Geometries of CT specimens.

Steel	Size (mm)							
	W	B	H	L	G	a_o	d	a_o/W
A204 Gr.A (C-1/2Mo)	50	1,5,10,25	60	62.5	27.5	25	12.5	0.5
	150	75	180	187.5	82.5	75	37.5	
A387 Gr.22 Cl.2 (2-1/4Cr-1Mo)	50	3,10,25	60	62.5	27.5	25	12.5	0.5
	175	87.5	210	218	105	87.5	44	

Table 4 Summary of fracture toughness test conditions.

Steel	Crack Plane Orientation	$K_{f\ max}$ (MPa$\sqrt{m}$)	Test Temperature (°C)	Displacement Speed (mm/min)	Separation of Fracture Surface
A204 Gr.A (C-1/2Mo)	CL	19	20-25	0.2-0.6	Cleavage Fracture at Liq. N. Temp.
A387 Gr.22 Cl.2 (2-1/4Cr-1Mo)	TL	16	0, -20 (-100,-50,+10,+20)	0.6-1.2	Subsequent Fatigue Cracking

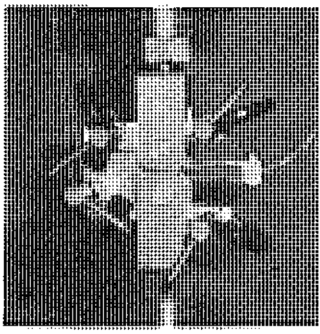

Photo 1 Setup of anti-buckling plates on CT specimen (1 mm thick).

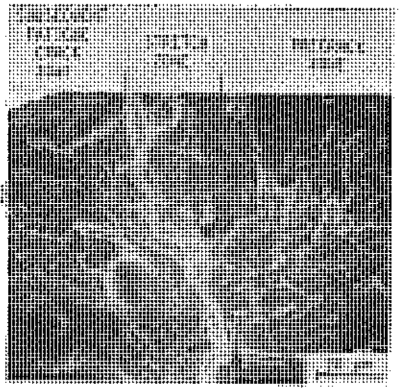

Photo 2 An example of fracture appearance of A204 Gr.A (C-1/2Mo) steel at room temperature separated by overloading at liquid nitrogen temperature. Thickness of the specimen is 10 mm and J=28 N/mm (K_I=80 MPa√m).

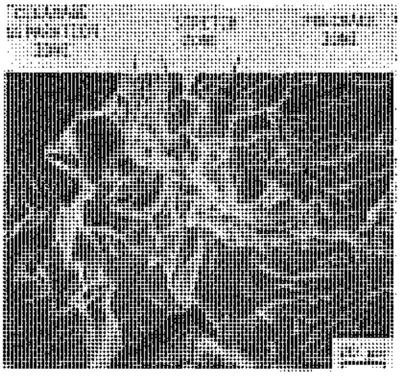

Photo 3 An example of fracture appearance of A387 Gr.22 Cl.2 (2-1/4Cr-1Mo) steel at 0°C separated by subsequent fatigue cracking. Thickness of the specimen is 10 mm and J=40 N/mm (K_I=95 MPa√m).

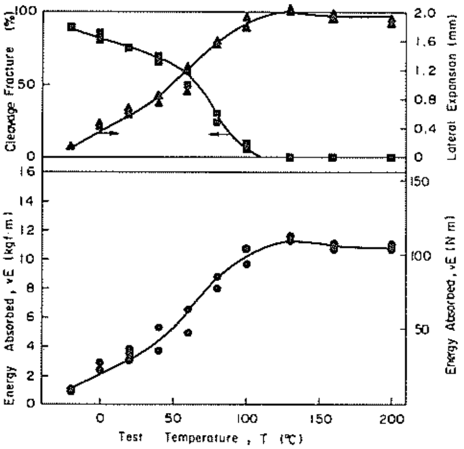

Fig. 1 Charpy V transition curve for ASTM A204 Gr.A (C-1/2Mo) steel.

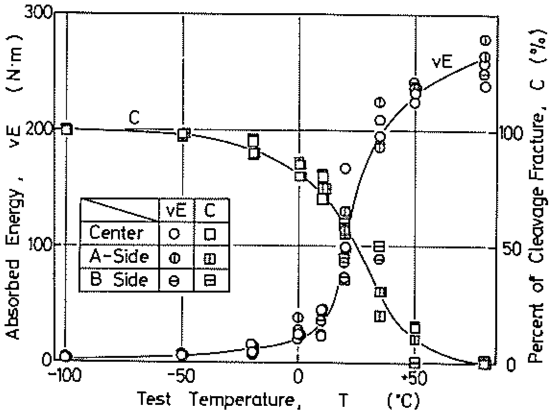

Fig. 2 Charpy V transition curve for ASTM A387 Gr.22 Cl.2 (2-1/4Cr-1Mo) steel.

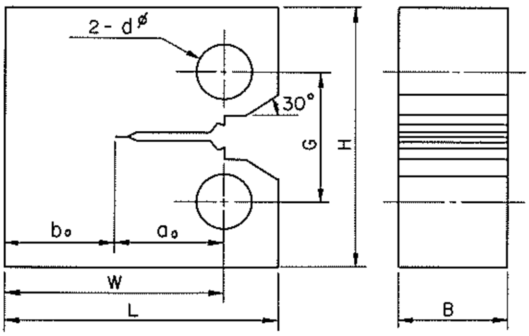

Fig. 3 Compact tension (CT) type toughness specimen.

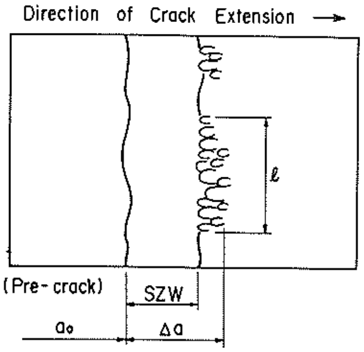

Fig. 4 Schematic fracture appearance of J_{IC} specimen.

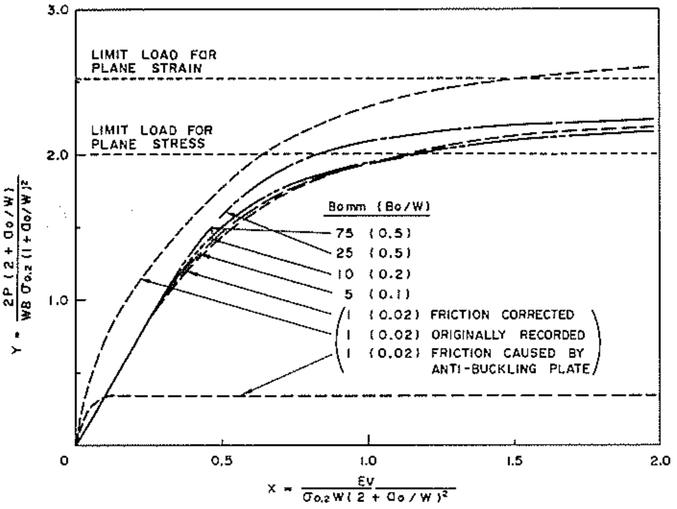

Fig. 5 Summary of normalized load versus load-line displacement curves of CT specimens for A204 Gr.A (C-1/2Mo) steel.

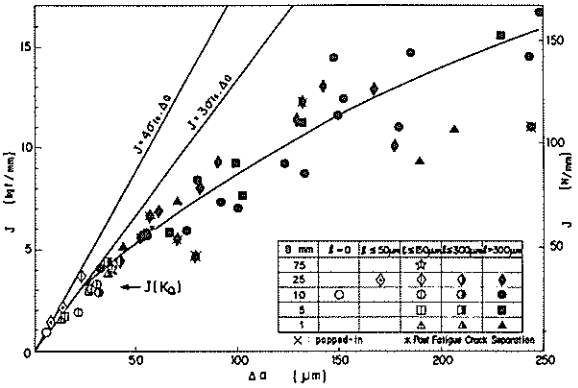

Fig. 6 J versus crack extension curve for A204 Gr.A (C-1/2Mo) steel at room temperature (20-25°C).

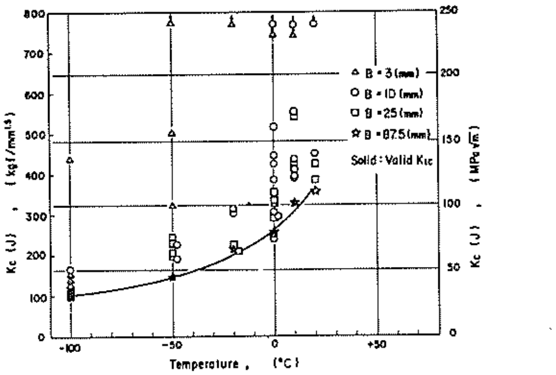

Fig. 7 Temperature dependence of fracture toughness, K_C, for A387 Gr.22 Cl.2 (2-1/4Cr-1Mo) steel.

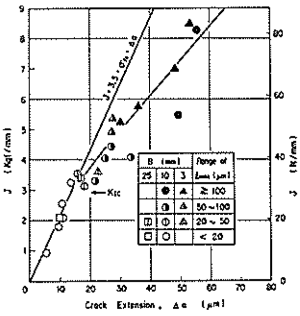

Fig. 8 J versus crack extension curve for A387 Gr.22 Cl.2 (2-1/4Cr-1Mo) steel at 0°C.

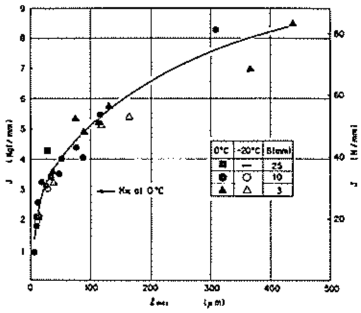

Fig. 9 J versus ℓ_{max} curve for A387 Gr.22 Cl.2 (2-1/4Cr-1Mo) steel at 0°C and -20°C.

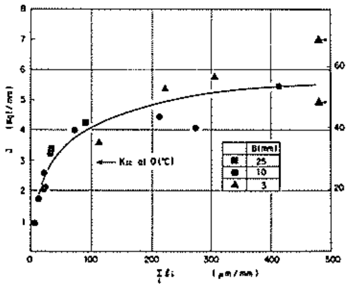

Fig. 10 J versus $\sum_i \ell i$ curve for A387 Gr.22 Cl.2 (2-1/4Cr-1Mo) steel at 0°C.

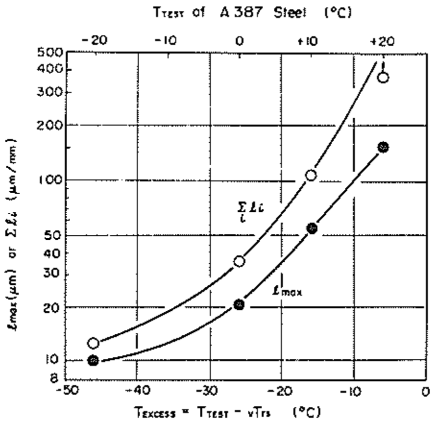

Fig. 11 $(\ell_{max})_{eff.}$ and $(\sum_i \ell i)_{eff.}$ as a function of excess temperature or test temperature for A387 Gr.22 Cl.2 (2-1/4Cr-1Mo) steel.