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DYNAMIC J_R CURVES FROM INSTRUMENTED IMPACT TEST OF UNPRECRACKED CHARPY V-NOTCH SPECIMENS OF AUSTENITIC STAINLESS STEEL

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ABSTRACT. A new (shift) procedure has been suggested for obtaining the J_R (J fracture resistance) curves of ductile alloys from the load-displacement traces of (unprecracked) CVN specimens (with CVN energy > 30 J) and demonstrated using instrumented impact test results from Charpy V-notch (CVN) and precracked CVN (PCVN) specimens of AISI 316 stainless steel. This involves generating the **pseudo-J_R curve** from CVN specimens using a key-curve method and also by the procedure due to Schindler (**Schindler curve**). Then the **pseudo-J_R curve** is shifted uniformly downward to bring it into coincidence with or slightly above the **Schindler curve**. This shift can be expressed as $J_{\text{pseudo}} + Q.p$, where p is the exponent in the power-law fitted to the **pseudo-J_R curve** and Q takes values of – 2 to – 4. The **shift-J_R curves** more truly reproduce the slopes of the PCVN-J_R curves (hence tearing resistance) than the **Schindler curves**, though the latter are easy to generate. However, the range of applicability, size restrictions applicable and other aspects (like influence of loading rate, use of blunting line) need further validation using tests on different materials. When validated, the new method will obviate the need for expensive and time-consuming precracking, at least for select materials and test conditions. These methods will be useful not only for quality control purposes, but even for conservative engineering design.

KEYWORDS. Stainless steel, Charpy V-notch, dynamic J_R curve, key-curve, pseudo-J_R curve, Schindler procedure

1. INTRODUCTION

Austenitic stainless steels (SSs) are widely used structural materials in fast reactors. Owing to the high toughness of austenitic SSs, measurement of their fracture toughness requires the use of elastic-plastic methods [1,2]. Though, for very accurate evaluation of toughness, precracked and large size specimens are necessary, there is continuing interest and effort in obtaining conservative estimates of J_{id} (dynamic fracture (initiation) toughness) or J_R (J fracture resistance) curves using small and blunt notched specimens, particularly Charpy V-notch (CVN) specimens [2-4]. These methods, when validated, will be useful not only for quality control purposes, but even for conservative engineering design.

In this paper, instrumented impact test results obtained at room temperature from CVN and precracked CVN (PCVN) specimens of AISI 316 SS in various aging and cold-work (CW) conditions are reported. J_R curves obtained for CVN and PCVN specimens by key-curve procedure [2] are compared with each other and with those obtained using the procedure proposed by Schindler [4]. A new (shift) procedure is suggested for obtaining J_R curves from unprecracked CVN specimens. This seems to be promising, but its range of validity and applicability needs further validation and verification by tests on materials with different toughness levels.

2. MATERIAL AND EXPERIMENTAL DETAILS

Material tested was AISI 316 SS in the solution-treated (ST), ST + 1073 K/50 h aged (H5), ST + 1073 K/1008 h aged (H8), ST + 20% cold-work (CW) and CW + double age (GT) conditions (see [3] for full details). Initial crack aspect ratio (a/W, where a is the crack length and W is the specimen width) varied from 0.2 (CVN) to 0.8. The CVN and PCVN specimens were tested at room temperature on a 358 J capacity Tinius Olsen Model 74 instrumented impact machine. Full details of the material, precracking, test and data reduction procedure are reported elsewhere [2,3]. All tests reported here were done at the maximum impact machine velocity, $V_0 = 5.12\ m.s^{-1}$.

3. J_R CURVE REDUCTION PROCEDURES

3.1. Key-curve and Shift Methods

The J_R curves are obtained from the test records of both CVN and PCVN specimens using the power-law key-curve procedure described by Sreenivasan et al. [2] . The J_R curve obtained from CVN specimen is much higher than the PCVN-J_R curve (which is mostly conservative and most likely to approximate the true material property). Hence, in this, the J_R curves obtained using (unprecracked) CVN specimens are referred to as **pseudo-J_R curves**. However, the key-curve J_R curves from CVN and PCVN specimens seemed to show similar slopes [2]. This suggests the possibility that the PCVN-J_R curves can be obtained by applying a suitable scaling or translation to the **pseudo-J_R** curves (**shift method**). This aspect is explored in this paper.

Assuming a power-law relation, J_R is given by the following relation:

$$J = C\ (\Delta a)^p \tag{1}$$

where C and p are fit constants (C and p from CVN specimens are indicated as pseudo). For constant slope, dJ/da must be constant. Therefore,

$$\mathrm{d}J/\mathrm{d}a = C\ .\ p.\ (\Delta a)^{p-1} = \text{Constant} \tag{2}$$

This can be true only if the new J_R curve is represented by:

$$J = C\ (\Delta a)^p + K\ (= Q.p) \tag{3}$$

where numerical constants K and Q are determined empirically by comparing the **pseudo-J_R curves** with the PCVN-J_R curves. Because of plasticity and notch-root effects, **pseudo-J_R curves** are much higher than the PCVN-J_R curves. Hence, for obtaining the PCVN-J_R curve from the **pseudo-J_R curve**, a negative shift must be applied to the **pseudo-J_R curve** and Q is negative (see, however, Section 4.3).

3.2. Schindler's Procedure for Obtaining J_R Curves

In recent analyses, Schindler uses only the power-law (Eqn. 1) for estimating the J_R curve as is done in the present paper. Schindler and coworkers [4] obtain constants C and p of the power-law (Eqn.1) from the following relations:

$$C = (2/p)^p\ .\ [\eta(a_0)/\{B.(b_0)^{1+p}\}].\ E_t^p.\ E_{mp}^{\ 1-p} \tag{4}$$

$$p = (3/4).\ [1 + E_{mp}/E_t]^{-1} \tag{5}$$

E_{mp} is the plastic energy upto $P_{\max}$ (maximum load), E_t is the total energy for the impact test and $\eta(a_0)$ is the well known eta-factor. We have used $\eta(a_0)$ given in [2].

4. RESULTS AND DISCUSSION

4.1. Key-curve J_R Curves and Application of the Shift Procedure

The power-law constants for the key-curve J_R curves are given in Table 1. Only the constants for the mean curves from the multiple specimens are given (separate fits for CVN and PCVN results in each heat-treatment condition). In most cases, the specimen to specimen scatter is small enough to justify this procedure. In making the fit, for each specimen, the maximum Δa was chosen to be equal to be 10% of b_0, the initial remaining ligament depth (= $W - a_0$, where a_0 is the initial a). The ASTM size criteria have not been evaluated since only the results from same size specimens are being compared. In cases where there is more than normal scatter, the curve from the specimen giving the lowest data is also shown in the figures. The J_{id} corresponding to the crack-initiation point (by the procedure in [2]) and $J_{0.2}$ (corresponding to a crack-extension of 0.2 mm) estimated from the mean key-curve power-law are given in Table 1 for comparison with the estimates by the Schindler procedure.

Figure 1 shows the key-curve results for the CW condition. The results from the PCVN specimens are close together and is well represented by the common fit curve shown (PCVN-J_R curve). The **pseudo-J_R curve** is much higher than the PCVN-J_R curve and to bring the **pseudo-J_R curve** into coincidence with the PCVN-J_R curve, the **pseudo-J_R curve** was shifted down using $Q = -4$ (Eqn. 3). The Q-factor used is shown in Figure 1 by the side of the arrow indicating the shift. The J_R curve obtained by this procedure is referred to as the **shift-J_R curve**.

4.2. J_R Curves by the Schindler Procedure

The constants of the power-law fit obtained by the Schindler procedure as also the estimated $J_{0.2}$ are given in Table 1. Application of the Schindler procedure to CVN specimens gives J_R curves that are higher than those obtained by applying the Schindler procedure to PCVN specimens (Sch,PCVN in Figure 1). In the following, **Schindler curve** refers to the J_R curve obtained by applying the Schindler procedure to (unprecracked) CVN specimen; this is almost in coincidence with or slightly lower than the key-curve PCVN-J_R curve. **Schindler curve** is poor in reproducing the slope of the PCVN-J_R curve. The **shift-J_R curve** better reproduces the slope of the PCVN-J_R curve.

4.3. General Discussion

Results for ST, H5 and GT material conditions are similar to those in Figure 1, but with different Q values as shown in Table 1. Figure 2 for the H8 material shows anomalous behaviour. This material has been aged for 1000 h at 1073 K and is expected to have extensive precipitation along grain boundaries. This results in intergranular ductile fracture with a very low impact energy (~ 28 J: see Table 1) [5]. In such cases, blunt-notched CVN specimen reportedly shows lower toughness than the PCVN specimen [6]. Hence the anomalous behaviour in Figure 2: CVN J_R curve is lower than the PCVN-J_R curve. Also, the Schindler curves from CVN specimens are lower than those from the Schindler curves from PCVN specimens. Moreover, the key-curve J_R curves from PCVN specimens show excessive scatter and odd behaviour. In this case, the **pseudo-J_R curve**, without any shift ($Q = 0$), is ultra-conservative (lower) with respect to the PCVN-J_R curves. Schindler has also stated that his procedure is applicable for CVN energies greater than 30 J [4].

From the above, it is evident that, when homogeneous deformation prevails and abnormalities like grain boundary fracture or other preferential fracture paths are not active, using a Q factor -2 to -4 for generating the **shift-J_R curve** from the **pseudo-J_R curve** gives conservative results. In the absence of the above mentioned abnormal deformation and fracture behaviour, the **shift-J_R curve** is in coincidence with or slightly higher than the **Schindler curve**. When the above mentioned abnormal fracture behaviour operates, the **pseudo-J_R curve**, without any shift, is ultra-conservative.

The observation of the near coincidence between the **shift-** and the **Schindler-J_R curves**, offers a reliable method to choose an appropriate Q value for a material. From the CVN specimen, generate the **pseudo-J_R curve** and also the **Schindler curve**. Then, by appropriate shift, bring the **pseudo-J_R curve** into coincidence with or slightly higher than the **Schindler curve**. From this, the Q value can be obtained. Though, **Schindler curves** are easy to generate and satisfactory for quality control and ranking purposes, the shift procedure proposed here helps obtain J_R curves which reproduce reliably the slope of the PCVN-J_R curves.

5. CONCLUDING REMARKS

A new method has been suggested for obtaining the J_R curves of ductile alloys from the load-displacement traces of (unprecracked) CVN specimens, with CVN energy > 30 J. This involves generating the **pseudo-J_R curve** from CVN specimens using a key-curve method and also the **Schindler-J_R curve** (J_R curve by the application of Schindler procedure). Then the **pseudo-J_R curve** is shifted uniformly downward to bring it into coincidence with or slightly above the **Schindler curve**. This shift can be expressed as $J_{\text{pseudo}} + Q.p$, where p is the exponent in the power-law fitted to the **pseudo-J_R curve** and Q takes values of -2 to -4. The shift procedure generates J_R curves that more truly reproduces the slopes of the PCVN-J_R curves (hence tearing resistance) than the **Schindler curves**, though the latter are easy to generate. However, the range of applicability, size restrictions applicable and other aspects (i. e., influence of loading rate, use of blunting line) need further validation using tests on different materials and conditions. When validated, the new method will obviate the need for expensive and time-consuming precracking, at least for select materials and conditions.

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TABLE 1

POWER-LAW CONSTANTS AND *Q* VALUES FOR CVN/PCVN SPECIMENS OF 316 SS BY KEY-CURVE AND SCHINDLER PROCEDURES

Sp. Code	*Sp. Type*	E_t/J	*p (Sch)*	*C (Sch)*	$J_{0.2}/(J.mm^{-2})$ *(Sch)*	P/Key-curve	C/Key-curve	$J_{id}/(J.mm^{-2})$ *Test*	$J_{0.2}(J.mm^{-2})$ *Test*	*Q*
GT	CVN	82	0.546	0.591	0.339	0.22	0.940	0.316	0.66	-1.5/ -2
"	PCVN	-	-	-	-	0.338	0.731	-	0.424	-
CW	CVN	102	0.529	0.787	0.378	0.146	1.207	0.605	0.955	-4
"	PCVN	-	-	-	-	0.303	0.634	-	0.389	-
H5	CVN	107.5	0.537	0.804	0.360	0.245	1.268	0.331	0.846	-2
"	PCVN	-	-	-	-	0.267	0.834	-	0.543	-
H8	CVN	28.5	0.569	0.188	0.290	0.185	0.272	0.12	0.202	0
"	PCVN	-	-	-	-	0.387	0.801	-	0.430	-
ST	CVN	159	0.514	1.300	0.413	0.266	1.997	0.532	1.301	-3
"	PCVN	-	-	-	-	0.182	1.076	-	0.803	-

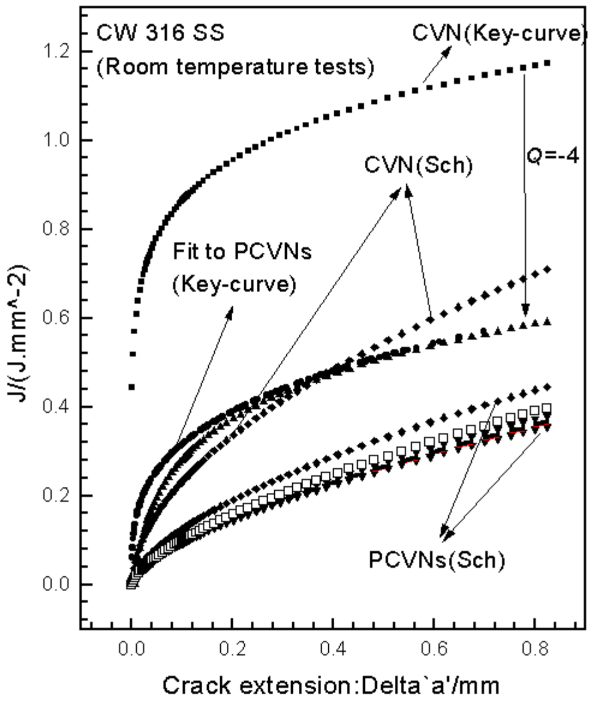

Figure 1. Shift and Schindler *J-R curves for CW 316 SS*

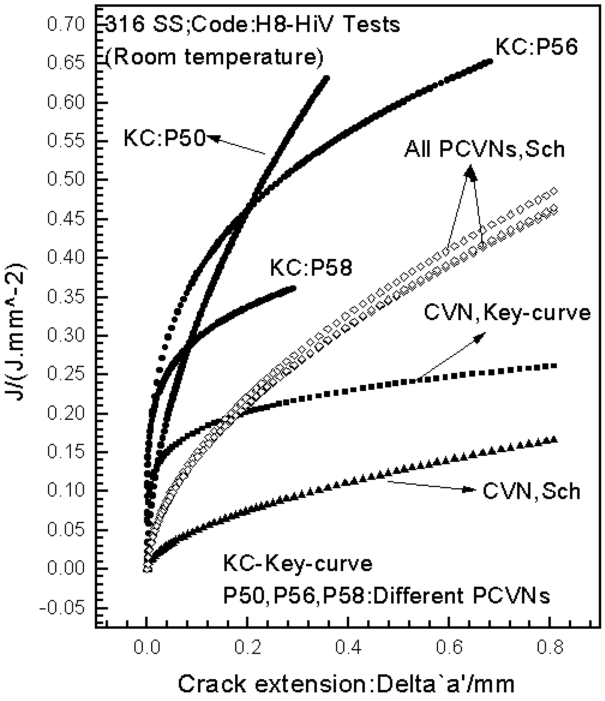

Figure 2. Shift and Schindler J-R curves for H8 316 SS