Strain Constraint of Circumferentially Notched Tensile Specimens for the Alternative Fracture Toughness Evaluation

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Standardized test methods of plain strain fracture toughness K_{IC} and elastic-plastic fracture toughness J_{IC} are time-consuming and expensive. On the other hand, a convenient new test method, named J evaluation on tensile test (JETT) of round bar with circumferential notch, has been proposed to evaluate the fracture toughness of the tough materials. Since JETT is not standardized yet, the size of JETT specimen should be carefully selected. Therefore the FEM calculations for the comparison of the strain constraint around the notch or crack tip of both specimens are needed before the experiments. In this research, the tables demonstrating the effective JETT specimen sizes as a function of a work-hardening exponent and a work-hardening coefficient were proposed. A fracture toughness of a work-hardening material can be evaluated by JETT specimen, while that of an elastic-perfect plastic material is difficult to be evaluated by it.

1. Introduction

Fracture toughness is one of the most important mechanical properties among various properties of structural materials for machinery. To evaluate the fracture toughness, J_{Ic}, of a material, the standardized method in ASTM E813[1] using the compact tension (CT) specimen is usually applied. Requirements for a valid J_{Ic} in the standard are governed mainly by two factors, a thickness of the specimen and a shape of the resultant crack front. Especially the thickness and initial ligament requirement described by the following equation is sometimes hard to satisfy for a tough material.

$$B \text{ or } b_0 > 25\left(J_Q/\sigma_{fs}\right) \tag{1}$$

where B is the specimen thickness, b_0 is the initial ligament and σ_{fs} is the flow stress (an average of the yield and the ultimate tensile strength).

Fracture toughness tests at liquid helium or nitrogen temperature have to be conducted in limited space. In another case, an effect of neutron irradiation on a toughness of the material for fusion reactor has to be evaluated by small specimens because of facility problems. Therefore to develop the materials for cryogenic structure or irradiated environment, another toughness test method for small specimen is indispensable.

A new test method, named J evaluation on tensile test (JETT), has been proposed to evaluate a fracture toughness[2-5]. JETT was originally developed to obtain critical J, focusing on an absorbed energy in a round bar with a narrow and deep notch during a tensile test. For development of a convenient test method by avoiding the many efforts[6,7] of introducing axisymmetric fatigue crack, the possibility of the test using EDM(electro-discharge machining) notch has been investigated[8]. As one of the approaches to clarify the usability of the JETT, an international round robin test (IRRT) using a commercial 316LN was performed under the framework of the VAMAS TWA 17 activity[9]. The same critical J values were obtained by JETT and ASTM E813-89[1] in the activity. However, the analytical comparisons on the stress distribution and strain constraint around the notch or crack tip of the both specimens was not made enough. Therefore the equation for the requirement of JETT specimen size could not be proposed yet.

In this research, finite element method (FEM) calculations for strain constraint around a notch or crack tip of both specimens were conducted. The dependences of a specimen size and a work hardening property on strain constraint were investigated. The table demonstrating the effective JETT specimen size as a function of work hardening properties was tried to be made.

2. Calculation Procedure

Substituting various n and α in the following Ramberg-Osgood equation, normalized stress-strain curves of various materials can be approximately simulated.

$$\left(\frac{\varepsilon}{\varepsilon_{0.2}}\right)=\left(\frac{\sigma}{\sigma_{0.2}}\right)+\alpha\left(\frac{\sigma}{\sigma_{0.2}}\right)^{n} \tag{2}$$

Elastoplastic finite element stress analyses of various materials by code ANSYS[10] were conducted using von Mises' yield criteria and the strain incremental theory. Strain constraint (stress tri-axis states) around a notch or crack tip and numeric line integral of J were evaluated. The size of the elements assigned to a notch or crack tip in JETT and CT specimens was equally defined. The J formula of an axisymmetric bar is derived from the following equation [11,12]

$$J=\frac{1}{b}\left\{\iint_{r,z} W dr dz+\oint_{\Gamma}\left[-W\cdot r\,dz+\vec{T}\frac{\partial\vec{u}}{\partial r}r\,dc\right]\right\} \tag{3}$$

where W is strain energy per unit volume, vector T and u are the external force and displacement on the path of the J integral respectively, b is the ligament length, c is the path length of line integral, and r, z are the cylindrical coordinate system. The first integral of the right side of eq.(2) is related to the energy through the boundary surface normal to circumferential direction, while the second integral is related to that normal to the line integral path, Γ.

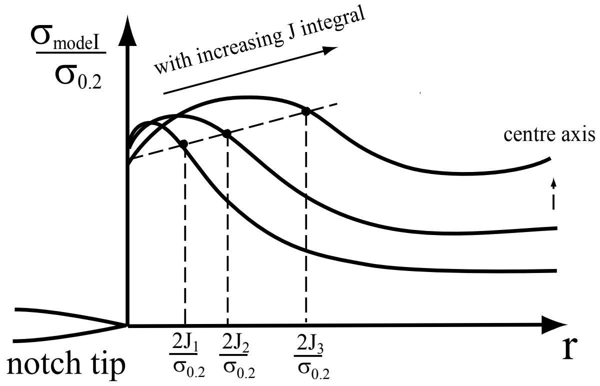

Fig.1 An example of stress distributions around a notch tip of a JETT specimen. With increasing J (from J_1 to J_3), mode I stress at normalized distance r'=2 and that at centre axis increase.

Fig.1 shows an example of stress distributions around a notch tip of a JETT specimen. Although a peak stress on the ligament in a plate specimen like CT is saturated with a constant value, that in a JETT specimen is not saturated and increases with J. Furthermore the same J does not always produce the same stress distribution and a peak stress around a notch tip.

Q-factor[13-16] is one of the indexes expressing a stain constraint around a notch or crack tip. It shows a difference of mode I stresses at dimensionless distance $r'=r/(J/\sigma_{0.2})=2$ between a stress under target condition and an ideal reference stress under plane strain condition.

$$Q = \frac{(\sigma_{\mathrm{mod}e\,\mathrm{I}})_{r'=2} - (\sigma_{\mathrm{mod}e\,\mathrm{I}})_{r'=2}^{ref}}{\sigma_{0.2}} \tag{4}$$

An ideal reference stress $\sigma_{\mathrm{modeI}}/\sigma_0$ at r'=2 depending on material work hardening property is around from 3 to 4. On the contrary, $\sigma_{\mathrm{modeI}}/\sigma_0$ at r'=2 under plane stress condition is around from 2 to 3. Therefore Q-factor of plane stress condition is around -1. A specimen with high Q-factor have a large peak stress around a notch tip. Since a peak stress of JETT specimen is not saturated and increases with J, Q-factor is also increases with J. In this research, JETT specimen with

$$-0.2 \le Q \le 0.2 \tag{5}$$

is considered to equivalent to plain strain CT specimen for convenience.

Even if a strain constraint of a JETT specimen is equivalent to CT, the effective fracture toughness can not always be obtained by JETT. A peak stress on the ligament of a JETT specimen is not always found around a notch tip but at the center axis of a bar. If the center axis stress is larger than a notch tip stress, a fracture from the center axis such as a cup and corn type fracture has priority. A position on the ligament where the peak stress is generated, is need to be around a notch tip. This consideration was also taken into account in FEM calculations for an effective JETT specimen size.

3. Results and discussion

Critical J is one of the fracture toughness values. It is defined from an absorbed energy at the onset of a crack growth. A Bended ligament of a CT specimen has tensile, compressive and neutral area on it and a crack in a ductile material shows sometimes stable growth before its final fracture. On the other hand, since the all cross section of a round bar is subjected to tensile stress, if an effective narrow and deep notch is introduced in a round bar, a final fracture is simultanous with the onset of the crack growth. Therefore the critical J of JETT specimens were related to all the integral area under load-displacement curve from start of loading to final fracture.

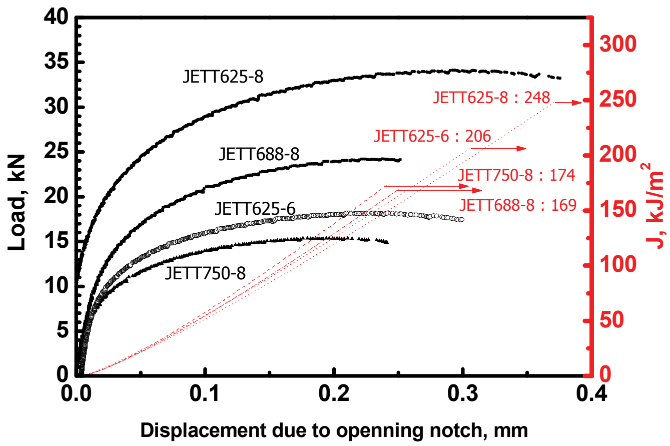

Fig.2 Experimental Load-d_c curve and J integral calculation of JETT

Fig.2 shows experimental load-displacement curves of manganese steel quenched from 800 ℃ in a oil. The stress-starain curve of this material obtained by experiment can be approximately shown by eq.(2) with n = 1.55 , α = 6.48 and $\sigma_{0.2}$ = 370MPa. The holizontal axis shows displacement due to openning notch.

$$d_c = d_{ex} - d_{nc} \tag{6}$$

where d_{ex} is a displacement measured by two displacement gages spanning the notch, and d_{nc} is an elastic displacement in the gage length ($G.L.$) supposing that the crack does not exist. The right vertical axis shows numerical line integral J value obtained by FEM of the same size specimen with the experimental one. In this research, for example, JETT750-8 indicates a ratio of notch and radius a/R=0.750, and radius R=8. Obtained critical J values depended much on the specimen size. Fig.3 shows FEM results of Q-factor with increasing J of JETT specimens. The right vertical axis shows Max location, a position on the ligament where the maximum open mode stress is generated. If an obtained critical J is within the range fulfilling eq.(5) and Max location being not around zero(the axis of a bar), this critical J and selected size of specimen are valid. On the contrary, if it is out of the range, another test with a different size specimen is needed. As for this material, the critical J obtained by JETT625-8, J_Q=248 KJ/m^2, is the nearest to J_{IC} =275 KJ/m^2 obtained by a plane strain CT specimen among JETT specimens, but it a little underestimates because the strain constraint is a little higher value , Q = 0.35, at J_Q=248 KJ/m^2.

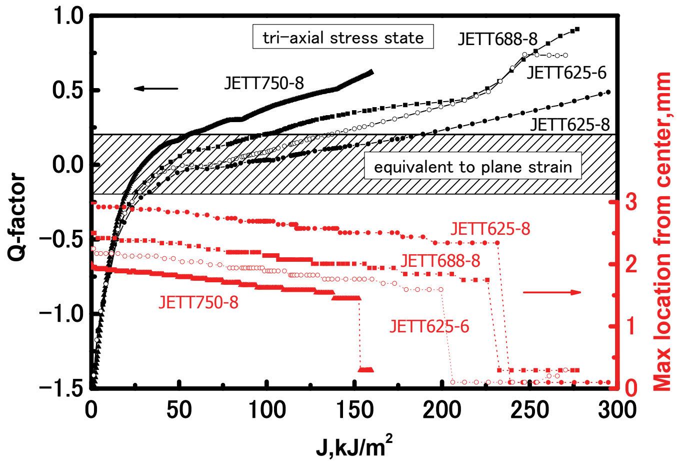

Fig.3 Strain constraint(Q-factor) and Max locaiton of JETT with increasing J. Equivalent strain constraint condition shown by eq.(5) is the hatched zone.

The same FEM calculations of various materials (various n and α in eq.(2)) were conducted and the above mentioned two conditions, eq.(5) is fulfilled and Max location is not around zero, were applied to JETT625-8 specimen. The $J/\sigma_{0.2}$ values related to the lower bound of eq.(5), the upper bound of eq.(5) and the Max location were defined J_a , J_b and J_c , respectively. If an obtained critical J/σ_y is more than J_a and less than smaller one between J_b and J_c , this critical J and selected size of specimen are valid. Table 1 shows J_a , J_b and J_c of various materials with JETT625-8. This table shows effective critical J values by using the specimen with R=8mm and a=5mm(JETT625-8). If an obtained critical J is not within the range shown in this table, another size of specimen have to be used. This table and the same tables of the other size of specimens are substituted for eq.(1).

On the other hand, a material with higher *n* (*n*=25), an elastic-perfect plastic material, have low Q-factor (less than or almost equal to - 0.2). The material does not have J_a or the range of effective critical J with the material is very narrow. Therefor a strain constraint equivalent to the plane strain can not be realized by JETT625-8 with higher *n*.

Table 1 Effective $J/\sigma_{0.2}$ depending on work-hardening properties of JETT625-8. *n*=25 shows nearly elastic-perfect plastic material.

JETT625-8: $J/\sigma_{0.2}$ [mm]			α								
			10	9	8	7	6	5	4	3	2
n	2	*Ja*	0.021	0.023	0.026	0.028	0.032	0.044	0.041	0.047	0.071
		Jb	0.101	0.043	0.047	0.043	0.048	0.044	0.430	0.584	> 0.7
		Jc	> 0.6	> 0.6	> 0.6	> 0.7	> 0.7	> 0.7	> 0.7	> 0.7	> 0.7
	4	*Ja*	0.051	0.052	0.054	0.046	0.048	0.050	0.052	0.055	0.059
		Jb	0.423	0.403	0.400	0.380	0.378	0.343	0.327	0.311	0.404
		Jc	> 0.65	> 0.65	> 0.65	> 0.65	> 0.65	> 0.65	> 0.65	> 0.65	> 0.65
	6	*Ja*	0.077	0.078	0.068	0.069	0.070	0.071	0.073	0.075	0.078
		Jb	0.420	0.427	0.419	0.411	0.414	0.400	0.406	0.412	0.437
		Jc	> 0.625	> 0.625	> 0.625	> 0.625	> 0.625	> 0.625	> 0.625	> 0.625	> 0.625
	8	*Ja*	0.084	0.084	0.085	0.086	0.087	0.088	0.090	0.092	0.095
		Jb	0.436	0.426	0.416	0.406	0.409	0.406	0.412	0.430	0.490
		Jc	0.544	0.551	0.559	0.568	0.574	0.609	0.620	0.645	0.683
	10	*Ja*	0.099	0.100	0.101	0.101	0.103	0.104	0.119	0.107	0.110
		Jb	0.486	0.479	0.484	0.474	0.477	0.485	0.495	0.495	0.514
		Jc	0.440	0.448	0.453	0.474	0.477	0.485	0.495	0.513	0.550
	12	*Ja*	0.114	0.115	0.116	0.117	0.119	0.119	0.135	0.137	0.126
		Jb	> 0.45	> 0.45	> 0.45	> 0.45	> 0.46	> 0.45	> 0.45	> 0.45	> 0.45
		Jc	0.372	0.370	0.387	0.400	0.404	0.417	0.431	0.440	0.450
	15	*Ja*	0.129	0.130	0.131	0.132	0.133	0.149	0.151	0.168	0.171
		Jb	> 0.42	> 0.42	> 0.42	> 0.42	> 0.42	> 0.42	> 0.42	> 0.42	> 0.42
		Jc	0.310	0.312	0.306	0.309	0.311	0.330	0.343	0.384	0.402
	20	*Ja*	0.159	0.188	0.183	0.191	0.198	0.206	0.229	0.233	0.211
		Jb	> 0.4	> 0.4	> 0.4	> 0.4	> 0.4	> 0.4	> 0.4	> 0.4	> 0.4
		Jc	0.284	0.276	0.280	0.280	0.266	0.273	0.266	0.272	0.298
	25	*Ja*	0.210	0.218	0.230	0.253	*Low constraint*				
		Jb	> 0.35	> 0.35	> 0.35	> 0.35					
		Jc	0.265	0.262	0.260	0.268	0.263	0.251	0.251	0.242	0.244

4. Conclusion

A critical J value obtained by JETT specimen depends much on a specimen size. If a strain constraint around a notch tip of a JETT specimen is equivalent to the plane strain CT specimen and a position on the ligament where the maximum open mode stress is generated is around a notch tip, the same critical J is expected to be obtained. Such the condition needed to JETT specimens can be expressed by the proposed effective J tables. These tables show that the effective specimen size depends not only the 0.2 % proof stress but also the work hardening property. As for an elastic-perfect plastic material, a strain constraint of JETT specimen is lower than that of the plane strain CT specimen. A fracture toughness of an elastic-perfect plastic material is difficult to be evaluated by a JETT specimen.

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