DETERMINATION OF FRACTURE TOUGHNESS OF STAINLESS STEELS - AN EVALUATION OF DIFFERENT J_{IC} TESTING PROCEDURES

R.Johansson* and J.-O.Nilsson*

Two stainless steels have been investigated with respect to fracture toughness and its orientational dependence. Comparison was made between the ASTM and JSME standard procedures.

The toughness in cold rolled tubes was found to be strongly anisotropic and attained a maximum for longitudinal specimens having a radial crack. Accordingly, maximum values of stretch zone width were observed for this orientation. The JSME method tended to give lower toughness values than the ASTM method.

INTRODUCTION

Stainless steels, employed in the oil and gas industry as production tubes, have been investigated with respect to fracture toughness. Although these tubes are cold worked approximately 55%, their toughness is so high that non-linear fracture mechanics has to be used.

Previous investigations have shown that the dimension requirements imposed by the ASTM E813 standard are only barely fulfilled for these steels and the volumes available in the tube wall (1). In some cases, for instance for longitudinal specimens having maximum toughness values the ASTM standard was even inapplicable. Therefore other procedures available for J_{IC} evaluation must be considered.

The present investigation aims at comparing different J_{IC}-evaluation methods with respect to their applicability for tough stainless steels.

* AB Sandvik Steel, R&D Centre, S-811 81 Sandviken, Sweden

EXPERIMENTAL

Cold rolled tubes were fabricated from two different steel grades. The nominal chemical compositions of the two grades are:

TABLE 1 – Nominal chemical composition

	Weight percent				
	C max	Cr	Ni	Mo	N
Sanicro 28, aust. stainless steel	0.020	27	31	3.5	
SAF 2205, duplex stainless steel	0.030	22	5.5	3	0.14

The heats were taken from conventional production. Sanicro 28 was hot extruded and cold rolled to tube size 89x19 mm. SAF 2205 was hot extruded and cold rolled to tube size 75x18 mm. The final reduction was in both cases approximately 55%.

Three-point bend specimens (3PB) with different crack orientations and a modified CT-specimen were cut out of the tube walls according to figure 1.

The three-point bend specimens had the dimensions 5x10x50 mm and the orientations L-R and T-L respectively, see figure 1. The CT-specimens, having the outer wall surface in the original condition and the inner surface machined flat, had the dimensions 19x46x48mm for Sanicro 28 and 18x42x44mm for SAF 2205. Care was taken to maintain the inner surface close to the notch in its original condition. The shape of our modified CT specimen differs from that suggested by ASTM E813, but it is believed that this is of minor importance. However, it was considered essential to test the entire wall section in order to incorporate both surface and bulk properties.

The fracture toughness testing was performed at room temperature according to the ASTM E813 (2) and JSME procedures (3-5). An evaluation according to a proposed modification of ASTM E813 (6) was also performed. The multiple specimen technique was used.

The displacement in the P-Δ curves for the 3PB specimens was determined using an LVDT, which was attached to the support platen and the extension rod.

The displacement for the CT-specimens was measured with a clip gauge attached to the specimen surface in front of the notch. Evaluation of the CT-results was based on the thickest section and the actual load displacement curve. A correction to load-line displacement was made assuming that the rotation centre is located in the middle of the ligament.

The J-values were corrected by subtracting the contribution from the compliance of the testing equipment. This was accomplished by recording the load-displacement curve for a stiff brick-type specimen.

The fatigue crack length, a, and the crack growth, Δa, were both determined from measurements on 9 equi-spaced points as suggested by Clarke et al (7) when evaluation was made according to the ASTM procedure. For the JSME procedure, the crack growth and the stretched zone width (SZW) were measured in the middle of the specimens at points 3/8, 4/8 and 5/8 of the specimen width respectively. All measurements were performed in a stereo microscope equipped with a measuring transducer. A magnification of 70 times was preferentially used. The specimens were heat tinted and fatigued before final fracture.

The effective yield strength defined as the mean value of $R_{p0.2}$ and R_m is given in the table below.

TABLE 2 - Effective yield strength σ_y in the longitudinal and transverse directions

Grade	Longitudinal MPa	Transverse MPa
Sanicro 28	928	758
SAF 2205	1038	960

RESULTS

Examples of the evaluation of the fracture toughness according to different procedures are shown in figures 2-7. In the table below all the results from the fracture toughness measurements are listed.

TABLE - J_{IC}-values for different evaluation procedures

Alloy	Specimen designation	ASTM	JSME	JSME SZW	ASTM Mod.
Sanicro 28	CT	286	210	358	300
	T-L	340*	260*	245*	370*
	L-R	1020*+	440*	470*	1050*+
SAF 2205	CT	-	-	115	-
	T-L	75	175	166	200*
	L-R	650*+	290*	290*	650*+

*) Dimensional requirements are not fulfilled
+) Slope of regression line too high

It should be pointed out that in many cases no valid determination of J_{IC} could be made since the dimensional requirement as formulated in ASTM E813,

$$b,\ B > 25\ J_{IC}/\sigma_y$$

was not fulfilled. These J_{IC}-values are indicated by an asterisk in Table 3. It can be concluded from Table 3 that the J_{IC}-values based on the J-resistance curves are with one exception lower for the JSME-method than for the ASTM-method. Furthermore, when comparing corresponding toughness values we find that the toughness of Sanicro 28 exceeds that of SAF 2205 without exception.

Figures 2-4 show examples of evaluation of Sanicro 28 according to three different methods, namely ASTM and the two JSME methods. All these evaluations are valid according to the standards. However, this was not the case for T-L specimens of Sanicro 28 although these specimens represent the same crack orientation as the CT specimens.

Owing to the high toughness in the radial direction specimens of type L-R did not give valid results for any material. This was also verified fractographically in terms of a larger portion of plane stress in these specimens compared with T-L specimens.

Figures 5-7 give examples of the evaluation of J_{IC} using the SZW as proposed by JSME. All evaluations based on SZW are well defined in the sense that a critical value of SZW, the so called SZW_c, is attained. However, this does not imply that the evaluation is valid in all respects.

The coefficient in the blunting line equation, here denoted by k, is shown in Table 4 for both alloys and all three specimen types. It should be pointed out that this coefficient k is related to the plastic constraint factor m, which is determined in COD experiments (8). However, the present investigation does not allow a direct conversion of k to m.

TABLE 4 - Experimental determination of the coefficient in the blunting line equation

Alloy	Specimen designation	$k = \frac{J}{\sigma_y \; \Delta a}$
Sanicro 28	CT	4.1
	T-L	2.6
	L-R	1.7
SAF 2205	CT	1.6
	T-L	1.2
	L-R	1.6

An evaluation of J_{IC} according to a proposal from Schwalbe and Heerens (6) has also been performed, see Table 3. The evaluation has been made with the aid of the experimental blunting line from the JSME evaluation and a 0.2 mm offset line. The crack length used in this modified method is measured in the same way as in the ASTM procedure. These J_{IC}-values do not differ much from the standard ASTM-values but are systematically somewhat higher.

DISCUSSION

It can be inferred from the results presented in Table 3 that the toughness of this particular heat of Sanicro 28 exceeds that of SAF 2205. However, it should be pointed out that a previous investigation of another heat of the duplex steel SAF 2205 (9) resulted in a toughness which was equal to that of Sanicro 28.

The results in Table 3 show that three-point bend specimens do not in general fulfill the dimensional requirements. This is because austenitic and duplex stainless steels are very tough compared with other more conventional constructional steels. The three-point bend specimens were chosen because, initially, it seemed possible to use them to investigate even thinner tubes having a wall thickness of 7 mm. However, the present investigation shows that the high toughness of these steels often requires larger specimens such as CT-specimens. Moreover, the CT-specimens include material from the entire tube wall, implying that both bulk and surface effects are incorporated. On the other hand, CT-specimens are restricted to just one orientation of the crack plane, while three-point bend specimens offer a possibility to investigate the toughness in various directions.

It is worth noting that the JSME-method tends to give lower toughness values than the ASTM method, which is in agreement with previous observations made by other authors (3,4,10). This is directly related to the different ways of defining crack extension, resulting in systematically longer cracks according to JSME. A practical consequence of this is that the dimensional requirement is easier fulfilled using JSME, although this does not necessarily mean that the JSME-method is more reliable than ASTM.

When using the SZW-method the behaviour at the crack tip is directly observed on the fracture surface. Therefore, it seems natural that the use of SZW gives a more correct physical description of incipient crack growth. This effect is also reflected in the different values of the critical SZW recorded for different crack plane orientations. In a previous investigation of similar stainless steels (9) it was shown that the anisotropy of the J-integral was intimately related to the elongation of the grains in the longitudinal direction of the tubes. Furthermore, the tip of the propagating crack was found to be more blunted when the crack grew in a direction perpendicular to the grain elongation. In the present investigation this same orientation gave rise to a larger value of SZW_c and correspondingly higher values of J_{IC}, which is in agreement with the previous evaluation according to ASTM.

Using the nomenclature in reference (6) SZW is related to J by the equation

$$SZW = d_n \frac{J}{\sigma_0} 0.4$$

where 0.4 is equal to the ratio between SZW and SZH (stretch zone height). The factor d_n is a function of the strain hardening exponent n, and the yield strain σ_0/E ($\sigma_0 = R_{p0.2}$). The calculated value of d_n for Sanicro 28 CT specimens is equal to 0.54 which is in agreement with the value for plane strain conditions predicted by Schwalbe in ref (11). It is also interesting to see that the d_n-value for Sanicro 28 T-L specimens is equal to 0.84 which is in agreement with the value for plane stress conditions in the same reference. However, the model fails to predict the d_n-value for the Sanicro 28 L-R specimens. It must be borne in mind that the model is based on continuum mechanics and can therefore not be expected to give perfect agreement for anisotropic materials. In the case of SAF 2205 the lack of agreement is even more pronounced. This is not surprising as duplex steels can be regarded as composite materials and therefore deviate more from the ideal continuum concept.

It was shown in Table 4 that there were large variations in slope between the blunting lines for different specimen types and alloys. With the use of experimental blunting lines it is judged that differences in materials properties are taken into account in a more proper manner. Therefore, those evaluations, which are based on experimental blunting lines seem more appealing and also give a physical basis for the assessment of J_{IC}.

CONCLUSIONS

1. An investigation of the toughness of cold worked tubes showed a highly anisotropic behaviour. All three methods employed showed that the toughness was highest for longitudinal specimens having a radial crack.

2. The JSME method tended to give lower toughness values than the ASTM method and that proposed by Schwalbe.

3. The stretch zone width (SZW) was found to be dependent upon crack plane orientation and attained a maximum for longitudinal specimens having a radial crack.

ACKNOWLEDGEMENTS

This paper is published by permission of AB Sandvik Steel. The paper is in part based on a dissertation by D.Edman, whose assistance is gratefully acknowledged. The authors also wish to thank G.Svensk and D.Lövgren for their technical assistance.

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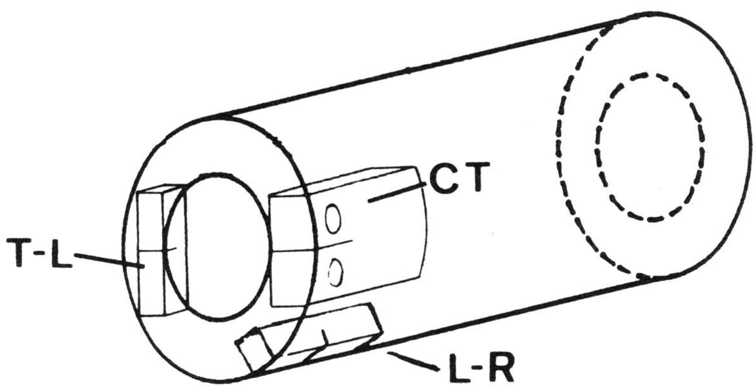

Figure 1 Schematic illustration of specimens used in the present investigation

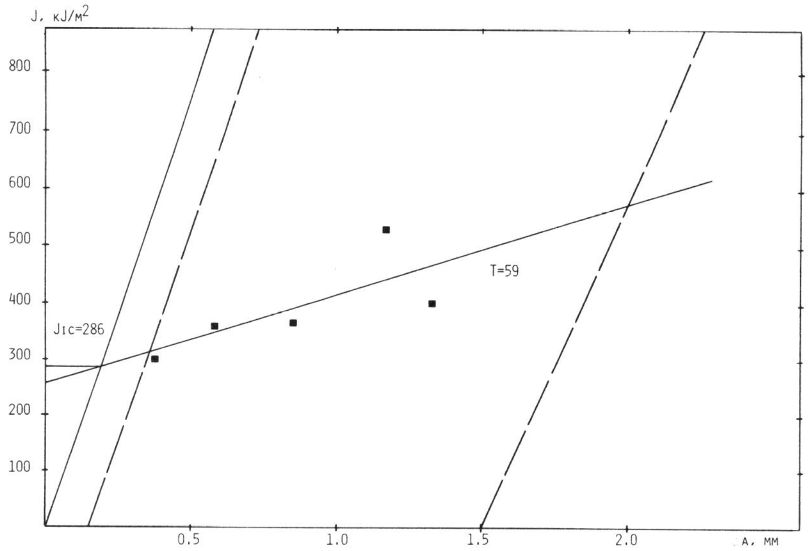

Figure 2 J_{IC}-evaluation of Sanicro 28 according to ASTM for CT-specimens

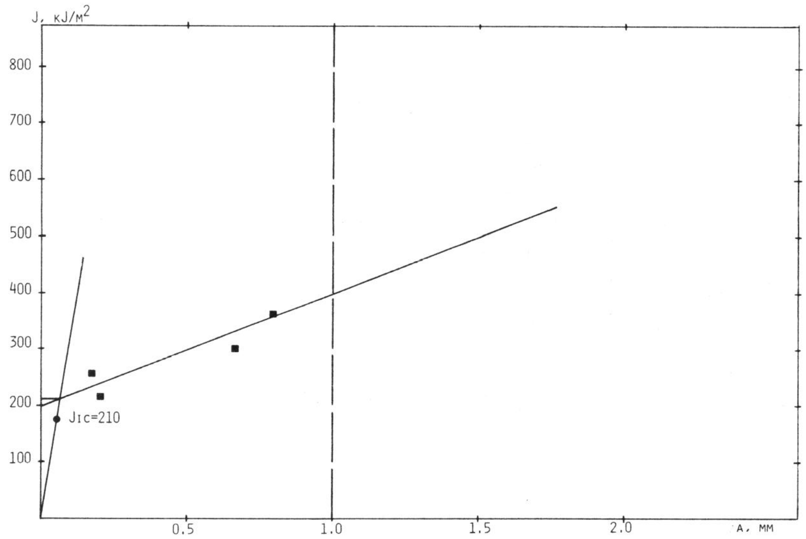

Figure 3 J_{IC}-evaluation of Sanicro 28 according to JSME for CT-specimens

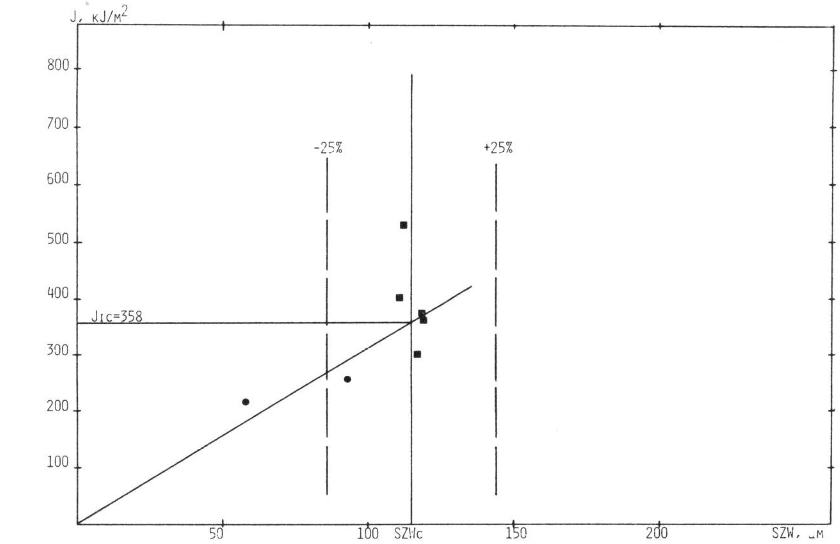

Figure 4 J_{IC}-evaluation of Sanicro 28 using the SZW-method for CT-specimens

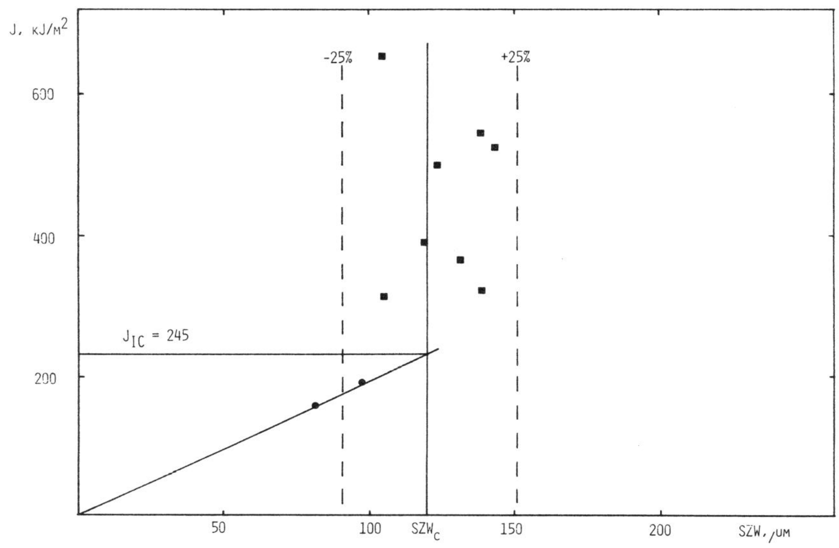

Figure 5 Evaluation of J_{IC} for Sanicro 28 based on the SZW using T-L specimens

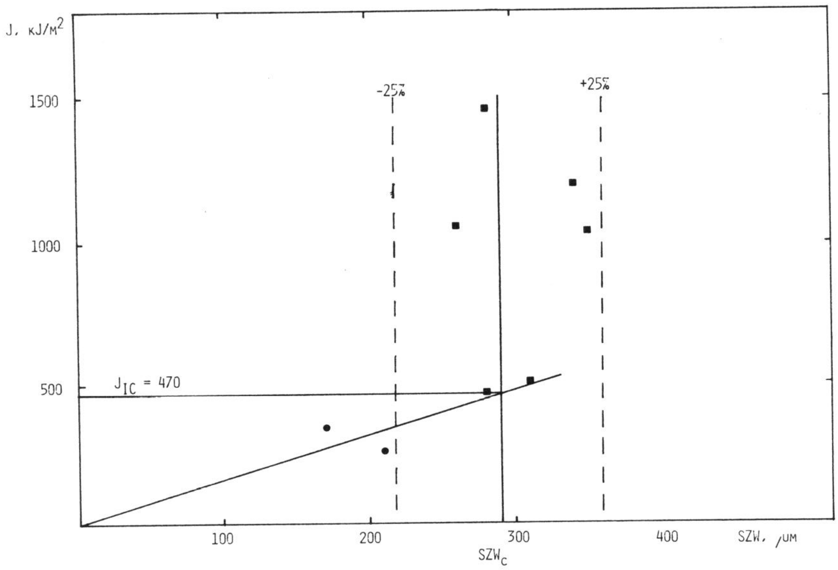

Figure 6 Evaluation of J_{IC} for Sanicro 28 based on the SZW using L-R specimens

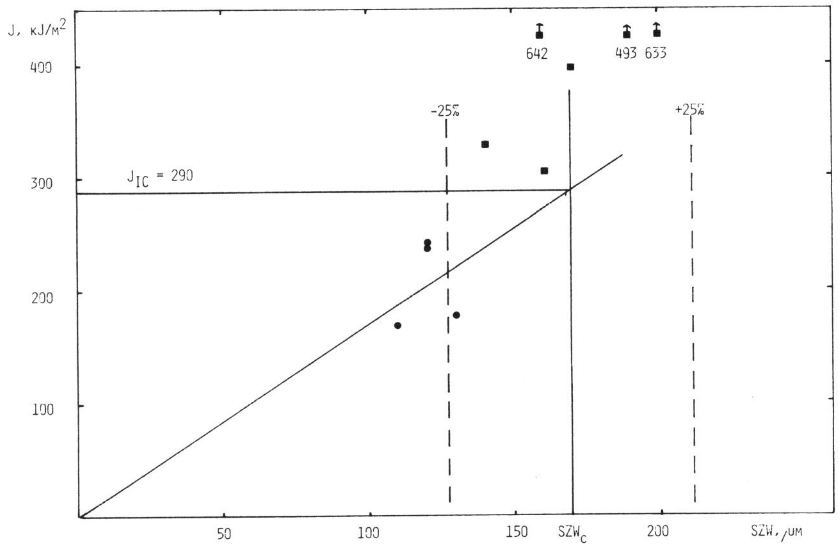

Figure 7 Evaluation of J_{IC} for SAF 2205 based on the SZW using L-R specimens