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EFFECTS OF STRAIN GRADIENTS ON
THE GROSS STRAIN CRACK TOLERANCE
OF A 533-B STEEL*

P. N. Randall

TRW Systems, Redondo Beach, California 90278
(Subcontract 3134)

J. G. Merkle

Oak Ridge National Laboratory,
Oak Ridge, Tennessee 37830

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ABSTRACT

To satisfy the need for a measure of fracture toughness at stress levels above yield, a quantity called gross strain crack tolerance has been proposed. It is the total elastic-plus-plastic strain measured at maximum load in a laboratory test of a specimen containing a surface crack, and is of course a function of crack size and temperature. The object has been to develop the test to produce results that can be used to estimate the tolerance of material in full-scale hardware for strain in the presence of a crack. Previous work utilized precracked tensile specimens of A 533-B steel to study the effects of specimen geometry and crack size as a function of temperature. Now, the effects of strain gradients have been studied by loading the specimen in bending or by placing the crack in the bottom of a groove. Analysis of the displacement measurements showed that proper characterization of all the strain gradients tested required consideration of the strain values at two locations. The first, defined as the gross strain crack tolerance (GSCT), was located in the net section normal to the crack plane at mid-crack depth, the approximate location along the crack border where fracture originated. The second strain value was the gross strain on the back face in the gross section above and below the crack.

At temperatures within the transition region, GSCT increased in direct proportion to the degree of tensile strain on the back face of the gross section. Tests in bending, which put the neutral axis between the crack tip and the back face, produced the lowest value of GSCT, while those in which the crack propagated into regions of increasing strain yielded the highest GSCT. These effects were attributed to the influence of back face strain on the development of the plastic zone and consequent relief of constraint.

KEY WORDS: fracture toughness, plastic strain, mechanical properties,
steel, transition temperature, surface cracks

ILLUSTRATIONS

1. Beam cross sections used to produce transverse strain gradients
2. Configuration of the double-groove tension specimen for Series 5 and the single-groove specimen for Series 6, tension, and Series 7, bending.
3. Typical views of extensometer system.
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5. Critical strain and COD values as a function of temperature for:
Series 1, $\epsilon_{\text{back face}}/\epsilon_{\text{cracked face}} = -1.0$, and
Series 2, $\epsilon_{\text{back face}}/\epsilon_{\text{cracked face}} = 0$,
compared to Tension Series (dashed lines).
6. Critical strain and COD values as a function of temperature for:
Series 3, $\epsilon_{\text{back face}}/\epsilon_{\text{cracked face}} = +0.50$, and
Series 4, $\epsilon_{\text{back face}}/\epsilon_{\text{cracked face}} = +2.00$,
compared to Tension Series (dashed lines).
7. Summary plot of COD values as a function of temperature for all Series.
8. Summary plot of values of gross strain in the net section at mid-crack depth as a function of temperature for all Series.
9. Interaction diagram relating the effect of gross strain at the back face above and below the crack on gross strain crack tolerance for all Series. Test temperature for each data point is shown beside the symbol.

INTRODUCTION

Most structural designs intend that general yielding should always precede fracture even in the presence of the largest expected flaw. To evaluate the margin of safety against fracture, therefore, the designer needs test data for his material in terms of its tolerance for strain in the presence of a flaw as a function of flaw size and temperature. This paper gives the third year's results of our effort to develop a test for gross strain crack tolerance. It is part of the HSST* program to advance the technology of fracture prevention in large pressure vessels. Results of that program are given in HSST program reports.

The reasons for studying the effects of strain gradients on gross strain crack tolerance are twofold. Previous test data (1, 2) have been obtained in axial tension, but the typical service application is a region of strain concentration, with gross strain gradients in the direction of crack advance and also along the normal to the crack plane. The thick-walled pressure vessel also has a strain gradient through the membrane wall. Thus, an understanding of strain-gradient effects is needed to guide the application of test data to design.

The second reason for this study is to broaden our understanding of the gross strain concept. Most would agree that crack propagation is caused by the local, crack-tip conditions of stress and strain, but no one knows how to measure them. Hence, the gross strain measurements made in the program were considered to be related to local conditions in two ways: as the driving force that governs the magnitude of local strain,

* Heavy Section Steel Technology program, F. J. Witt, Director, Oak Ridge National Laboratory of the U.S. Atomic Energy Commission.

and as the measure of relief of constraint through the extension of plastic zones to free surfaces.

The test plan was confined to one size of surface crack (0.22-in. deep), the middle size of the three tested last year. After rechecking the test results for loading in uniform tension, four Series of bend tests were run, plus three Series where the crack was placed in the bottom of a groove in the face of a tension or bend specimen. Strains measured at various locations on the specimens were analyzed to find those that gave the most consistent explanations of results for all specimen geometries.

PROCEDURE

Material

All test specimens were taken from Plate 02, one of the 12-in. thick plates that was especially rolled from A 533-B steel for the HSST program. Only mid-thickness material 3.5 in. or more from either plate surface was used, to avoid surface effects such as those from varying cooling rate. Orientation of the specimens was such that the material was stressed in the rolling direction and the direction of crack advance was through the plate thickness. Room-temperature value of yield and ultimate strength were 72 and 92 ksi, respectively. Detailed information is found in Ref. 1 - 3.

Specimen and Loading Configurations

Transverse strain gradients were studied with beam specimens loaded in four-point bending. The specimen proper was 0.60 in. thick by 2.64 in. wide by 22 in. long, with a semi-elliptical surface crack 0.68 in. long by 0.22 in. deep at midspan on one face of the specimen. Cracks were grown in bending fatigue, with a stress cycle of +4 to +39 ksi, once the crack appeared at the end of the ground slot used for a crack starter.

Three degrees of severity of transverse strain gradient were tested, as shown in Figure 1, Series 1, 2 and 3. Beam depth was varied by welding on a backup bar of the same material, in the manner illustrated in Figure 1 so the specimen proper would function as a cover plate for the built-up beam. The welds did not extend into the gage length, because there is no shear to transmit between the specimen and backup bar in the midspan region between the loading points.

In the first three test Series, strain decreased in the direction of crack advance. In Series 4, strain was made to increase in the direction of crack advance by welding the backup bar to the cracked face as shown in Figure 1. This configuration simulates a crack in the inner surface of a heavy-walled vessel.

Axial strain gradients combined with transverse gradients were studied by means of specimens in which the crack was placed in the bottom of a groove. For Series 5, we used a double-grooved tensile specimen, 0.75 in. thick by 2.64 in. wide, bearing round-bottomed grooves on both faces as shown in Figure 2. The net section was 0.60 in. thick, the same as for Series 1-4. Mild notch effects (K_t was 1.47) were desired in this Series to permit interpretation of the results as being primarily caused by the axial gradient resulting from the fact that gross stress in the region beyond the groove was only 80 percent of the average stress at the groove. For Series 6, we used a single-grooved tensile specimen, also shown in Figure 2, for which K_t was 1.68. Transverse strain gradients were greater in this case. Finally, for Series 7 we used the same configuration as for Series 6, but loaded it in bending (K_t was 1.44 approximately).

The cracks grown in the grooves were somewhat shallow relative

to their length. Since we chose to keep crack depth constant throughout, the specimens were re-fatigued to a crack length of 0.80 in. for Series 5 and 0.90 in. for Series 6 and 7.

Displacement Measurements

Techniques used earlier⁽²⁾ for the tension Series were continued in this work with some modification of the extensometers and the method of attachment to the specimen necessitated by the curvature developed in bending. Table 1 defines the strain values that are to be discussed by describing the displacement measurements on which they are based. The extensometer system is described therein by reference to Figure 3. Post-test micrometer readings of width and thickness reduction were also used. The resulting reduction-of-area value was converted to a value of total longitudinal strain by the expression $\epsilon = 0.25 + \text{R.A.}/(1 - \text{R.A.})$, where the elastic portion was taken to be that at yield, nominally 0.25 percent.

For Series 1 - 3, five records were obtained from the seven extensometers. Load was recorded as the abscissa on three X-Y or X-YY plotters. Displacements ϵ_{gn} , cracked face and ϵ_{gn} back face are recorded on one plotter, and ϵ_{gg} values (average of left and right) on another. A third single pen plotter recorded COD versus load. For Series 4 through 7, there were only four records.

The critical values of the strains derived from these measurements were those at maximum load. In most tests, fracture occurred on rising load, which makes this definition of critical strain very clear-cut. At the highest test temperature in each Series, however, the strain tolerance was such that load passed through a maximum for other causes. In tension, the cause was tensile instability wherein the important material property was the strain hardening coefficient and the significant

geometric change was the reduction of area. In bending, Series 1 - 4, however, when the deflection was large the reaction of the outer roller supports rotated inward from the vertical. This change in the geometry of loading eventually produced a maximum in the load. Its occurrence was so dependent on beam depth and span that maximum load was not significant in the bend tests unless caused by fracture.

Reduction of the displacement data for Series 1 - 4 to obtain ϵ_{gnc} required some analysis, because a ductile specimen produced a large amount of relative rotation of the gage blocks. Derivations of the expressions used to obtain surface strains ϵ_{gnc} from the recorded displacements are given in Ref. 3.

EXPERIMENTAL RESULTS

Uniform Tension

The base line for comparison of strain gradient effects was the tension data for the 0.22 in. deep crack, reported previously,⁽²⁾ supplemented by some additional tests. The results, plotted in Figure 4, show a consistent pattern of transition behavior for the displacement values ϵ_{gnc} , ϵ_{ggc} and COD with the foot of the transition at -20°F . The curve labeled " ϵ_{gnc} from R.A." (gross strain in the net section obtained from reduction of area measurements taken 0.2 in. back from the fracture) was included to indicate the degree of heterogeneity of strain within the 3.2 in. gage length spanning the net section. In later comparisons of the results for all eight Series, more consistent results were obtained by using " ϵ_{gnc} from R.A.". As a point of interest, the reduction of width was nearly equal to the reduction of thickness.

Strain Gradient Effects

For Series 1 (neutral axis at midthickness) and Series 2 (neutral axis at back face), the logarithm of critical strain and COD values is plotted as a function of test temperature in Figure 5, with the tension data added for reference. Width of the crosshatched band between the plots for strain in the net section at the cracked face and at the crack-tip depth is a measure of the extent of the strain gradient. Note how gradually the strain tolerance develops with rising temperature, compared to the tension test results. Another significant difference is the proximity of ϵ_{ggc} to ϵ_{gnc} in the bend Series; i.e., there was little net section effect, compared to that seen in tension. The visual appearance of the bend specimens confirmed this in that the curvature seemed to be uniform throughout the central six inches between loading points without a visible kink at the cracked section.

Series 3 and 4, plotted in Figure 6, were also bend specimens having the neutral axis 0.6 in. above the back face of the specimen proper, the difference being that the crack advanced into an increasing strain field in Series 4. Development of the transition in Series 3 was far less abrupt than in Series 4. It would seem logical for the tension data to fall in between that for Series 3 and 4, but it did not. The slope was right but there was a 40-degree upward shift in the foot of the transition. Our explanation for this rests on the difference in the manner of loading. Unlike the tension specimen, Series 3 and 4 specimens were forced to deform equally in the gross and net sections. This can be seen in Figure 6, which also reveals that strains in the gross section on the cracked face in Series 3 and on the other face in Series 4 were in the plastic range even at the lowest temperatures. Relief of constraint

caused by such gross-section yielding is known from experience to promote GSCT.

Series 5 (double groove) and Series 6 (single groove) were both tested in tension to see what strain tolerance the material could develop when the crack lay in the localized strain field of a groove. Comparison of results with those for the basic tension Series reveals that the groove had little effect on the plots of ϵ_{gnc} , obtained from reduction of area measurements. This is surprising, because axial strain gradients should have been enhanced by the groove, and the measurements of ϵ_{ggc} plotted in the figure confirm this fact. We therefore are forced to assume that the groove does not focus strain at the crack-tip region; i.e., that a given value of ϵ_{gn} did not produce as high a value of ϵ_{ℓ} in this case as in tension. Confirmation of this explanation is given in Figure 7, which shows the close agreement of COD values for Series 5 and 6 with those for the tension Series, COD being considered the best measure of relative values of ϵ_{ℓ} in these tests. Similarly, the results for Series 7 (single groove bend) showed the effect of the groove to be small, and we again are forced to assume that the groove does not focus strain at the crack tip to the degree that one might expect.

DISCUSSION

The gross strain concept is so simple that it is easily dismissed as being obvious, until one tries to choose locations for the strain measurements that will make them useful in the study of fracture phenomena and in the application of test data to design. Establishment of quantitative definitions for the terms used in the title of this report was one of the more pertinent results of the test program. We begin by first summarizing the experimental results.

Specimen cross section in the plane of the crack and crack size were constant throughout the program, hence the proximity of the crack tip to free surfaces at the net section was the same in all cases. Transverse strain gradients were obtained by testing in bending, and axial gradients were obtained by the use of grooved specimens tested in tension. A Series consisted of seven specimens, which were tested at different temperatures as needed to define the transition in strain to maximum load from, nominally, 0.2 to over 2.0 percent. Displacements were measured at several places to define the gross strains front and back in both the net and gross sections.

As expected for this steel, the transition temperature phenomenon was exhibited by all eight series of specimen geometry and loading conditions. However, all attempts to find a common critical strain value that yielded the same temperature dependence for all eight series failed. Instead, the same pattern was obtained whether the ordinate was COD as shown in Figure 7 or gross strain in the net section at the cracked face, or at the crack-tip depth, or at mid-crack depth as shown in Figure 8.

The breadth of the region within the family of curves was roughly 100 degrees, a very considerable effect of specimen and loading configuration on gross strain crack tolerance. Its lower bound was formed by data for the series loaded in bending with no backup bar, and its upper bound was that of the bend series with the backup bar welded to the cracked face. Presumably these effects may also be described as the result of strain gradients, with the highest gradient tested producing the lower bound and the reversed gradient the upper bound. The intermediate gradients generally fell logically in between these extremes.

To take a first step beyond phenomenology, we base the explanation of these strain-gradient effects on the resulting changes in constraint at the crack tip region. This line of reasoning follows the earlier hypothesis⁽²⁾ which related ϵ_{ℓ} , the local crack-tip strain, and $\epsilon_{\ell c}$, its critical value for fracture, to the measured gross strain values. There was, of course, a cause-and-effect relationship between ϵ_{gn} , the gross strain in the net section and ϵ_{ℓ} through the requirements of compatibility and continuity. Beyond that, however, there was a relationship of the critical values of $\epsilon_{\ell c}$ to both ϵ_{gnc} and ϵ_{ggc} through their effect on constraint at the crack tip. Constraint was qualitatively defined as the degree of triaxial tension. This hypothesis seemed to explain the test results of the size-effect study as well as certain net-section effects.

To examine the application of the hypothesis that strain gradients affect GSCT through their effect on constraint, we plotted the test results on the interaction diagram, Figure 9. The ordinate is intended to be the gross strain value that is the forcing function for ϵ_{ℓ} , the local crack-tip strain at the point of initiation of rapid crack propagation. For Series 1 - 4, it was chosen to be the value of ϵ_{gnc} (3.2 in. gage length) computed at mid-crack depth. For Series 5, 6 and 7, ϵ_{gnc} at mid-crack depth was a strain value obtained as described in Ref. 3. For the tension series, it was discovered that the values of ϵ_{gnc} for a 3.2 in. gage length did not fit a consistent pattern of isotherms on the interaction diagram. The values of " ϵ_{gnc} from R.A." did fit the diagram and were therefore used. The abscissa is intended to be the gross strain value that characterizes the effects of strain gradient on constraint at that point. For that, the ideal strain value would seem to be the one

measured at the back face free surface where the plastic zone from the crack tip comes to the surface in plane strain deformation. Experimental strain values from several locations approximating the ideal were plotted to see which gave the most consistent picture on the interaction diagram. Values finally used were: for tension and for Series 1 - 4, ϵ_{ggc} , back face, and for Series 5, 6 and 7 " $\epsilon_{backface}$ " obtained from the displacement in a gage length on the back face of 1.2 inches spanning the crack plane.

Data from each Series should plot as a nearly straight line radiating out from the origin with increasing temperature. Disregarding net section effects and other anomalies, data for Series 1 should slope upward into the second quadrant at 45° . Tension should occupy the 45° line in the first quadrant, with Series 4 below it and Series 3 above. Series 2 should plot vertically. Series 5, 6 and 7 did not fit the diagram when gross strain in the gross section was used for the abscissa, hence an average net section strain on the back face was used as described above.

Conclusions to be drawn from the interaction diagram are as follows. The effect of strain gradients on gross strain crack tolerance can be measured by considering two gross strain values:

- a. ϵ_{gnc} at mid-crack depth, which seems to be the best measure of gross strain crack tolerance under strain-gradient conditions and is therefore defined as GSCT.
- b. ϵ_{ggc} , back face above and below the crack, the best measure of strain-gradient effects.

From examination of Figure 9, one may write a simple expression for gross strain crack tolerance (GSCT) at a given temperature under some condition of strain gradient as follows:

$$GSCT = GSCT_{tension} + f_g [\epsilon_{back\ face} - \epsilon_{back\ face, tension}]$$

The slope, f_g , of the isotherms is roughly +1.0. However, if one considers the broadest range of variables, the situation is probably as shown in the inset, Figure 9. At the very low temperatures at which plastic strains are confined to the vicinity of the crack tip, constraint should be constant at its maximum value, irrespective of back face strain. At high temperatures where failure is by tensile instability rather than by crack propagation, back face strain again should be unimportant. Hence, f_g is nearly zero at temperatures representing the bounds of the transition region, and is approximately +1.0 in the center of the region.

To explain the upward slope of the isotherms with increasing back face tensile strain, we rely on slip line field theory to provide a picture of flow emanating from the crack tip region. It can occur by wedge actions in both of the principal transverse directions. Measurement of thickness reduction revealed that this did in fact take place. The effect of a favorable strain gradient is to facilitate the establishment of the wedge-action flow pattern at low values of ϵ_{gn} ; i.e., by relieving constraint it causes ϵ_{gc} to rise to a high value before ϵ_g becomes large. When bending produces a neutral axis - a region of near zero strain below the crack tip - the necessary wedge action cannot develop.

CONCLUSION

It has been observed experimentally that the gross strain crack tolerance of the test material for a flaw of given size and shape, at a given temperature, depends strongly on the strain gradient, especially at temperatures just above the transition temperature. This effect, which can be described in terms of a strong interaction between ϵ_{gnc} at mid-crack depth, which is the forcing function for crack propagation, and $\epsilon_{\text{back face}}$, which is the agent for relief of constraint, has implications

regarding the workability of strain energy density theories of fracture. Since strain at failure varies with strain gradient, other things being the same, so does strain energy density at the same point of reference. Therefore, the strain energy density at a reference point cannot, by itself, be sufficient for predicting fracture test results for one strain gradient from another, if one of them is the bending case where some strain is compressive and the other is not. Compressive strain on the back face of a beam contributes to the total energy just as tensile strain at the back face does in a tensile test, but our work shows that they have opposite effects on gross strain crack tolerance.

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TABLE 1--Notes on Displacement Measurements

	Strain Value	Displacements Measured	Method	Gage Length (Inches)	Location of Gage Length	Gage Points
All series	ϵ_{gnc} from R.A.	Width and thickness reduction	Micrometer (post test)	-	0.2 inch back from fracture	-
	COD (crack opening displacement)	Separation of adapters spot welded to cracked face	Extensometer	0.2	Centered on crack at specimen surface	Spot welds
Series 1 to 4 (See Figure 3)	ϵ_{gnc} , cracked face and ϵ_{gnc} , back face	Separation of adapters on gage blocks, top and bottom (see text)	Extensometer	3.2	Centered on crack plane	Fillet welds on gage blocks
	ϵ_{ggc} , cracked face and ϵ_{ggc} , back face	Separation of horizontal pins on gage blocks top and bottom	2 Extensometers - Average of left and right	1.0	From 1.6 to 2.6 inch from crack plane, left and right	Fillet welds on gage blocks
	$\epsilon_{crack-tip}$ depth and $\epsilon_{mid-crack}$ depth	Obtained by analysis from ϵ_{gnc} , cracked face and ϵ_{gnc} , back face	Linear interpolation	3.2	0.22 inch, and 0.11 inch respectively, below surface of cracked face, centered on crack plane	
Series 5 and 6 (See Figure 3)	ϵ_{groove}	Separation of adapters spot welded to surface of groove on cracked face	2 Extensometers - Average of left and right	0.2	0.5 inch in from edge of specimen	Spot welds
	ϵ_{back} face	Separation of adapters spot welded to back face	Extensometer	1.2	On back face, spanning the groove	Spot welds
	ϵ_{ggc} , cracked face and ϵ_{ggc} , back face	Separation of gage holes	Hamilton inside micrometer, modified	0.5	From 1.0 to 1.5 inch from crack plane	.062 dia. hole
	$\epsilon_{crack-tip}$ depth and $\epsilon_{mid-crack}$ depth	Obtained by semigraphical analysis (See text)				
Series 7 (See Figure 3)	ϵ_{groove}	Same as Series 5 and 6				
	ϵ_{back} face	Separation of pins on gage blocks top and bottom	4 Extensometers - Average 2 top and 2 bottom	1.2	Gage blocks welded to both edges of specimen	Fillet welds on gage blocks
	$\epsilon_{crack-tip}$ depth and $\epsilon_{mid-crack}$ depth	Obtained by semigraphical analysis (see text)

Figure 1. Beam cross sections used to produce transverse strain gradients.

SERIES 5 - DOUBLE - GROOVE SPECIMEN

SERIES 6 - DOUBLE - GROOVE SPECIMEN TESTED IN TENSION
 SERIES 7 - DOUBLE - GROOVE SPECIMEN TESTED IN BENDING

Figure 2. Configuration of the double-groove tension specimen for Series 5 and the single-groove specimen for Series 6, tension, and Series 7, bending.

Extensometer in place
on one set of ϵ groove
adapters.

Gage block

Pin

Figure 3. Typical views of extensometer system.

Figure 4. Critical strain and COD values as a function of temperature for surface-cracked specimens tested in tension.

Figure 5. Critical strain and COD values as a function of temperature for:
 Series 1, $\epsilon_{\text{back face}}/\epsilon_{\text{cracked face}} = -1.0$, and
 Series 2, $\epsilon_{\text{back face}}/\epsilon_{\text{cracked face}} = 0$,
 compared to Tension Series (dashed lines)

Figure 6. Critical strain and COD values as a function of temperature for:
 Series 3, $\epsilon_{\text{back face}}/\epsilon_{\text{cracked face}} = +0.50$, and
 Series 4, $\epsilon_{\text{back face}}/\epsilon_{\text{cracked face}} = +2.00$,
 compared to Tension Series (dashed lines)

Figure 7. Summary plot of COD values as a function of temperature for all Series.

Figure 8. Summary plot of values of gross strain in the net section at mid-crack depth as a function of temperature for all Series.

Figure 9. Interaction diagram relating the effect of gross strain at the back face above and below the crack on gross strain crack tolerance for all Series. Test temperature for each data point is shown beside the symbol.