QUALITY CONTROL FOR NUCLEAR GRADE AUSTENITIC STAINLESS STEELS USING CHARPY IMPACT TESTING

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ABSTRACT

Standard Charpy specimens of an austenitic stainless steel of grade 316 aged at different time-temperature combinations were precracked to different initial crack lengths and then tested in an instrumented impact testing machine; stretch zone sizes were also determined from the broken halves using SEM fractography. From these results several alternative estimates of the fracture toughness could be determined. It was shown that the total energy to fracture per unit fractured area was a J-like parameter, whose variation with the initial ligament length could be formally described using established fracture mechanics relations, even though the applicable size restrictions were not met.

KEYWORDS

AISI 316 SS, Ageing, Instrumented impact testing, Precracked Charpy specimen testing, Sensitization.

INTRODUCTION

The need for a more meaningful parameter than the Charpy V energy, C_V, for characterising the fracture toughness of austenitic stainless steels has been widely felt (Server and others 1977, Witzke and Stephens 1978, Wullaert and Server 1980). To be useful for large scale testing (e.g. for quality control) it is desirable that such a parameter could be generated from rapid tests on small size specimens. In the present work ageing-induced embrittlement in a 316 stainless steel was studied using precracked Charpy specimens; also stretch zone size measurements were carried out on the broken specimens. Information from these could be used to generate different empirical and semi-empirical fracture toughness parameters. These are discussed with respect to the simplicity of the testing and the meaningfulness of the information. It is proposed that the total energy to fracture per unit area of fracture is the most easily determined parameter; it is also shown that under rather drastic assumptions this can be correlated to a "J-like" estimate of fracture toughness.

EXPERIMENTAL

The chemical composition of the 316 SS (Heat LMA) was C 0.06, Ni 11.95, Cr 16.92, Mo 2.2, Mn 1.6, Si 0.54, P 0.036 and S 0.02 (all wt. percent). Solution annealed blanks of this material were aged for the specified time-temperature combinations indicated in Table 1, quenched in water, machined to Charpy specimens (55 mm x 10 mm x 10 mm with standard V notch) and then precracked to required crack lengths following the guidelines of ASTM E399. The cracks were in the LT orientation. Impact tests were carried out at room temperature in a Tinius Olsen Model 74 impact testing machine provided with Dynatup model 500 instrumentation and calibrated with AMMRC specimens and also to the appropriate ASTM and Indian standards. Dial energy values were correct to 0.5J and the accuracy of load and energy (from load-time oscillographic trace) signals calibration was about 3%. Nine point average fatigue crack lengths, a_0, were determined on the broken halves; the maximum difference of the average crack length and the actual crack front (except at the surfaces) was within about 7%. Load time traces were converted into the load displacement plots by first correcting for variation in hammer velocity and then for machine compliance (Fearnehough and Hoy 1964). Fractured surfaces were examined in a Philips Model PSEM 501 Scanning Electron Microscope to characterise the fracture as well as to measure the stretch zone size (Vaidyanathan and others 1984). From the stretch zone values measured at midsection for both the broken halves the crack opening displacement at crack initiation, δ_i, was obtained. These values are shown in Fig.1. The corresponding plastic deflection values, d_i, were calculated using the relation

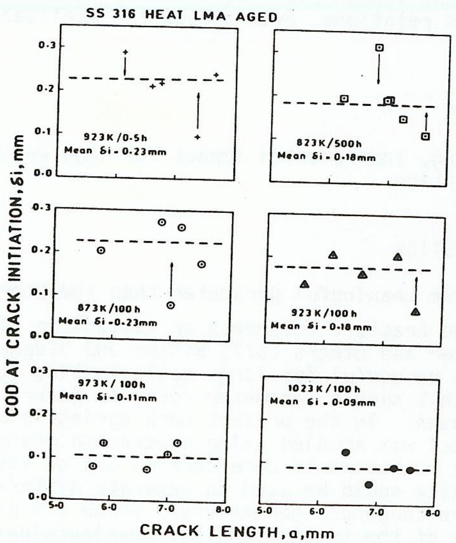

Fig.1 Variation of δ_i with crack length and heat treatment

TABLE 1 Variation of J_i, J_m, J_1 and J_{nl} with Ageing Treatment (Heat LMA: SS 316)*

Heat Treatment	J_i	J_m	J_1	J_{nl}	Δa_i
	(95% confidence intervals)				
E_1 (923K/0.5hrs)	0.299±0.248	0.926±0.110	$J_1 = 0.480+0.307(\Delta a)$	$J_{nl} = 0.817(\Delta a)^{0.5012}$	0.135
C_7 (823K/500hrs)	0.260±0.187	0.837±0.074	$J_1 = 0.384+0.372(\Delta a)$	$J_{nl} = 0.774(\Delta a)^{0.620}$	0.172
D_6 (873K/100hrs)	0.286±0.257	0.820±0.29	$J_1 = 0.397+0.336(\Delta a)$	$J_{nl} = 0.760(\Delta a)^{0.564}$	0.177
E_6 (923K/100hrs)	0.186±0.120	0.697±0.159	$J_1 = 0.259+0.316(\Delta a)$	$J_{nl} = 0.586(\Delta a)^{0.676}$	0.183
F_6 (973K/100hrs)	0.139±0.104	0.591±0.179	$J_1 = 0.246+0.234(\Delta a)$	$J_{nl} = 0.498(\Delta a)^{0.596}$	0.118
G_6 (1023K/100hrs)	0.141±0.077	0.586±0.154	$J_1 = 0.363+0.154(\Delta a)$	$J_{nl} = 0.541(\Delta a)^{0.383}$	

* All J values in $J\text{-}mm^{-2}$, Δa values in mm.

d_i (cm) = 2.5 δ_i / b_0 (Mutoh and others 1980) to obtain the plastic displacement at crack initiation. (b_0 is the initial value of remaining ligament length, $b_0 = W - a_0$ with W = 10 mm as the specimen depth). From this, the energy to crack initiation, E_i, was determined. Also from the maximum load point, P_m, the corresponding energies E_m were determined.

RESULTS AND DISCUSSION

The aim of the present investigation was to search for an index of toughness more "meaningful" than C_V and at the same time obtainable by a simple and rapid test. The parameters obtainable are therefore classified in increasing order of sophistication for the experimentation needed: (a) those obtained without instrumentation of impact testing: dial energy, E_D, as a function of crack length, and average fracture energy $E_f = E_D/Bb_o$, B = 10 mm is the specimen width, (b) those obtainable from the load-time trace: these include (i) E_m (ii) the dynamic yield stress $\sigma_{yd} = 2.85\ P_{GY}/b_o^2$ where P_{GY} is the general yield load (Server 1978), (iii) J_m, the slope of the straight line passing through origin in a plot of $2E_m$ vs Bb_o; J_m is an apparent J integral for crack growth initiation assuming that this occurs at the maximum load and (iv) Witt's equivalent energy parameter K_{Icd} (Witt and Mager 1972) and (c) parameters requiring identification of initiation, δ_i , E_i and J_i, the last quantity being an apparent J integral value for crack initiation and is obtained from the slope of the line passing through the origin in a plot of $2E_i$ vs Bb_o.

In the present investigation the fracture morphology showed more or less transgranular fracture (Vaidyanathan and others 1984). However, so far as crack initiation is concerned, while for 873 K/0.5 hrs and 923 K/0.5 hrs specimens the stretch zone was continuous and crack initiation transgranular, for 973 K/100 hrs and 1023 K/100 hrs specimens the crack initiation involved both trans-and inter-granular failures, the stretch zone tending to become discontinuous. Indeed, qualitatively, the incidence of intergranular fracture seemed to increase in proportion to embrittlement; it was however, difficult to unequivocally determine the effect of crack length on this in a given batch of specimens. Datta and Wood (1981) for quenched and tempered AISI 4340, observed a changeover from microvoid coalescence to intergranular crack initiation (quasi-cleavage being the mechanism of crack propagation in either case) in certain cases depending upon heat treatment, strain rate and temperature of testing, and notch root radius. For the present results, an explanation similar to that offered by these authors is possible; depending upon impurity segregation, particle/matrix interaction, stress system and stress magnification requirements, strain energy density might have reached a sufficiently high level locally for double slip band to be operative promoting intergranular initiation. In any event, in addition to the fact that the measurement of δ_i in these specimens was difficult, the measured value and the J_i obtained therefrom can only be considered as pointers.

For some of the highest crack length specimens tested, average time period of oscillation, τ , was greater than $t_{GY}/3$ where t_{GY} is the time to general yield. However in these cases $2.3\ \tau < t_{GY} < 3\tau$ and 0.915 dB response time $t_R = 1.4\ \tau$ so that a smoothing could be taken recourse to determine P_{GY} and C_M (Wullaert and Server 1980). Accuracy of correction for machine compliance, C_M, depends upon the accuracies in determination of t_{GY} and P_{GY}. Therefore, purely from this aspect the E_m values are better determined than the energy values prior to this. J_i and J_m values were determined by taking the mean values of $2E_i/Bb_o$ and $2E_m/Bb_o$ respectively. For J_i values the results from specimens with δ_i values away from the average (indicated by arrows in Fig.1) were also included. These parameters are indicated in Table 1. A part of the observed scatter of J_m is no doubt owing to the inaccuracy in the determination of C_M. However, this could also be due to the fact that J_m is not a proper fracture toughness parameter. This is borne out by the facts that estimates of J_i are always smaller than J_m, and that J_m decreases as a_0 increases (Fig.2). Witzke and Stephens (1978) have obtained a good correlation by using the relation

$$K_{IC}^2 \ \propto \ [E/(1-\nu^2)]\ (J_m/2) \qquad (1)$$

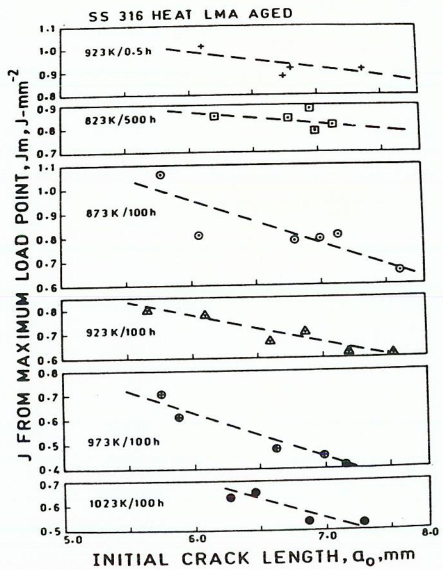

Fig.2 Variation of J_m with crack length and heat treatment

with an empirically determined proportionality factor 1.2. The correlation was obtained for a wide range of materials with K_{IC} as high as about 200 MPa-m$^{1/2}$ ($J_m \simeq 0.3$ J-mm^{-2}). As the present J_m values are larger by a factor of about 2 to 3 it is not obvious that this correlation should extend to the present instance. Increasing crack length shifts the crack initiation point towards the maximum load; therefore an empirical parameter J_{m}, for a_o = 10 mm could be obtained by extrapolating the J_m vs a_o relation to

a_o = 10 mm. Its theoretical significance however is not obvious.

The simplest parameter determined is of course the average energy to fracture, $\bar{E}_f$. Since dial energy values are correct to 0.5J and b_o values to 0.01 mm, $\bar{E}_f$ was determined in the present experiments to about 4% accuracy or better. Meaningful correlations, if obtained, with E_D will provide the simplest and best solution to the problem. For this purpose we define J_f

$$J_f = 2\bar{E}_f = 2E_D / Bb_o \qquad (2)$$

As expected from J_m results, J_f also was found to vary with b_o apparently in a linear fashion and obviously $J_f > J_i$. It is clear that energy absorbed per unit of fractured area is not constant and requires correction for both B and b_o terms, that is W and a_o. One possible correction is by using the relation

$$K_{IC}^2 = (J_f / 4) \quad \left[E / (1-\nu^2)\right] \qquad (3)$$

(Roland and others 1972, Sovak 1982) which is similar to equation (1). However there is another empirical approach possible. It should be remembered that while the following equations are written in terms of J, size and specimen geometry independence are not implied. It is enough for our purpose if the following conditions are valid (Ernst and others 1981): (1)PW/Bb^2 is a function of (x/W) alone, where x = load line displacement; (2) J = 2U/Bb for nongrowing crack, where U is the work done; (3) a deformation theory basis of J is valid; independent of history, J = J (x,a) for fixed W. Next we make the assumption that for all practical purposes, crack growth to final separation obeys the relation

$$J_1 = J_{o1} + C_1 (a - a_o) \qquad (4)$$

Clearly the above conditions, if J_1 were a true fracture toughness parameter, are resonable for a material which has undergone stable crack extension till nearly complete separation. Using equation (64) of Ernst and others (1981),

$$dJ \simeq - (J/b) \ da + 2dU/Bb \qquad (5)$$

Using (3) and (4), we obtain

$$E_D/Bb_o = \bar{E}_f = J_{o1} + \tfrac{1}{2}C_1 b_o \qquad (6)$$

The coefficients J_{o1} and C_1 determined by linear least square fit are indicated in Table 1. Equation (6) shows that $\bar{E}_f$ should vary linearly with b_o, as has been observed empirically (Fig.3).

Since the operational definition of J_i used here is consistent with the definition of J used above, we should expect that $J_{o1} \simeq J_i$. It is however found that $J_{o1} > J_i$. Carlson and Williams (1981) have proposed that in view of the pronounced nonlinearity near crack initiation in valid J-R curve testing,

$$J_{nl} = C_{nl} (a - a_o)^n \qquad (7)$$

is a better description of their data, C_{nl} and n being constants. Here suffix nl refers to the nonlinear approximation made. Using equation (7) in place of equation (4), along with equation (5), we obtain

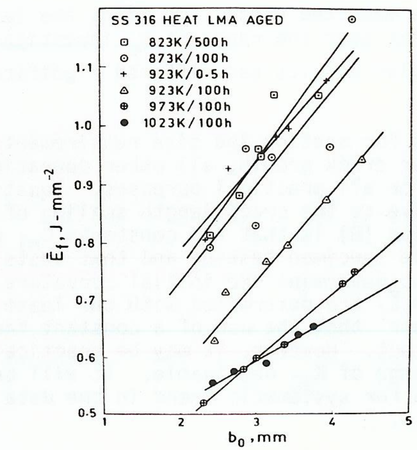

Fig.3 Variation of $\bar{E}_f$ with b_o and heat treatment

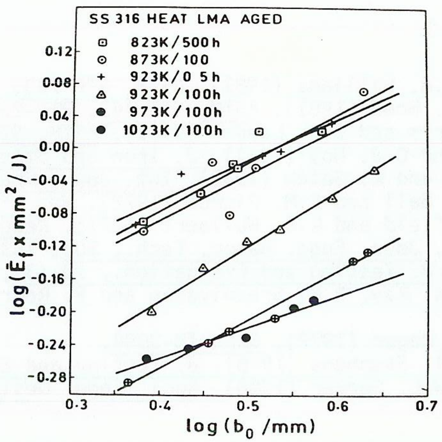

Fig.4 Variation of log $\bar{E}_f$ with log b_o and heat treatment

$$\bar{E}_f = E_D/Bb_o = \frac{C_{nl}}{1+n} \cdot b_o^{\ n} \qquad (8)$$

This equation shows that a log-log plot of $\bar{E}_f$ vs b_o, should be linear; Fig.4 shows that this is a reasonable correlation. The constants were determined by linear least square fit of log $\bar{E}_f$ vs log b_o. Also now if we estimate Δa_i

such that $C_{nl}\ (\Delta a_i)^n = J_i$, the values of Δa_i are quite small (Table 1) and more or less in the expected range. By using the least square fit constants, it was found that over the range of b_o investigated the linear and nonlinear fit gave similar results and differed significantly at low Δa values only.

Quite obviously, except for meeting the size requirements for J-controlled crack tip singularity or crack growth, all other operational features of J parameter are obeyed, for all practical purposes. Equation (8) can be considered as an alternative to the crack length scaling of Sovak (1982). The disadvantages of equation (8) is that the constants C_{nl} and n are to be determined from multiple specimen testing and that tests should be conducted at very low b_o values to determine the initial curvature accurately, but this is also the range where E_f are determined with the least accuracy. From the above results it is clear that the use of a constant factor in equation (3) is fundamentally incorrect. However, it may be practically acceptable in view of the accuracy range of K_{IC} obtainable. It will be curious to examine if the present explanation for systematic trend in the data is fortuitous or has a more fundamental basis.

CONCLUSION

Uninstrumented Charpy impact test of precracked specimens can yield a J like quantity J_f, whose variation with b_o is formally describable on the basis of fracture mechanics relations.

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