EFFECT OF SPECIMEN SIZE ON J_{Ic} FOR A Ni-Cr-Mo ROTOR STEEL IN THE UPPER SHELF REGION

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ABSTRACT

The J integral method is used for determining the K_{Ic} fracture toughness transition curve of a 28 NCD8-5 rotor forging steel. The tests are carried out on a series of homothetic compact tension specimens of different thickness ranging from 15 mm to 150 mm.

In the transition region, where fracture occurs suddenly by cleavage, there is satisfactory agreement between K_{Jc} values calculated from J_{Ic} and K_{Ic} values determined previously according to the ASTM E399 standard.

At the upper shelf, where fracture takes place by ductile tearing, the critical values J_{Ic} depend very largely on specimen dimensions. The influence of thickness B and uncracked ligament length (W-a) is then shown independently by means of tests carried out on compact tension specimens of varying thicknesses. The results obtained by the interrupted loading method and the A.C. potential drop technique show that the critical value J_{Ic} increases with ligament length but remains practically independent of thickness. It is suggested that the onset of tear propagation corresponds approximately to the generalized plastic deformation through the ligament. The critical value J_{Ic} determined experimentally at initiation would thus increase with ligament length (W-a) up to a minimum specimen size such that initiation occurs before the general yield.

KEYWORDS

J-integral ; CT specimen ; crack initiation ; A.C. potential drop ; specimen dimensions ; rotor steel.

INTRODUCTION

It appears to be widely recognized today that the plane-strain fracture toughness K_{Ic} of medium-strength steels can be determined, using the J integral method, by means of a subsized specimen loaded in the elastic-plastic regime. According to Begley and Landes (1972, 1977), the critical value J_{Ic} at the onset of crack growth is a material property provided the thickness B and uncracked ligament length (W-a) verify the condition :

$$B, (W-a) \geq \alpha\left(\frac{J_{Ic}}{\sigma_f}\right) \qquad (1)$$

where α is equal to 25 and σ_f is the average of the 0.2% offset yield strength (σ_{ys}) and the ultimate tensile strength (σ_{ut}).

In the temperature range where fracture occurs suddenly by cleavage, the results obtained by different authors (Begley and Landes, 1977 ; Marandet and Sanz, 1977a) make it clear that there is satisfactory agreement between K_{Ic} values determined under the conditions required by the ASTM E399 standard and K_{Jc} values derived from J_{Ic} according to the following relationship :

$$K_{Jc} = \sqrt{\frac{E}{(1-\nu^2)} J_{Ic}} \qquad (2)$$

In the temperature range where propagation and fracture take place by ductile tearing, the results published in the literature appear to be less convincing. The independence of J_{Ic} with respect to the specimen dimensions B and (W-a) has been infered from a limited amount of data (Begley and Landes, 1977 ; Griffis, 1975). Furthermore, these data display contrary variations of J_{Ic} as a function of size and yield α coefficients of 25 or 50. This is in contradiction with the recent observations of Blauel (1978) and Williams (1979) who point out a continuous increase in J_{Ic} with specimen size, although the two preceding conditions are still satisfied. However, it seems to be clear that J_{Ic} measurements may yield conservative estimates of K_{Ic} when fracture is fully ductile (Logsdon, 1976).

In order to shed light on this subject, we undertook a systematic investigation of the effect of specimen size on J_{Ic} in the transition range as well as at the upper shelf. The A.C. potential drop technique is used for detecting crack initiation. The critical values J_{Ic} thus obtained with a single specimen are compared with those deduced from the interpretation of the crack resistance curves $J-\Delta a$ according to the draft recommendation recently proposed by the ASTM Committee E24-08 (1980).

MATERIAL AND PREPARATION OF SPECIMENS

The studied material is a quenched and tempered bainitic rotor forging steel of the 28 NCD8-5 type. The test ring comes from the bottom of a 40 tons ingot forged to the following dimensions : outer diameter 1500 mm, inner diameter 580 mm, thickness 400 mm. The piece received quality heat treatment including austenitization at 850°C for 6 hours and 30 minutes, quenching in water and then tempering at 620°C for 7 hours, followed by slow cooling. Chemical composition and mechanical properties of the material are given in Table 1.

TABLE 1.

Chemical composition								
Element	C	Si	Mn	S	P	Ni	Cr	Mo
% weight	0.295	0.275	0.630	0.007	0.009	1.95	1.35	0.425

Tensile properties at room temperature				Charpy properties		
σ_{ys} (MPa)	σ_{ut} (MPa)	Elongation (%)	Reduction in area (%)	TK 28J (°C)	FATT (°C)	Ductile level (J)
675	831	19.5	67	-100	-20	145

We previously determined the K_{Ic} fracture toughness transition curve according to the ASTM E399 standard using homothetic compact tension specimens of thickness B equal to 150 mm (CT 150), 100 mm (CT 100) and 75 mm (CT 75). These specimens were taken from the test ring so that the notches are radial and their end is located on a circle of 1180 mm diameter.

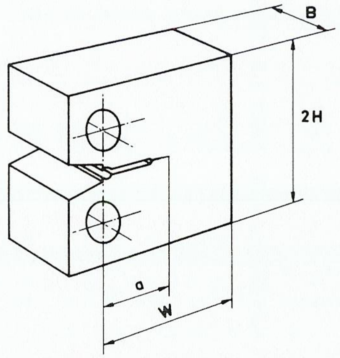

Fig. 1. Specimen configuration for J testing.

J_{Ic} measurements in the transition range were made on modified compact specimens of the CTJ type (Fig. 1) taken in the same manner from the broken halves of large thickness CT specimens previously tested. The use of an extensive range of CTJ specimens of variable thickness (Table 2) enabled us to investigate separately the influence of thickness and uncracked ligament length on J_{Ic} at room temperature where fractures are fully ductile.

TABLE 2.

Type of specimen	CTJ 15	CTJ 25	CTJ 40	CTJ 75
Thickness (mm)	15-10-5	25-20-15-10-5	40-25-20-15	75-50-25

EXPERIMENTAL PROCEDURE

The J integral is calculated from the load, load-point displacement curve using the modified Merkle and Corten (1974) derivation :

$$J = \frac{A}{B(W-a)} \; f(a/W)$$

where A is the area under the load, load-point displacement record in energy units

B is the specimen thickness

(W-a) is the initial uncracked ligament

a is the original crack size

$f(\frac{a}{W})$ is a dimensionless coefficient value which corrects the tensile component of the load. Values are given in a table (Clarke and Landes, 1979).

When fracture is initiated by ductile tearing, J_{Ic} is determined by two different methods :

- The A.C. potential drop method (50 Hz) developed by IRSID (Marandet and Sanz, 1977a ; Marandet and co-workers, 1978) is used for determining J_{Ic} with a single specimen. This technique makes it possible to detect the first stages of the stable crack growth process at the crack tip.

- The interrupted loading method recommended by the ASTM Committee E24-08 which is based upon the interpretation of a crack resistance curve $J-\Delta a$ developed using multiple specimens. J_{Ic} is defined at the intercept between the best straight line that fits the experimental data and the blunting line having the equation : $J = (\sigma_{ys} + \sigma_{ut})\, \Delta a$.

RESULTS

In the Transition Range

The KIc fracture toughness transition curve is given in Fig. 2. It should be pointed out here that not all the specimens of large thickness verify the condition $B > 2.5 \left(\frac{K_Q}{\sigma_{ys}}\right)^2$ required by the ASTM E399 standard. Since the tests carried out with homothetic compact tension specimens of different thicknesses B showed that K_Q becomes independent of specimen size for $B \geq \left(\frac{K_Q}{\sigma_{ys}}\right)^2$ with $P_{max}/P_Q \leq 1.1$, we shall nevertheless consider these values of K_Q to be valid values of KIc. These experimental results are moreover in excellent agreement with the KIc fracture toughness transition curve estimated on the basis of the Charpy V-notch transition curve thanks to the correlation proposed by Marandet and Sanz (1977b).

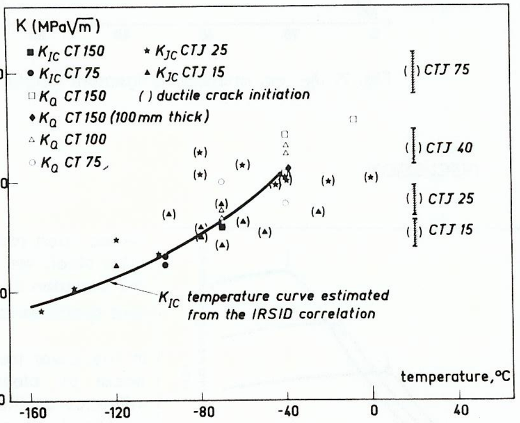

Fig. 2. Fracture toughness transition curve.

The values of K_{Jc} deduced from J_{Ic} for CTJ 15 and CTJ 25 specimens are indicated on the same diagram. In the lower part of the transition curve where fracture takes place by cleavage, K_{Jc} gives a proper evaluation of toughness. On the other hand, where fracture is initiated by ductile tearing, the values of K_{Jc} no longer increase with temperature. They reach an upper plateau the level of which depends on the specimen type. The change from an initiation mode to another also appears to depend on specimen size. The transition thus occurs towards -95°C for CTJ 15 specimens and towards -80°C for CTJ 25 specimens. We did not determine precisely these temperatures for all the types of specimens considered but it is noted that the CTJ 75 specimens still exhibit brittle facture at -40°C whereas all the specimens tested at 20°C exhibit a fully ductile behaviour.

In the Ductile Range

We considered it of interest to examine in greater detail the effect of specimen size in the ductile range and to determine which of the dimensions, thickness or ligament length, is critical. For this purpose, tests were conducted at room temperature using CTJ 15, CTJ 25, CTJ 40 and CTJ 75 specimens of varying thickness.

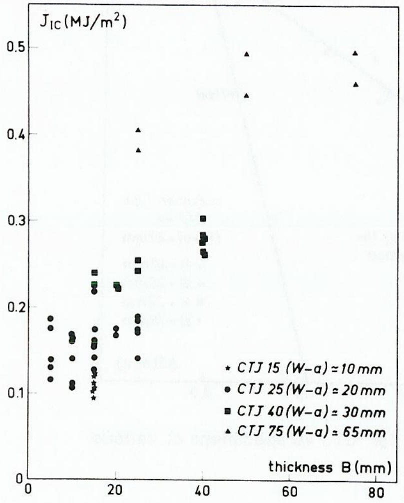

Fig. 3. J_{Ic} vs. specimen dimensions.

Results obtained by the A.C. potential drop method.

Figure 3 indicates the values of J_{Ic} obtained by this method as a function of the dimensions B and (W-a). For the same ligament, the specimen thickness does not appear to have a great influence on the measured value of J_{Ic}. For certain types of specimens, J_{Ic} nevertheless increases slightly with thickness but the effet is not shown clearly. On the other hand, it is noted that J_{Ic} depends to a great extent on ligament length. Thus, for a thickness of 25 mm, the value of J_{Ic} varies from 0.17 MJ/m² to 0.40 MJ/m² when the ligament increases from 15 to 65 mm. The size effect which appears in Fig. 3 is partially complicated by the inherent scattering of values in toughness measurements.

Results obtained by the interrupted loading method.

The crack resistance curves J - Δa plotted respectively for specimens of the CTJ 25 (Fig. 4) and CTJ 40 (Fig. 5) type are practically independent of thickness except for the CTJ 25 specimens of smaller thickness (5 and 10 mm) for which the experimental points move away from the average curve ; nevertheless the straight lines adjusted on these points appear to converge towards the same value of J_{Ic}. As the limited number of specimens of the CTJ 75 type did not permit an observation of the effect of thickness on the J - Δa curve, an average line was plotted.

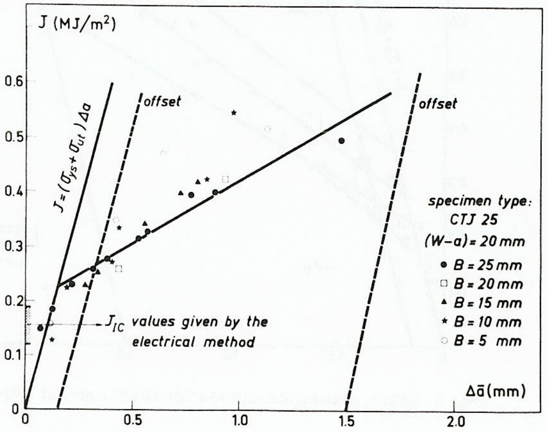

Fig. 4. J vs. crack extension for CTJ 25 specimens of various thicknesses.

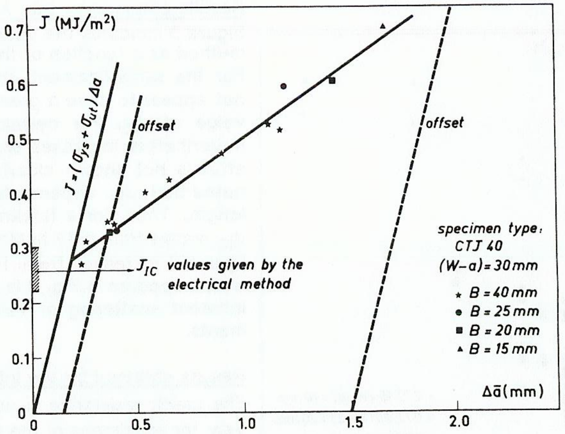

Fig. 5. J vs. crack extension for CTJ 40 specimens of various thicknesses.

The results obtained on the four types of specimens (Fig. 6) show in an unquestionable manner an increase in J_{Ic} with ligament length although the condition (W-a) $\geq 25 \left(\frac{J_{Ic}}{\sigma_f}\right)$ is always fulfilled.

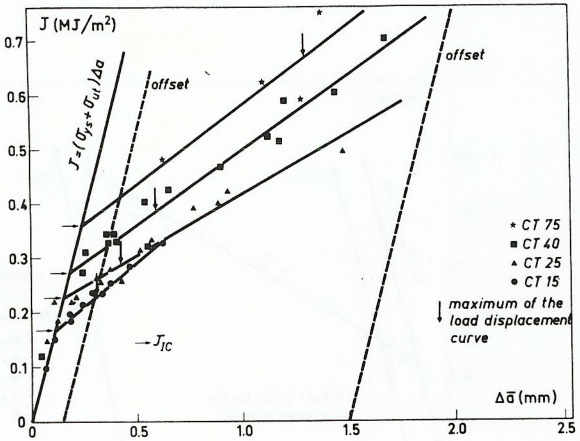

Fig. 6. Crack resistance curves for specimens of different size.

The two measurement methods, lead to slightly different values, but they indicate the same tendency toward variation of J_{Ic} with ligament length (Fig. 7). J_{Ic} increases with (W-a) and appears to reach a maximum value only for a ligament greater than 80 mm, which corresponds to test specimens of large size.

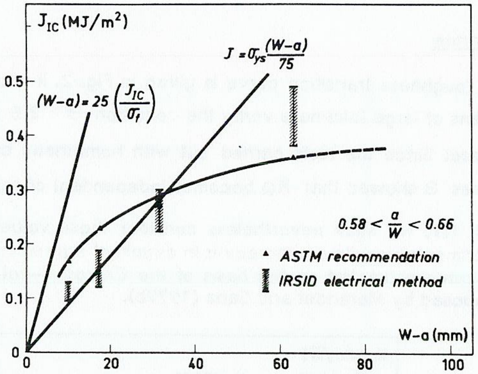

Fig. 7. J_{Ic} vs. uncracked ligament length.

DISCUSSION

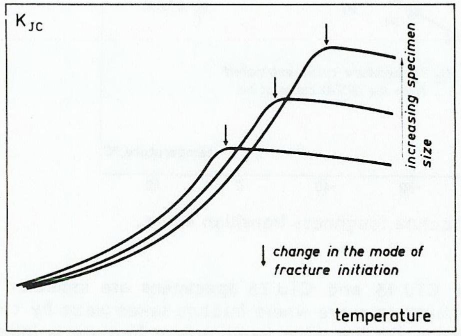

Fig. 8. Schematic variation of K_{Jc} with temperature for different specimen sizes.

Based upon results obtained on the 28 NCD8-5 rotor steel, we propose a qualitative diagram of the variation in K_{Jc} with temperature for different specimen sizes (Fig. 8).

In the lower part of the curve, all the fractures occur by cleavage. Specimen size has little influence on the values of K_{Jc}, which are practically equal to K_{Ic} as we observed in Fig. 2. However, several authors, such as Pisarski (1979), Hogiwara and Mimura (1979) have observed a shifting of the K_{Jc}-temperature curves toward the lower temperatures as specimen size decreases. In this temperature range, the J integral is nevertheless a good means of evaluating toughness because it makes use of specimens of much smaller size than those necessary for a K_{Ic} test as per the ASTM E399 standard.

At higher temperature, the fracture mode depends on the dimensions of the test specimens. The transition from a cleavage fracture to one initiated by ductile tearing takes place when the triaxiality is no longer sufficient so that the cleavage stress can be reached before plastic strain occurs. Since the triaxiality of the stresses is directly related to specimen size, the change in the fracture initiation mode will be produced at a temperature which decreases as the specimen size decreases

The results obtained on CTJ 25 and CTJ 15 (Fig. 2) specimens indicate that the values of K_{Jc} tend toward an upper shelf when the fracture is ductile, the shelf level being a fonction of the type of specimen. At a temperature defined within the ductile range, J_{Ic} thus increases with specimen size even when the condition B, (W-a) $\geq 25 \left(\frac{J_{Ic}}{\sigma_{f\,s}}\right)$ is verified. In a recent paper, Marandet, Devaux and Pellissier-Tanon (1979) have attempted to explain this increase in the value of J_{Ic}. They showed that, for homothetic specimens loaded below the limit load, the same plastic strain conditions correspond approximately to the same value of $J/[\sigma_{ys}(W-a)]$. A finite element calculation on the CT 50 specimen of A 508Cl.3 steel has made it possible to establish that general yield (or limit load) is reached shortly after the load corresponding to J_{Ic}, measured as per the ASTM recommendation. Furthermore, it is noted that the value of J associated with the limit load is close to $J = \frac{\sigma_{ys}(W-a)}{75}$. These results tend to prove that specimens behave as if the onset of ductile tearing moved with the beginning of general yield until, finally, for a sufficient specimen size, the onset of ductile tearing is produced before the limit load. The J integral at crack initiation thus becomes independent of specimen size. In fact, the reasons for such a correspondence are not known. This would however explain, as we have shown, why the value of J_{Ic} measured in the ductile range depends on the uncracked ligament length and is practically independent of thickness.

In Fig. 7, we have plotted the equation $J = \sigma_{ys}(W-a)/75$. A certain agreement is observed between this line and J_{Ic} calculated by the two methods.

In the case of the investigated steel, the value of (W-a) guaranteeing the independence of J_{Ic} with respect to the ligament appears to be fairly high. The coefficient generaly recognized, $\alpha = 25$, is quite insufficient ; a value of the order of 150 to 200 would be more appropriate if one does not wish to underestimate the toughness of the steel.

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