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# SIGNIFICANCE OF CHARPY-V TEST PARAMETERS AS CRITERIA FOR QUENCHED AND TEMPERED STEELS

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# Significance of Charpy-V Test Parameters as Criteria for Quenched and Tempered Steels

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*Metallurgy Division*

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13. ABSTRACT


The general availability of Charpy test equipment is an incentive to develop reliable fracture resistance criteria based upon some parameter of this test method, but the parameters are difficult to interpret into structural parameters. The development of fracture mechanics technology in recent years has clarified the reasons for the difficulties in developing more generalized $C_V$ energy criteria for various steels. This new understanding has led to adjustments in $C_V$ energy for variations in the yield strength of steels, and a table of values has been incorporated in ASTM standards and ASME codes for the conventional low-strength steels. The extension of this approach to the use of a $C_V$ energy index for quenched and tempered (Q&T) steels has not evolved because of the broader range in the mechanical characteristics of Q&T steels.

A ductility parameter has been suggested to replace the energy parameter as the criterion of performance of a Q&T steel. The lateral expansion (LE) of the $C_V$ specimen has been hypothesized to be a self-adjusting index of fracture resistance to compensate for the wide range in the yield strength of Q&T steels. This hypothesis is examined in this report using information from an extensive bank of data generated at NRL as well as the information in the literature. The conclusion drawn from this extensive amount of data on steels ranging in yield strength from 80 to 220 ksi (Abstract continued)

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| | ROLE | WT | ROLE | WT | ROLE | WT |
| Fracture resistance criteria | | | | | | |
| Charpy impact test | | | | | | |
| $C_v$ lateral expansion | | | | | | |
| Drop-weight nil-ductility-transition temperature | | | | | | |
| Dynamic Tear test | | | | | | |
| Fracture mechanics | | | | | | |
| High-strength steels | | | | | | |

(56 to 155 kgf/mm$^2$) is that a fixed value of $C_v$LE can in no way compensate for a variation in yield strength as required by the principles of fracture mechanics. This conclusion is supported by the equations relating $C_v$ parameters to elastic fracture mechanics parameters and by a graphical treatment of the data which show $C_v$LE to be directly proportional to $C_v$ energy with only a 12 ft-lb variance for the full range of Q&T steels.

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PROBLEM STATUS

This report completes one phase of the problem; work on other aspects of the problem is continuing.

AUTHORIZATION

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# SIGNIFICANCE OF CHARPY-V TEST PARAMETERS AS CRITERIA FOR QUENCHED AND TEMPERED STEELS

## INTRODUCTION

The trend for increased use of the weldable high-strength quenched and tempered (Q&T) steels has stimulated a concern for a practical and accurate criterion for the fracture resistance of these materials. Because of the general availability of Charpy V ($C_V$) test equipment, the use of a reliable criterion in this test method would be desirable. Unfortunately, this empirical test was based upon the performance of material in a 10-mm-square sample using a shallow, dull notch, and the original intent was to use the energy parameter as a criterion for fracture resistance. The most noteworthy correlation between $C_V$ energy values and structural performance was that for the World War II ship plate steels (1). Although this correlation was meaningful for World War II ship steels, early NRL studies demonstrated conclusively that different customized $C_V$ energy criteria are needed to peg specific critical flaw size vs stress level relationships for each low-strength steel (2-8).

The difficulty in the use of $C_V$ energy criteria stimulated the search for a more basic criterion such as ductility or fracture appearance. The relationships between the energy and the ductility parameters have been extensively investigated (3-6,8) for the low-strength steels. These studies documented the fact that the course of the fracture appearance and the notch-root contraction (ductility) transition curves parallel the $C_V$ energy transition curves as shown in Fig. 1. Since the $C_V$ energy curve provided the most direct definition of the transition features, no advantage was gained by reference to the other criteria measurements for these steels.

For guidance in the selection of a proper $C_V$ energy criteria, an ASTM standard, ASTM A593, and an ASME Boiler Code specification, SA593, have been developed to set the right value for various low-strength steels and preclude brittle fracture. These ASTM and ASME guides were predicated on a correlation of $C_V$ energy and NDT temperatures of each steel. The NDT temperature test, ASTM E-208, provides the index to a specific level of structural performance, and the performance of these materials throughout their fracture resistance transitions is predictable on the basis of this index.

Unfortunately, the same critical temperature approach cannot be used for high-strength steels because of their higher and greater range of yield strengths (70 to 150 ksi). In addition, their upper shelf fracture resistance is less effective because of the trade-off in fracture resistance with increasing yield strength. With the need for increasing the fracture resistance as yield strength increases in order to maintain a specific level of structural performance, criteria other than $C_V$ energy have been proposed as previously described for the low-strength steels (9-12). The one criterion that has received extensive attention is the lateral expansion ($C_V$LE) of the specimen on the side opposite the notch. This "ductility" parameter is supposedly self-compensating for the required increase in energy to resist the propatation of fractures when the yield strength of the material in increased (11). If true, the negotiation procedures for setting specification criteria between producers and users will be greatly simplified.

The purpose of this report is to examine the significance of the $C_V$ parameters for the Q&T steels and to determine whether an improved index of the fracture behavior and

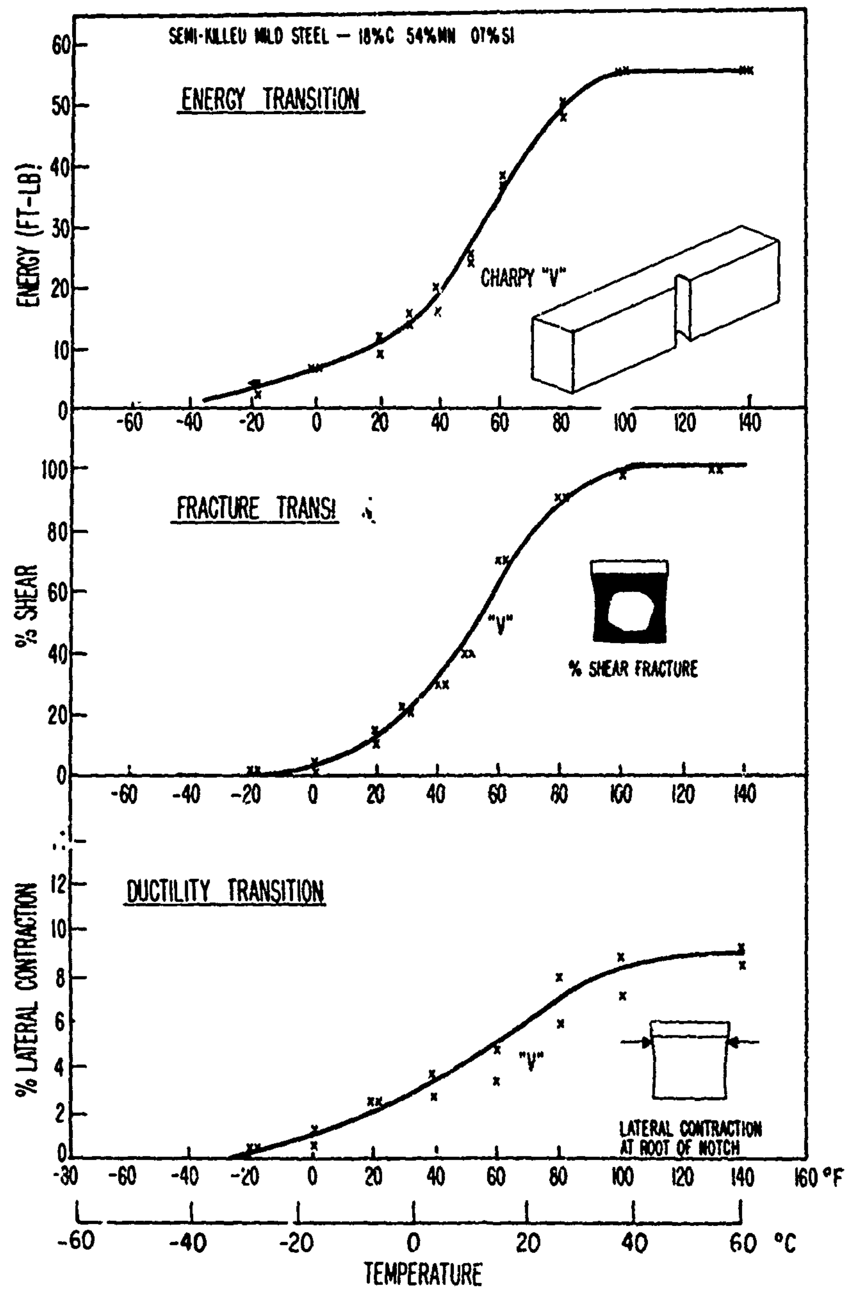


Fig. 1 - Illustrating the direct correspondence among the three $C_V$ test parameters—impact energy, percentage of shear fracture, and lateral contraction—for a low-strength steel in the temperature transition region

structural performance for these higher strength steels can be obtained through the use of a fixed $C_V$ LE criterion. The relationships between $C_V$ energy, $C_V$ LE, and yield strength for Q&T steels were analyzed to establish the validity of this postulate for both the temperature transition region and the upper shelf region (temperatures above the transition) of high-strength, Q&T steels. The information in an extensive $C_V$ test data bank was examined with respect to $C_V$ energy and yield strength relationships at fixed values of $C_V$ LE. This large amount of primary data covering a broad range of yield strength provided a statistically significant analysis concerning the self-adjusting characteristics of the $C_V$ LE criterion to variations in the yield strength of steels.

## REVIEW OF $C_V$ TEST PARAMETERS AND PROPOSED CRITERIA FOR SPECIFICATIONS

The experimental data and summary relationships that are most frequently cited as the basis for the use of the $C_V$ LE parameter as a fracture resistance criterion in specifications are shown in Fig. 2 (11,13). The lower relationships in Fig. 2 show $C_V$ energy increasing as the tensile strength of the steel increases for various selected values of $C_V$ LE. The upper set of lines shows a similar linear relationship of increasing $C_V$ energy with yield strength for selected values of $C_V$ LE. On the basis of these data, it is proposed that a fixed level of $C_V$ LE indicates some specific level of structural performance. Two values, 15- and 35-mil $C_V$ LE, have been recently adopted for use in certain codes and standards. For example, the 15-mil $C_V$ LE criterion is a mandatory requirement in several Q&T steels that have been approved for construction of ASME Code pressure vessels (e.g. the A517 and A645 steels). Also, in January 1972, the ASME adopted a 35 mil $C_V$ LE criterion for inclusion in Section III (Nuclear Power Plant Components) of the Code.

## CHARACTERIZATION OF Q&T STEELS IN THE TEMPERATURE TRANSITION REGION

It is generally recognized that the temperature transition features of steels are dependent upon strain rate and stress state or constraint. In principle, a full-thickness test provides the direct approach to the complex triaxial stress state which is the constraint aspect. In practice, it is generally more practical to use small, standardized test specimens and develop quantitative reference criteria by correlating test results to the structural performance of the section in question. A rational test method is one that provides a direct correspondence to the performance of the metal in service. These methods require deep, sharp,tip notches or weld cracks, and they must not provide ambiguous information concerning the fracture resistance of the metal in a specific structural application. In other words, a fracture resistance test method should be rational with respect to the constraint it imposes upon the metal sample, so that it can provide quantitative criteria with a direct correspondence to the theoretical and actual performance of the metal in a structure. This subject was discussed in detail in a recent report by Pellini (14).

Examples of test methods that have a rational basis are (a) the Drop-Weight Nil-Ductility Transition (NDT) temperature test (15), (b) the Plane Strain $K_{Ic}$ Fracture Toughness test methods (16), (c) the Robertson Crack-Arrest temperature test method (17), (d) the modified Robertson-type wide plate tests (18,19), and (e) the Dynamic Tear (DT) test method (20,21). The first two methods are the only rational fracture toughness test methods adopted in recent years by both the ASTM and the ASME Boiler and Pressure Vessel Code. The DT test method is currently a MIL Standard, and it is being standardized under the auspices of the ASTM Committee E-24 on Fracture Testing of Metals.

Unfortunately, the $C_V$ test does not meet the requirements of a rational fracture resistance test method. The constraint aspects of the $C_V$ specimen are compromised by the specimen design; i.e., shallow, dull notch, insufficient thickness, and inadequate

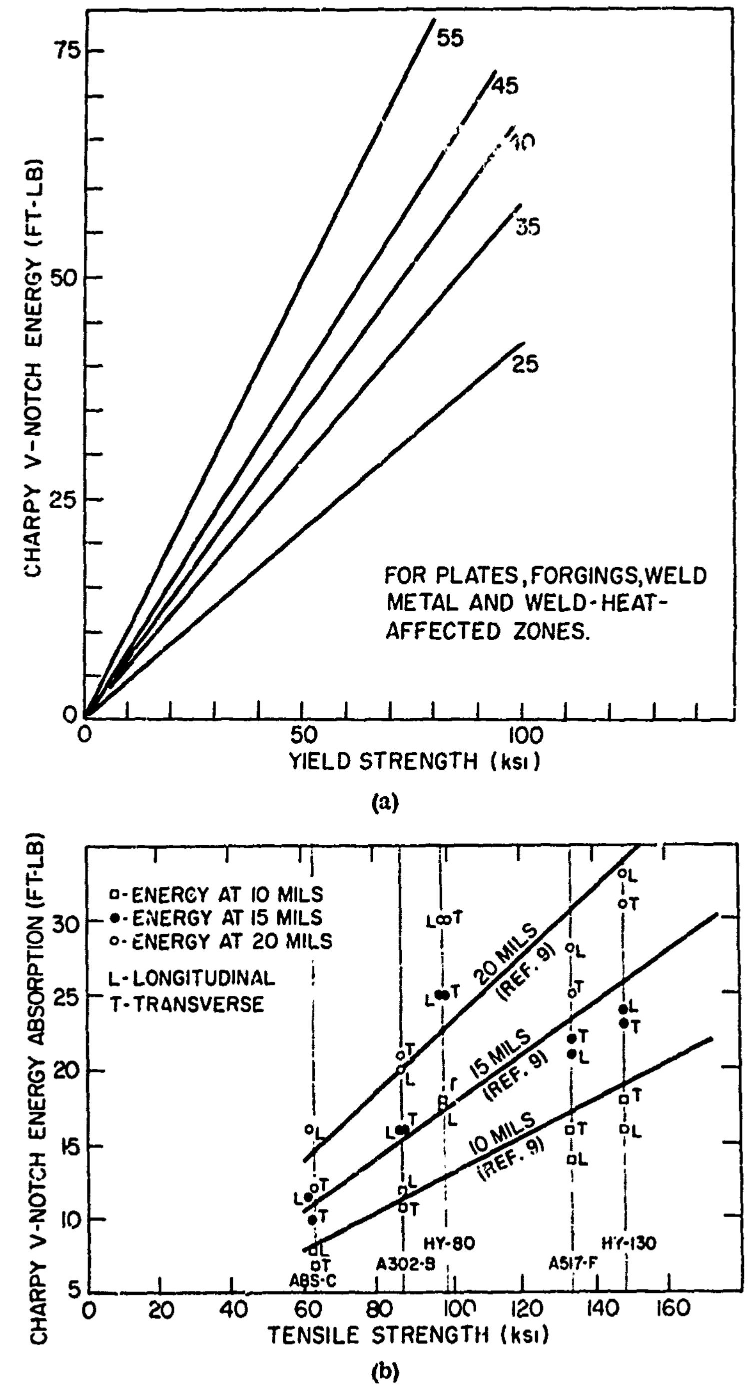


Fig. 2 - (a) Proposed relationship between $C_VE$ and yield strength for various levels of LE (Ref. 13) (b) Data supporting an hypothesis that $C_V$ energy increases with the tensile strength of steels for any fixed value of ductility as lateral expansion (LE) (Ref. 9-11)

crack extension distance. For purposes of illustrating the errors in characterization of temperature transitions of Q&T steels when constraint conditions are relaxed as much as the design of the $C_V$ specimen allows, the temperature transition features of three Q&T steels are discussed in the following examples.

HY-130 Steel

The true fracture toughness transition for a 1-in.-thick HY-130 steel plate is defined by the DT energy transition in Fig. 3 (22). For this material the fracture appearance change (flat to slant) of the DT specimens corresponds to the rapid rise in DT energy in the transition region from 500 ft-lb at -100°F to a high upper shelf value of 4300 ft-lb at 0°F (a factor of 8.6 increase in energy absorption). The 500 ft-lb level and the flat fracture shown for the DT specimen at the toe region of the transition are indicative of the brittle, plane-strain fracture state. With increasing temperature, the characteristic fracture mode becomes mixed mode, and the amount of shear lip on the DT fracture surfaces increases up to the full-slant appearance for the upper shelf toughness level, 4300 ft-lb.

The performance of this HY-130 steel in the $C_V$ test is compared to its true temperature transition features in Fig. 3. The $C_V$ energy transition exhibits a very gradual slope in the transition region. The $C_V$ LE transition also exhibits a low slope similar to that observed for the $C_V$ energy transition. The 15-mil $C_V$ LE transition temperature would be approximately -140°F. This is far below the temperature at which flat, plane-strain, brittle behavior can occur. Also, note the contrast in the fracture appearance of the steel in the two specimens. There is a complete change (flat to slant) in fracture appearance in the DT specimens, while there is very little change in the $C_V$ fracture appearance over the entire temperature span from -100° to +80°F. The low level of the constraint conditions in the $C_V$ specimen does not induce a sharp transition in this Q&T steel.

Additional analysis of the transition features of this sample of HY-130 steel can be made by normalizing the data relative to their respective shelf value as shown in Fig. 3, bottom. In normalized form, both $C_V$ energy and LE data still feature a shallow and indistinct transition temperature region, in contrast to the sharp transition of fracture toughness with respect to temperature defined by the DT test. At -100°F the DT specimen fractures in a plane-strain mode while the $C_V$ specimen fractures in a mixed mode. It is evident from the data given in Fig. 3 that the $C_V$ test provides a limited definition of transition characteristics of this Q&T steel that would be difficult to interpret without the DT test data. Certainly, the $C_V$ LE parameter for this steel provides no better discrimination of the temperature transition than the $C_V$ energy parameter.

2-1/4Cr-1Mo Steel (A336 Type F22)

The errors in a characterization of the fracture toughness properties of Q&T steels and the complexities encountered by interpretation of $C_V$ test results are dramatically illustrated by the pneumatic burst tests of two seamless tube air flasks shown in Fig. 4. The failure analysis of these two air flasks has been reported in detail (23,24), and only certain aspects are summarized briefly below.

Both vessels were constructed of Q&T 2-1/4Cr-1Mo steel (A336 Type F22) and each contained a 2-ft-long, sharp slit machined to approximately 75% of the 1-in. wall thickness. The two burst tests were conducted at approximately the same temperature and resulted in totally different fracture modes, as shown in Fig. 4, top. The E-71 flask fragmented with mixed mode fractures exhibiting moderately heavy shear lips; the E-75 flask was split open without fragmentation and exhibited full slant fracture surfaces.

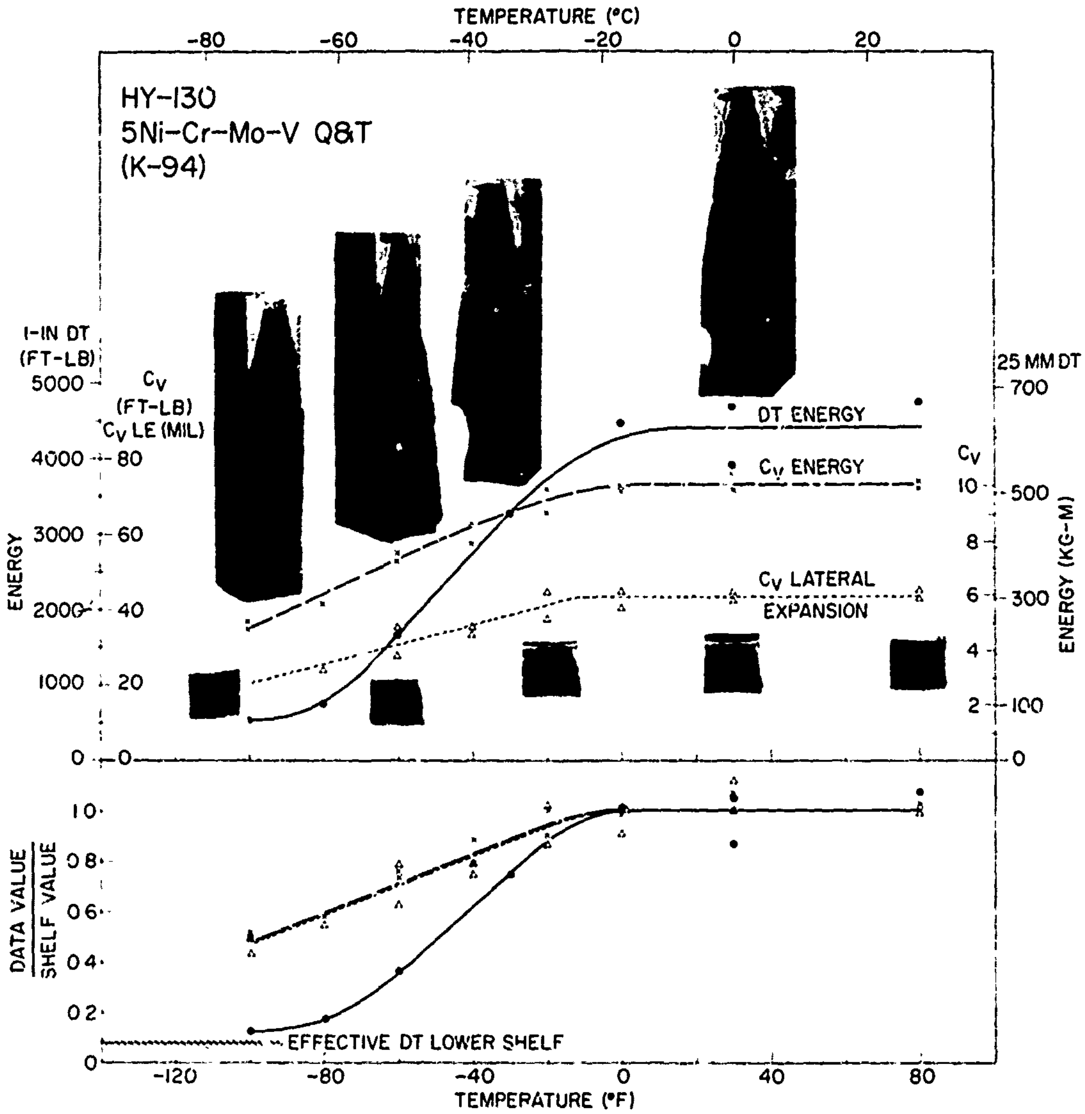


Fig. 3 - Comparing the transition temperature features of 1-in. DT specimens in a Q&T HY-130 steel to the transition of various parameters of the $C_V$ test. Note the direct correspondence between the change in fracture appearance and the sharp rise in DT energy, and that these features are absent in the $C_V$ test.

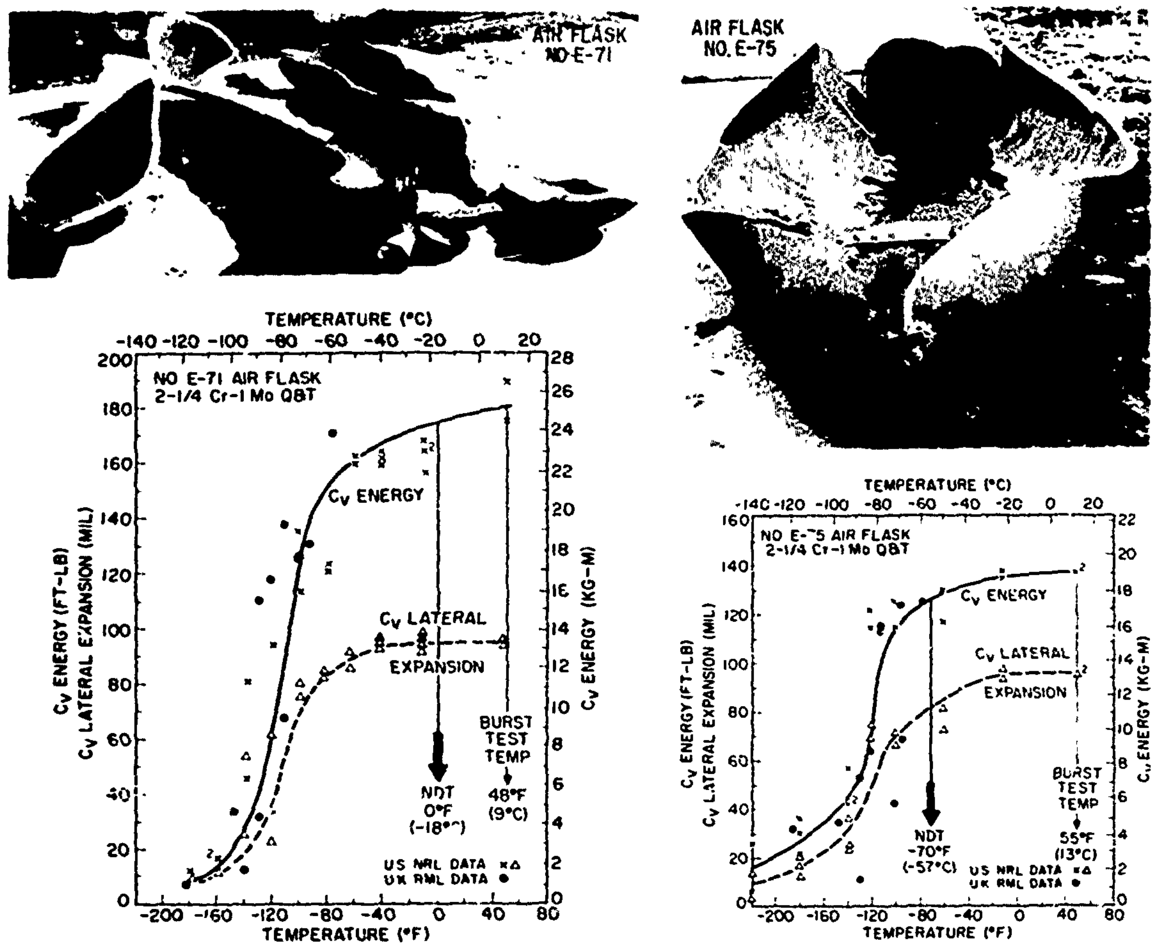


Fig. 4 - Illustrating an apparent anomolous performance of two pressure vessels in 2 1/4 Cr - 1Mo Q&T steel during a burst test. The fragmentation-type fracture (top left) would not be expected since the burst temperatures of both vessels correspond to similar upper shelf temperatures of the Charpy test parameters $C_VE$ and $C_VLE$ (Ref. 22, 23).

Fig. 5, top, illustrates that the fracture modes of both vessels were predicted exactly by the fracture analysis diagrams (FAD) which are indexed to the NDT temperature* (24). The NDT of the E-71 flask was 0°F, which is approximately 50°F below its burst test temperature. Accordingly, this flask should be expected to burst and fragment with mixed mode fractures as is shown in Fig. 4. The NDT of the E-75 flask was -70°F, which is 125°F below the burst test temperature. Accordingly, the fracture analysis diagram predicts that flask E-75 should be expected to fracture in full slant (shear) mode as shown for this flask in Fig. 4. The performance of these two flasks illustrates the rationality of the NDT test.

Robertson crack-arrest temperature (CAT) determinations at approximately 1/2 $\sigma_{ys}$ loads were conducted for both of these air flasks at the Culcheth Reactor Materials Laboratory (RML) in the United Kingdom. Excellent agreement was obtained with the CAT predicted by the NDT-derived FAD location and the experimentally determined 1/2-$\sigma_{ys}$ CAT for both of these air flasks as shown in Fig. 5, bottom. Therefore, the performance of the two flasks was not anomolous with respect to the Robertson test results.

The $C_v$ data for the two air flask steels, presented in Fig. 4, were obtained by NRL and RML, and the data are in good agreement. Particularly striking are the extremely high $C_v$ energy and $C_v$ LE index values at the burst temperature and even at the NDT temperatures for these Q&T 2-1/4Cr-1Mo air flask steels. Note that for both materials, the $C_v$ 15-mil LE temperature is more than 100°F below the respective NDT temperatures of these air flasks. Since a finite fracture toughness level of $K_{Id}/\sigma_{yd}$ = 0.5 is present in steels at their NDT temperature (25), it is evident that both of these air flask steels would be extremely brittle at their respective $C_v$ 15-mil LE temperatures. The performance of the two flasks was anomolous to the performance of the steel in the $C_v$ test, and that is why the two samples of a Q&T steel were evaluated with the rational test methods in the analysis of the failures.

It is obvious from the analysis of the data given in two previous examples that not only the $C_v$ energy but also any other $C_v$ parameter such as LE and percentage of shear may not be used with confidence for indexing the temperature transition of Q&T steels. The "usual" interpretation of all three types of $C_v$ transition curves (energy, LE, and percentage of shear) would have resulted in predictions that were very much in error for the two types of steels. The failure of the $C_v$ test to accurately characterize the fracture properties of these Q&T steels negates the validity of the $C_v$ 15-mil LE criterion "at the lowest service temperature" as a valid index of the temperature transition region for any Q&T steel without prior correlation with results from a rational test.

## $C_v$ ENERGY OR LE AS A FRACTURE RESISTANCE CRITERION FOR Q&T STEELS

Extensive $C_v$ test data were available from a previous NRL study of the fracture characteristics of the AISI 4300 steels (26). These data were reexamined with respect to $C_v$ energy, LE, and yield strength relationships. In addition to the NRL $C_v$ test data which included the full transition range for all of the steels, other $C_v$ energy vs LE data for Q&T steels reported by Gross (11), PVRC (13), and American Bureau of Shipping (27) were added to this study. These data provided a substantial data bank based on over 800 $C_v$ specimens from various Q&T steels that ranged from 80 to 225 ksi (56 to 158 kgf/mm$^2$) yield strength in room temperature tests. This broad coverage of Q&T steels permitted a comprehensive analysis to be made of $C_v$ parameters and yield strength relationships.

* A detailed analysis of structural performance to be expected in pneumatic or hydraulic burst tests of air flasks featuring very long (10 to 20 times wall thickness) flaws is given in Ref. 23.

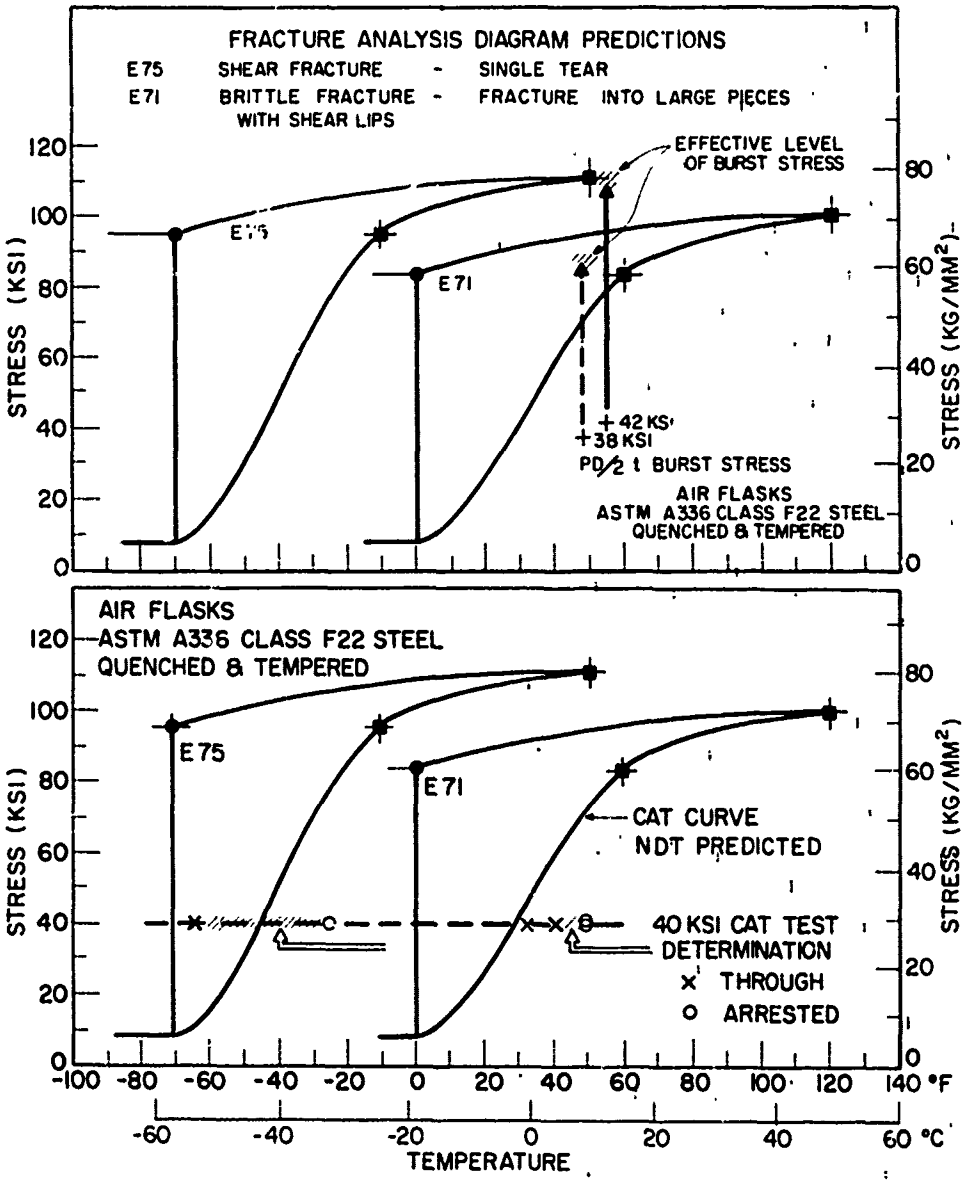


Fig. 5 - The fracture analysis diagrams (FAD) predicting the observed structural performance of the two air flasks in Fig. 4. The NDT index and the RML crack arrest temperature predicted a 70°F shift in the FAD and a mixed-mode fracture for the steel that fragmented in the burst test.

Figure 6, top left plot, represents the PVRC $C_v$ energy vs LE data for type 4340 bolting materials. The data are from eight lots of material covering the following variations: (a) diameters from 3 to 6-3/4 in. (8 to 17 cm), (b) room temperature yield strengths between 140 to 150 ksi (98 to 105 kgf mm$^2$), and (c) air-melted, vacuum-degassed, and vacuum-arc remelted steels. The dashed lines encompassing 90% of the data illustrate the scatter normally expected of these 4340 Q&T bolt steels. Figure 6, top right, illustrates the $C_v$ energy vs LE data encompassing low (0.38%) to high (0.44%) carbon content 4340 Q&T steel plates from the NRL studies. Similar data are shown in Fig. 6, lower left plot, for the 4320, 4330, and 4350 steels from the NRL studies and in Fig. 6, lower right, for a variety of Q&T steels, as noted by the legend code and data reference source.

A close linear relationship between the two parameters, $C_v$ energy and LE, is clearly evident from the data shown in Fig. 6, and all data fall within the same scatterband. Although the width of the scatterband precludes the development of a reliable short-range correlation, the average trend in the full span of the data indicates a direct proportionality between $C_v$ energy and LE. In this set of data, the $C_v$LE parameter is not independent of the $C_v$ energy parameter, and one cannot, therefore, choose a fixed value of LE and expect the $C_v$ energy to increase automatically with an independent property such as yield strength. It is evident that any adjustment in $C_v$LE for a variation in yield strengths of even the same material but subjected to a different heat treatment would have to lie within the width of the scatterband.

The two $C_v$LE criteria that have been proposed as being important for material specifications are the $C_v$ 15-mil LE and the $C_v$ 35-mil LE values. When the range of the values of $C_v$ energy for these two criteria of $C_v$LE are plotted for all of the Q&T steels in this report, the scatterband will fall within the bounds shown in Fig. 7. Note that the width of the scatterbands for 15- and 35-mil LE in Fig. 7 corresponds exactly to the range in $C_v$ energy expected at these fixed values of LE from the limits of the scatterbands in Fig. 6. The data indicate an essentially fixed relationship of $C_v$ energy to the 15-mil $C_v$LE value over the entire yield strength range which is an order of magnitude. Fewer steels are shown at the 35-mil $C_v$LE level because the higher yield strength steels did not develop to 35 mil of LE. The best-fit relationship between $C_v$ energy and yield strength for a 35-mil $C_v$LE criterion is noted to be a horizontal band also. The conclusion to be drawn from all of these data is that basically the 15-mil and the 35-mil $C_v$LE criteria are independent of yield strength.

## ANALYTICAL PROPOSALS FOR THE $C_v$ 15-MIL LE CRITERION

The ASME adoption of the $C_v$ 15-mil LE criterion for Q&T steels was supported on the claim that this value agreed best with fracture mechanics considerations (11). From linear elastic fracture mechanics and the Ratio Analysis Diagram (RAD) concepts for fracture toughness characterization (28,29), it is recognized that steels of increasing yield strength require higher values of $C_v$ energy to give comparable structural performance. If a given value of LE is indicative of constant level of toughness, regardless of yield strength, then it must provide the same static or dynamic ratio of $K_{Id}/\sigma_{yd}$. Note that it is the ratio (a measure of plastic zone size) and not the absolute value of $K_{Ic}$ that determines structural behavior. The validity of this hypothesis is considered below.

The hypothesis of the $C_v$ 15-mil LE is that it automatically provides for an increase in $C_v$ energy with increasing yield strength. This statement can be expressed mathematically as a straight line relating $C_v$ energy and yield strength:

$$C_v = m\,\sigma_{ys}, \quad (1)$$

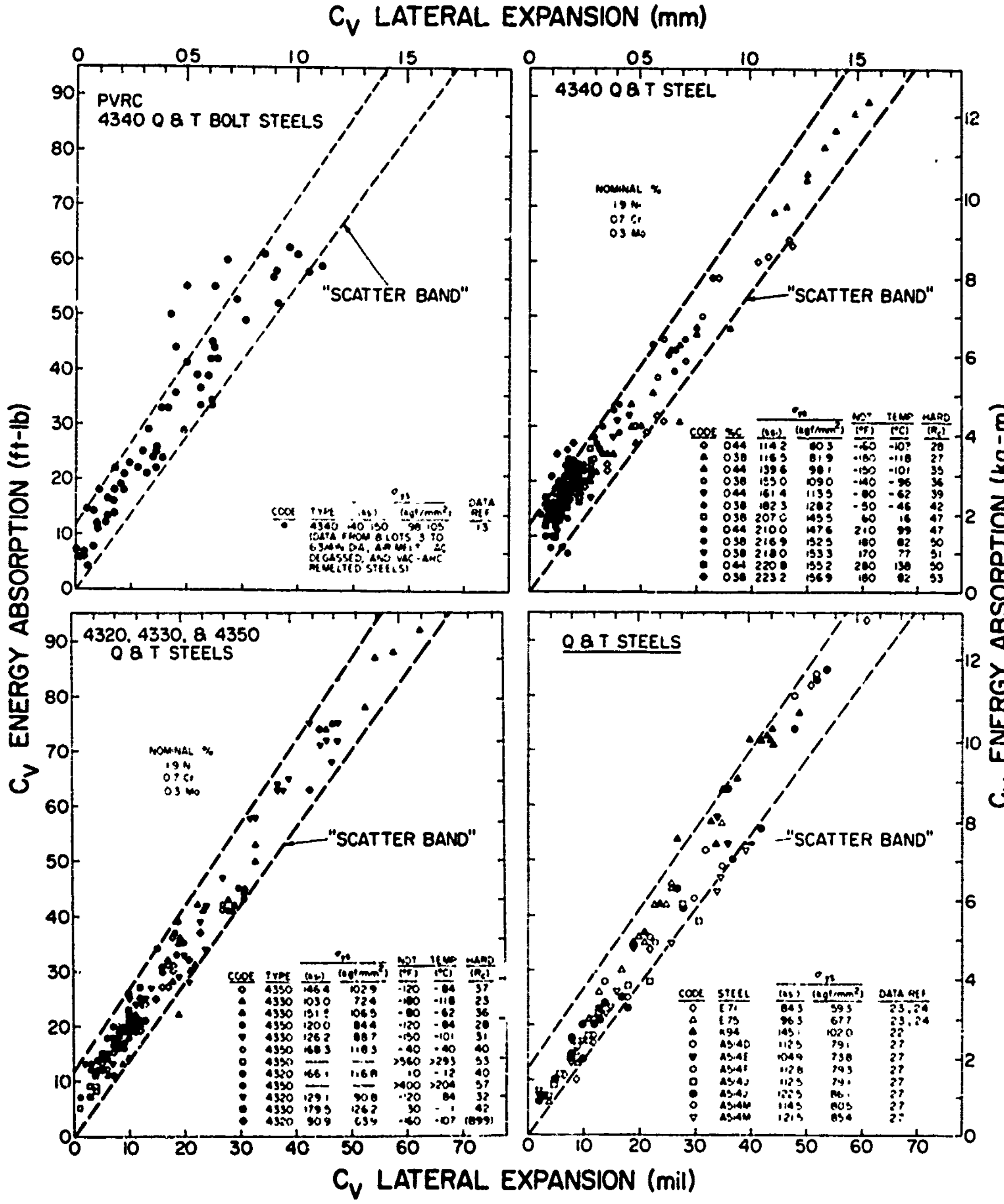


Fig. 6 - A summary of $C_V$ test data for Q&T steels from NRL studies and from the literature showing that a linear relationship exists between $C_VE$ and $C_VLE$, and the same narrow scatterband of 12 ft-lb for all groups of materials ranging in yield strength from 80 to 220 ksi

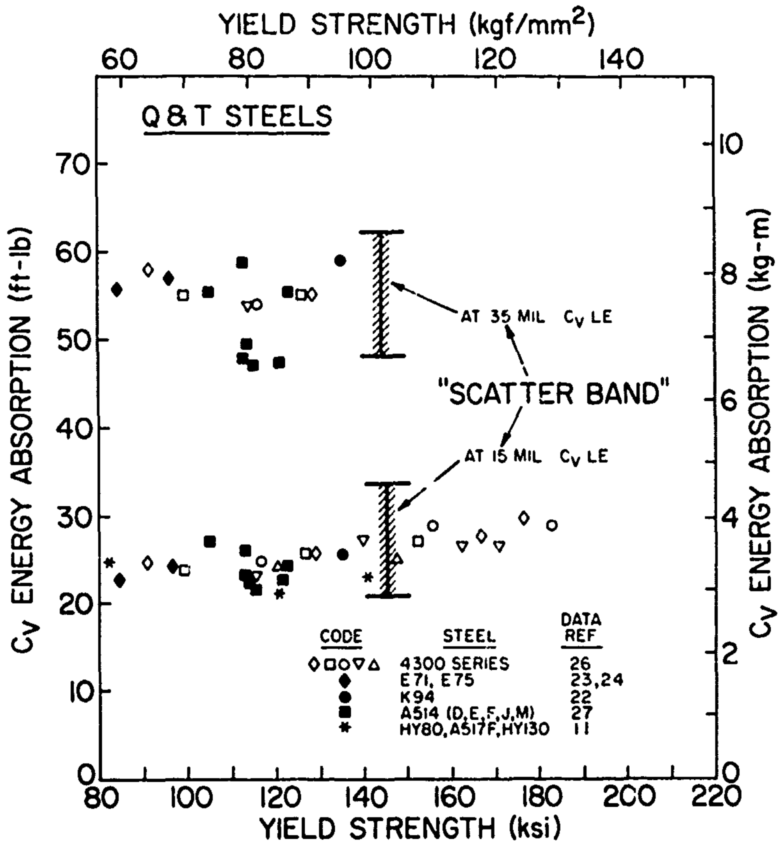


Fig. 7 - Illustrating the lack of any trend for $C_VE$ to increase with the yield strength of Q&T steel at fixed values of 15-mil and 35-mil LE

where m is the slope of the line and $\sigma_{ys}$ is the yield stress. Note that the value of m would be determined experimentally for a given LE value as illustrated in Fig. 2. Next, consider the correlation between the upper shelf value of $K_{Ic}$ and the $C_v$ energy developed by Rolfe and Novak (30):

$$\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 = 5\left[\frac{C_v}{\sigma_{ys}} - 0.05\right], \tag{2}$$

where $C_v$ is the energy in ft-lb, $\sigma_{ys}$ is in ksi, and $K_{Ic}$ is the toughness in ksi $\sqrt{in.}$ Combining Eqs. (1) and (2) shows that

$$\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 = 5 \ (m - 0.05). \tag{3}$$

Thus Eq. (3) indicates that the choice of a given level of LE will yield the same fracture toughness (where fracture toughness must be expressed as the $K/\sigma$ ratio and not K by itself) for any value of yield stress.

Another equation relating $C_v$ energy and $K_{Ic}$ has been proposed by Barsom and Rolfe for the transition temperature region (31), namely

$$K^2_{Ic} = {}^2E \ C_v{}^{3/2}, \tag{4}$$

where E is the modulus of elasticity in ksi, $K_{Ic}$ is in ksi $\sqrt{in.}$, and $C_v$ is in ft-lb. Equations of similar form have been proposed by Corten and Sailors (32) for both $K_{Ic}$ and $K_{Id}$ in the transition temperature region. This region is of primary concern as it pertains to the 15-mil $C_v$LE criterion which is in the transition temperature region for the Q&T steels. Substituting Eq. (1) into Eq. (4) shows that

$$\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 = \frac{2E \ m^{3/2}}{\sqrt{\sigma_{ys}}} \ . \tag{5}$$

Equation (5) indicates that the choice of a fixed value of LE does not yield an invariant $K_{Ic}/\sigma_{ys}$ ratio with changes in $\sigma_{ys}$. In fact the value of LE must increase with $\sigma_{ys}$ to maintain a fixed value of toughness, and therefore the mathematical relationships between linear elastic fracture mechanics parameters and $C_v$ parameters project the same complex problems with a $C_v$LE criterion as discussed with the graphical analysis of $C_v$ parameters in the previous section.

## SUMMARY AND CONCLUSIONS

Although a statistical analysis of the World War II Liberty Ship fractures indicated that a 15 ft-lb $C_v$ energy index provided protection from the initiation of catastrophic fractures from small flaws, it has not been possible to extrapolate this criterion to predict the performance of other steels. It is recognized by the engineering profession that adjustments in $C_v$ energy are needed for different types of steels to provide the same protection against small flaws in structures, and these adjustments have been included in the ASTM A593 specification for pressure vessel steels. However, this specification applies only to the lower strength (i.e.,C, C-Mn, C-Mn-Si, and low-alloy) steels for which $C_v$ energy vs NDT correlations have been developed. The correlations do not include the newer, high-strength, Q&T steels.

To provide a $C_v$ criterion free from the problems of customizing the energy value for each material, a ductility parameter ($C_v$LE) has been proposed as a better criterion than energy for fracture resistance. The hypothesis was that the $C_v$LE parameter is self-compensating for changes in the yield strength or the tensile strength of steels, and that the 15-mil $C_v$LE value agrees with fracture mechanics considerations. Within the past three years, $C_v$LE criteria have been inserted into several ASTM and ASME material specifications.

In this study an extensive amount of $C_v$ test data were reviewed to substantiate and validate the above hypothesis. Validation would justify the more extensive use of the $C_v$LE criteria which has been proposed for the high-strength steels. Data from over 800 $C_v$ specimens from approximately 50 different Q&T steels, ranging from 80- to 225-ksi yield strength, were analyzed. Unfortunately, no support for the claims in the hypothesis was found and adverse conclusions were drawn.

For Q&T steels the data show that $C_v$ energy and $C_v$LE rise together in the transition region as a function of temperature and its difficult to relate the $C_v$ transition temperature range to the structural performance of certain Q&T steels. This irrationality of the $C_v$ specimen lies in its undefinable constraint capacity rather than the criterion whether it is energy or a ductility parameter. Therefore, it must be recognized that a $C_v$ fracture resistance criterion for Q&T steels such as 15-mil $C_v$LE has no unique, self-adjusting capabilities to compensate for the changes in the tensile properties of various steels. In fact, the interpretation of a $C_v$ criterion must be developed by other fracture tests that are rational.

The development and understanding of theoretical fracture mechanics in the past decade has been of significant benefit to the engineer. It has illuminated this need for rational methods for measuring and analyzing the fracture resistance properties of structural metals. A rational test method can provide criteria that directly correspond to the structural performance of a metal. Although the $C_v$ test fails to meet the requirements of a rational method, $C_v$ parameters can be correlated with results that have been obtained with rational fracture resistance test methods. Unfortunately, this requires the development of specific correlations for each grade of steel, and the practical solution is the direct use of a rational test method such as the DT test method.

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