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TOUGHNESS CHARACTERIZATION AND CRITERIA FOR STEEL IN CRITICAL A--ETC(U)

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Toughness Characterization and Criteria for Steel in Critical Applications

E. A. LANGE

Metals Performance Branch
Material Science and Technology Division

March 28, 1978

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The fracture toughness of high-strength low-alloy (HSLA) steels and the conventional structural steels can vary over a wide range from an elastic to a plastic performance. Prediction and certification of structural performance is discussed, and a structural-integrity technology which integrates linear elastic-fracture mechanics (LEFM) with the more metallurgically oriented empirical analyses is described. Examples of the critical features of practical test methods are given to illustrate the advantages of using a new test, the Dynamic Tear (DT) test, for characterization purposes. Although test results for toughness

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characterization must be quantitative, the requirements for toughness criteria in material specifications are usually not as restrictive unless structural performance must be certified. Certification of a high level of structural performance will justify the use of high-quality materials.

CONTENTS

TOUGHNESS CHARACTERIZATION AND CRITERIA FOR STEEL IN CRITICAL APPLICATIONS

INTRODUCTION

All metals by definition have elastic and plastic properties. In structural design elastic stress analysis is simplified by the linear relationship between stress and strain, but the analytical treatment of elastic-plastic behavior can be extremely complex because of the variability of localized plastic flow. Plastic flow can be significantly decreased by the introduction of mechanical notches that tend to build up triaxial stress systems, and ultimately a fully constrained ligament tends to perform in an elastic manner.

Unfortunately, a metallurgical crack, such as a crack from fatigue or hydrogen, makes the worst mechanical notch and the best stress concentrator. As a crack increases in size, it tends to make the net section fracture elastically rather than deform plastically. Defining a metal's resistance to the extension of a crack under various mechanical conditions is called "toughness characterization."

The most rigorous portion of the technology concerning toughness characterization is called "linear elastic-fracture mechanics" (LEFM). This is an analytical approach which becomes more complex when the plastic zone at the crack tip is sufficiently large to cause the net section to deform in a nonlinear manner. Although attention has been given to nonlinear, elastic-plastic fracture technology, the analysis of elastic-plastic fracture remains essentially empirical or short range in application [1-3].

The application of LEFM to improve the integrity of structures has primarily concerned the ultrahigh-strength alloys. The fracture problems in structures of the lower-strength steels frequently permit a LEFM analysis to be conducted, but a LEFM analysis only applies when brittle fracture occurs. Although LEFM has its place, complete fracture-toughness characterization of high-strength low-alloy (HSLA) and conventional structural steels involves the development of relationships between the mechanical and the metallurgical parameters that control the fracture process and the transition in toughness from elastic to plastic behavior. Using information concerning toughness in the transition region and service factors concerning the minimum temperature, stress level, and constraint conditions, a designer can specify the quality level that is needed to certify the performance of any steel used in fracture-critical structural elements.

In the design process, the selection of materials for fracture-critical applications starts with the consequences of failure. The consequences of failure set the level of performance that should be certified for the structure and the monetary base to achieve it. This part of the design process is called a Structural-Integrity (SI) Analysis; it considers the trade-offs with respect to design refinement, material quality, and controls for fabrication and inspection. All of these factors are optimized with respect to economics and availability as a part of the SI analysis.

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It is usually emphasized by material producers that the integrity of a structure does not depend on the fracture toughness of the material alone. However, fracture mechanicians emphasize that in most structures where nominal stresses exceed 15 ksi (103 MPa) the criterion used for fracture toughness is the key to certifiable performance. The need for a certified performance also becomes a justification to specify and use high-quality materials. In other words, the criterion for fracture toughness that is set by the designer in a material specification is the element that assures the performance of critical members of a structure in the presence of any credible flaw. It is hoped that the increased use of SI analyses and quantitative criteria for fracture toughness not only will result in a demand for more materials of high quality but will also provide documentation for protection from a product-liability lawsuit in the case of misapplication or an accidental overload [4].

FRACTURE TESTS FOR TOUGHNESS CHARACTERIZATION

Analytical Fracture Tests

A fracture test for characterization purposes must provide results that can be related to structural performance in terms that a designer can understand, such as a critical flaw size and stress relationship. Since the conventional structural steels and the HSLA steels have elastic and plastic fracture properties, a plane-strain (elastic) fracture test provides excellent analytical criteria for toughness, but plane-strain tests cannot characterize the full range of fracture properties in these steels. Therefore, with respect to analytical tests methods, current research concerns elastic-plastic tests, such as the J-integral and Crack-Opening-Displacement (COD) tests, which extend toughness-measurement capabilities beyond the plane-strain regime. The plane-strain regime may be defined by the constraint requirement in the American Society for Testing and Materials Standard ASTM E399 with respect to section thickness, i.e.:

$$B \geqslant 2.5\,(K_{Ic}/\sigma_{ys})^2, \tag{1}$$

where thickness B must be equal to or greater than 2.5 times the square of the ratio of the stress-intensity factor K_{Ic} over the yield strength σ_{ys}.

A significant amount of stable crack growth can occur in an elastic-plastic fracture test, but the critical load derived from these tests is independent of geometry only when it relates to the first extension of the crack front. This makes the J-integral test useful for obtaining a plane-strain fracture-toughness value without the above restrictions on B, but the applicability of such critical J-integral (J_{Ic}) values to indicate structural performance when some stable crack extension can occur is highly questionable. The calculated performance may or may not be highly conservative when the value for toughness does not pertain to a critical or unstable condition in the section of concern. Even if this dilemma did not exist, the analytical tests require instrumenting the specimen, and this makes the tests too expensive to conduct for routine characterization or quality-control purposes.

Although the plane-strain and elastic-plastic test methods with instrumented specimens are not suitable for routine testing of HSLA and conventional, low-strength structural steels, the results of the more practical tests can be correlated to the basic fracture-toughness parameters [5]. The basic criteria for plane-strain toughness K_{Ic} and related terms such as β, where

$$\beta = 1/B(K_{Ic}/\sigma_{ys})^2 \quad (2)$$

can then be used for defining the boundary conditions for elastic or elastic-plastic behavior. The plane-strain limit has been referred to the condition in Eq. (1) where $\beta = 0.4$, and the upper bound for the elastic-plastic regime has been taken as $\beta = 1.0$, indicating that under a tensile load through-thickness yielding will occur prior to the crack becoming unstable [1,3]. When the toughness of the material in a structural element falls within these regimes, the relationships between stress and flaw size can be based upon the principles of LEFM.

High Strain Rate Considerations

The need for toughness characterization at high strain rates is evident from service experience. Well-documented failure analyses have shown that the majority of catastrophic failures are caused by cleavage fractures [6,7]. Cleavage fractures travel at high speeds, and they create their own high strain rate at the crack front. Therefore, any local condition that can initiate a small cleavage crack, such as a hydrogen-embrittled heat-affected zone in a weldment, inherently creates a high-strain-rate condition even though the nominal load stress is static. Certainly, structures with static loads can be protected by a high-static toughness, but this protection can be circumvented by a small pop-in crack.

A high strain rate is most easily attained in a specimen using a bending load; this is why three-point-loaded specimens have dominated the dynamic-test procedures. In these practical tests, the specimen is completely broken, and either a fracture appearance or an energy criterion is used as a measure of toughness.

Complete toughness characterization should include information on appearance and energy, but an energy parameter is a more quantitative and practical criterion than fracture appearance, especially in the elastic-plastic regime. This is particularly the case for materials with fine substructures, such as quenched-and-tempered products, where the brittle-fracture mode does not have a bright appearance as in as-rolled or normalized products. Also, other appearance criteria, such as percent slant (shear lip), can be limited because fractures that are propagated in the rolling direction are often flat in appearance, but they are fully ductile in performance. One significant advantage of an energy criterion for elastic and elastic-plastic fractures is that it can be related to the LEFM criteria [5,8].

Standard Dynamic Fracture Tests

The four dynamic fracture tests that have been standardized by ASTM are listed in Table 1 with information concerning specimen design and criteria of performance. A detailed discussion on the effects of specimen design on test results and the interrelationships between test results can be found in Ref. 4. Only a brief discussion of the principles of specimen design and the objective of the committees that standardized these particular tests will be given here.

The Charpy test was designed many years before steels were welded or LEFM was conceived. It was known, however, that notches tended to make steel products fracture in a brittle manner, and therefore a small specimen was devised with various notch configurations which could readily be machined. In the 1940's, many studies were made of the test

Table 1 — ASTM Standard Tests for Dynamic Fracture Toughness

Tests*	Specimen Size	Notch Design	ASTM Committee	ASTM Standardization	Criteria of Performance
C_v	10 X 10 mm	Machined	E-28	E-23-33	Energy % Shear Lateral Expansion
DWT-NDT	5/8 X 2 X 5 in. (16 X 50 X 127 mm) 3/4 X 2 X 5 in. (19 X 50 X 127 mm) 1 X 3 X 14 in. (25 X 75 X 356 mm)	Brittle Weld	ASTM-ASME	E208-66	Break No Break
DWTT	t X 3 X 12 in. (t X 75 X 305 mm)	Pressed Notch	E24.03.01	E436-71	% Shear
DT	5/8 X 1-5/8 X 7 in. (16 X 41 X 178 mm)	Machined Notch with a Pressed Tip	E24.03.02	E604-77	Energy

*C_v = Charpy V-Notch; DWT-NDT = Drop-Weight-Nil-Ductility-Transition; DWTT = Drop Weight Tear; DT = Dynamic Tear

results obtained from the various Charpy specimens, and the energy value from the V-notch specimen (C_v) was the only criterion that could be correlated to the performance of any structure. The first and most noteworthy was the correlation of the C_v energy value of 15 ft-lb (20 J) to World War II ship fractures [9]. Subsequently it was found that it was necessary to develop separate C_v correlations for each specific steel, and therefore a "ductility" criterion was proposed as a more general criterion for toughness [10].

All of the criteria for toughness from a C_v specimen, energy, shear, and lateral expansion, are manifestations of the plasticity involved in the fracture of a Charpy specimen, and therefore they are all interrelated [11]. Unfortunately such metallurgical parameters as microstructure influence the relationships to a greater extent than mechanical parameters such as yield strength (Fig. 1). The cause of the variations in the correlation of energy to lateral expansion, as shown in Fig. 1, makes any criterion from a C_v specimen difficult to interpret except a very low value (<10 ft-lb [<14 J]), which indicates that the material is brittle. Similar problems have been found in attempts to correlate results with fatigue cracked C_v specimens to K_{Ic} values where an overestimation of toughness by a factor of 2 can be made when the C_v specimen enters the elastic-plastic regime [12,13].

The Drop-Weight-Nil-Ductility-Transition (DWT-NDT) temperature test was developed to provide a reliable index to the start of the transition region. In other words, below the NDT temperature, dynamic toughness is so low that small cracks can initiate cleavage fractures that can destroy a structure catastrophically. The DWT-NDT test was the first standardized test to use a specimen with a natural crack for the notch. Based upon the size of this crack and a bending load, the break to no-break index is equivalent to K_{Id}/σ_{yd} = 0.5 [14]. This level of toughness requires a section at least 5/8-in. (16-mm) thick to provide a plane-strain fracture condition, and this limitation in specimen thickness and the singular

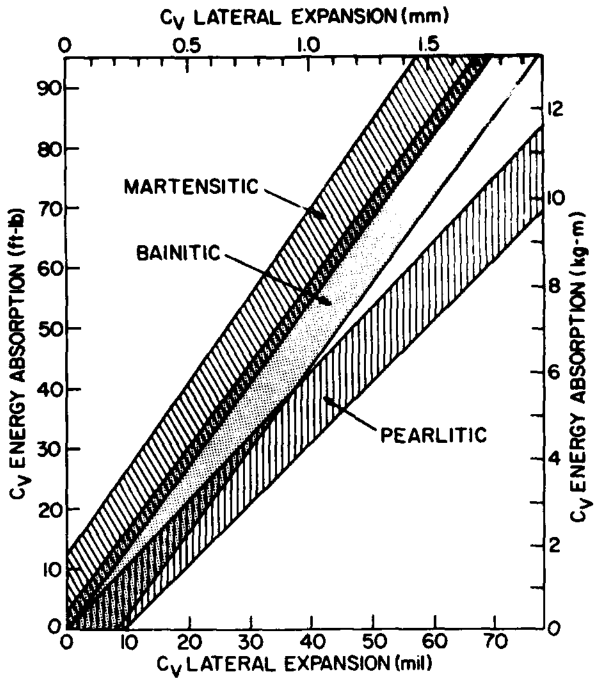
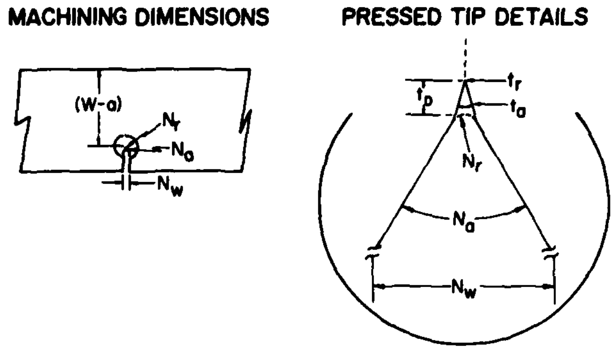


Fig. 1 — The effect of microstructure on the relationship between the energy and lateral expansion of Charpy *V*-notch specimens

index to the start of the temperature-transition region are limiting features of the DWT-NDT test. In addition, the DWT-NDT test uses a brittle-weld bead as a crack starter, and the heat of welding may improve the properties of the base material in the heat-affected zone and arrest the small pop-in crack. Thus, the DWT-NDT can only be used reliably with steels having a pearlitic microstructure.

The Drop-Weight Tear Test (DWTT) has been widely used for the assessment of the percent shear fracture in line-pipe steels. Problems emerge when the test is extended to sections thicker than the current 0.75-in. (19-mm) limit or when an energy measurement is attempted [15]. This is partially due to the relatively shallow notch in the specimen which makes the net section deform plastically prior to the initiation of the fracture even in thin specimens. This action simulates the mechanics of a crack propagating in a pipe, and it probably accounts for the correlation between cracks arresting in certain line pipes when the fracture is greater than 80-percent shear. The DWTT is relatively simple to perform, but the results must be directly correlated with structural performance, because there is no correlation between appearance and the analytical parameters for toughness, such as K_{Ic}.

The test that was developed for broad range measurement of fracture toughness is the Dynamic Tear (DT) test. The key features in the design of the DT specimen are the notch and the net section. A machined notch with a sharp tip (Fig. 2) effectively simulates a crack without the expense of growing and controlling a uniform fatigue crack in low-strength metals. The pressed tip with <0.001-in. (<0.025-mm) root radius was extensively studied



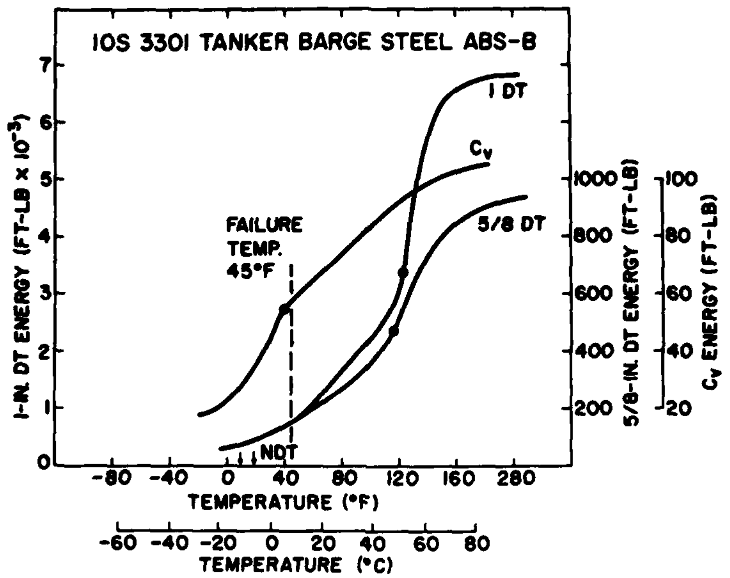
DIMENSIONS AND TOLERANCES FOR NOTCH TIP			
PARAMETER	UNITS	DIMENSION	TOLERANCE
NET WIDTH (W-a)	IN. MM	1.125 28.5	± 0.020 ±0.5
MACHINED NOTCH WIDTH, N_w	IN. MM	0.0625 1.60	± 0.005 ± 0.12
MACHINED NOTCH ROOT ANGLE, N_a	DEGREES	60	±2
MACHINED NOTCH ROOT RADIUS, N_r	IN. MM	0.005 0.13	MAX. MAX.
PRESSED TIP DEPTH, t_D	IN. MM	0.010 0.25	±0.005 0.12
PRESSED TIP ANGLE, t_a	DEGREES	40	±5
PRESSED TIP ROOT RADIUS, t_r	IN. MM	0.001 0.025	MAX. MAX.

Fig. 2 — Detail design of the notch in a Dynamic Tear specimen (ASTM E604)

by the ASTM committee that standardized the specimen. As with all toughness tests for steels conducted at temperatures in the transition region, the reproducibility of test results depends upon the alloy and the microstructure in the various product forms [16]. The net section of the DT specimen is nearly equal to twice the thickness that provides a sufficiently long fracture path for the crack to develop its natural shape. This design feature also allows the plastic-zone size to fully develop and expands the energy range in the elastic-plastic regime.

The importance of specimen design on toughness characterization has been demonstrated many times by the data generated in failure analysis. One recent example will be given here to illustrate the analytical capability of the DT test and the difficulty in relating C_v data to structural performance. From average C_v and DT data, the transition-temperature characteristics of the ABS-B and ABS-C steels that were respectively in the deck and gunnels of the Tank Barge IOS 3301 being propelled by the Motor Vessel *Martha Ingram* are presented in Fig. 3. This barge fractured in a catastrophic manner from a fast propagating crack that started from a small flaw at the toe of a reinforcement weld on the deck [17].

The failure temperature of the barge was 45°F (7°C), which was 20° to 30°F (11° to 17°C) above the NDT temperature. For both steels, the fracture surface was less than 20-percent shear in appearance. This low-toughness behavior can be seen by the shape and



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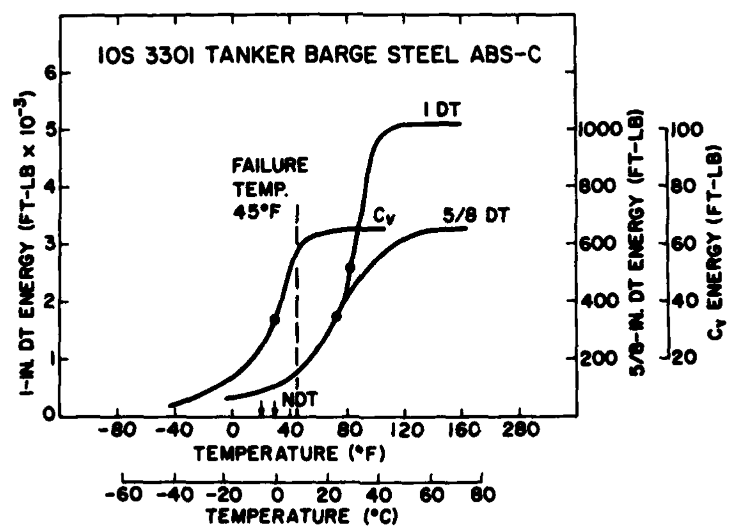


(b)

Fig. 3 — The effect of specimen design on the toughness characterization of the ABS-B (a) and ABS-C (b) steels in the Tank Barge IOS 3301 that fractured catastrophically on Jan. 10, 1972

position of the DT energy curves for the full section, 1 in. (25 mm), and the 5/8-in. (16-mm) specimens. In the Class B steel, only a slow rise in toughness occurred above the NDT temperature until the midtransition temperature was reached, and then toughness increased sharply with temperature. In contrast, the increase in C_v energy was very pronounced at the NDT temperature; in fact, the C_v energy for the ABS-B steel at the failure temperature was 55 ft-lb (75 *J*). This high value is not normally associated with fractures that initiate from small flaws. Note that the C_v energy of the ABS-C steel (as rolled) in the gunnels was even higher, 60 ft-lb (81 *J*), at the failure temperature. The fracture appearance of the fracture in the C_v specimen was more than 90-percent shear while the fracture appearance of the steel in the structure was less than 20-percent shear. The data from the C_v, DWT-NDT, and DT tests for these two conventional structural steels illustrate the need for proper specimen design when toughness in the temperature-transition region is being determined for characterization purposes.

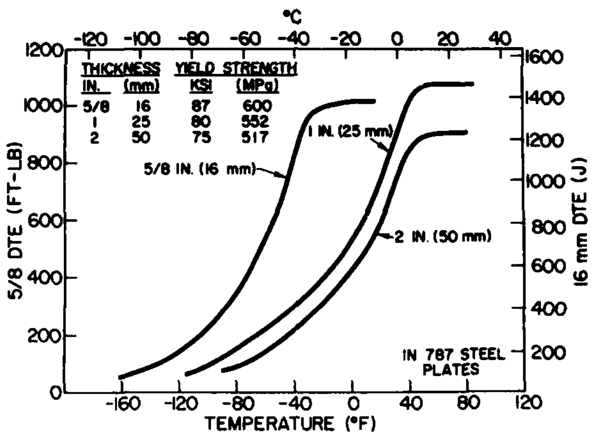
Toughness-characterization studies must also consider the metallurgical effects of mechanical processing when specific alloys are evaluated. The metal-processing effects are especially important when mechanical properties are subsequently developed by heat treatments such as quench-and-temper (Q&T) or quench- and age (Q&A). The variations that can occur in the temperature-transition characteristics of the same alloy in various product forms are illustrated in Fig. 4 for alloy IN 787. This alloy has recently been given the ASTM designations of A710 for plate and A707 for forgings.

In Fig. 4(a) are shown the temperature transition features of IN 787 steel in 5/8-, 1-, and 2-in. (16-, 25-, and 50-mm)-thick plates from the same heat of steel and the same aging heat treatment after rolling. Note that the midpoint in the DT energy transition of the 1- and 2-in. (25- and 50-mm) plates has shifted approximately 60°F (33°C) above that for the 5/8-in. (16-mm)-thick plate. The midtransition temperature of a 2-in. (50-mm)-thick section will occur at an additional 40°F (22°C) higher temperature, placing the midtransition temperature of a 2-in. (50-mm)-thick plate at 40°F (4.4°C). In this heat-treated condition, the thinner plates would have good toughness characteristics for fracture-critical structures in arctic locations, but a different heat treatment would be recommended for thick plates.

In Fig. 4(b), the temperature-transition features of IN 787 steel in two thick forgings are shown. Both forgings were given a Q&A heat treatment which may have accounted for the steepness of the transition region compared to that for the IN 787 steel in the plate products. Low carbon contents (<0.10 percent) are common to many HSAL steels, and steels with low carbon contents tend to have a narrow transition-temperature range, as seen in Fig. 4(b). Note also that there is a 50°F (28°C) shift in the location of the transition region for the steel in the insert-nozzle forging compared to that for the steel in the weld-neck flange. This is a significant variation in toughness, and it illustrates the need for good process control to maintain optimum mechanical properties in components of the HSLA steels.

CRITERIA FOR SPECIFICATIONS

The criteria used for fracture toughness in material specifications do not necessarily have to relate to a specific level of structural performance. The criterion selected for many steels, such as a 20-ft-lb (27-*J*) value or a 0.015-in. (0.38-mm) lateral expansion value for a C_v specimen, is an arbitrary measure of a minimum quality with no relationship to the



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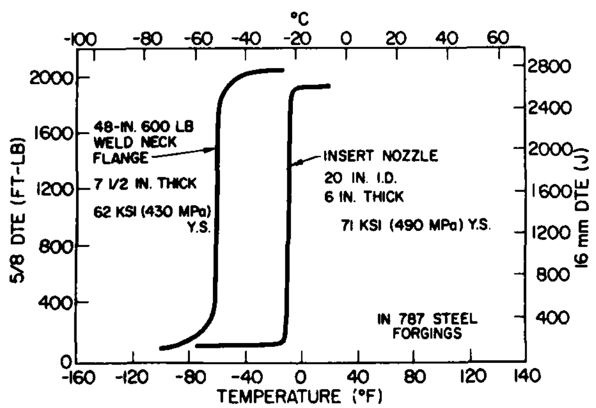


(b)

Fig. 4 — The effect of metal processing on the toughness characteristics of high-strength, low-alloy steel IN 787: (a) plate products, ASTM A710-Gr. A; (b) forgings, ASTM A707-Gr. L5

performance of the material in a structure. Since a variety of products is usually covered in a material specification, and they may be used in a wide range of structures, it is not practical for a toughness criterion in a general specification to be quantitative.

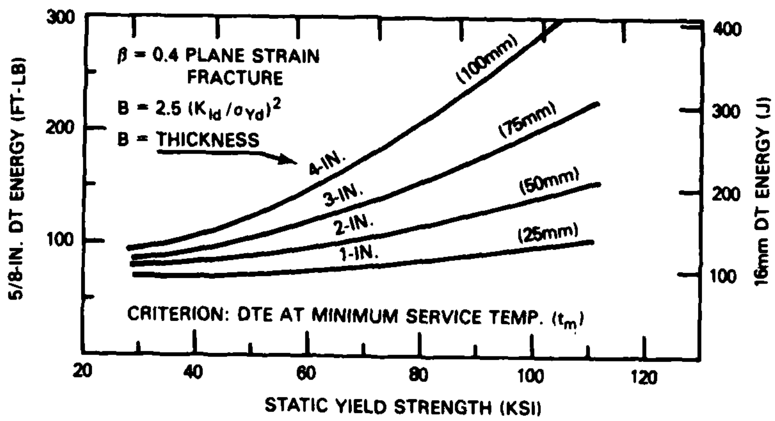
Toughness criteria in military specifications, such as MIL-S-16216 for HY-80 steel which is used in critical military structures, are more restrictive than toughness criteria in industrial specifications. For example, the 50-ft-lb (68-J) C_v energy at -120°F (-84°C) criterion in MIL-S-16216 for HY-80 steel ensures that this material in plate sections up to 2 in. (50 mm) thick will have a fully ductile performance at ice-water temperatures. This high level of performance is needed for combatant structures, but it would be excessively conservative for most conventional structures. Except for regulated structures, such as nuclear pressure vessels, or structures designed to the minimum standards fixed by some codes or rules, the minimum level of performance is a matter of engineering judgment that can only be set by the design engineer, and he should have all of the necessary information to make a proper judgment.

It was previously stated that using materials with high levels of fracture toughness is the economical way to achieve a high level of structural performance [4]. Although high-quality materials may be a good investment, they are not always available, and a selection must be made from alternative materials. When a fracture-safe level of toughness cannot be ensured (plastic regime), a certain minimum toughness level is selected, and structural integrity can be assured by surveillance procedures that preclude cracks from becoming critical in size. The other alternatives to structural integrity are redundancy or low nominal stresses.

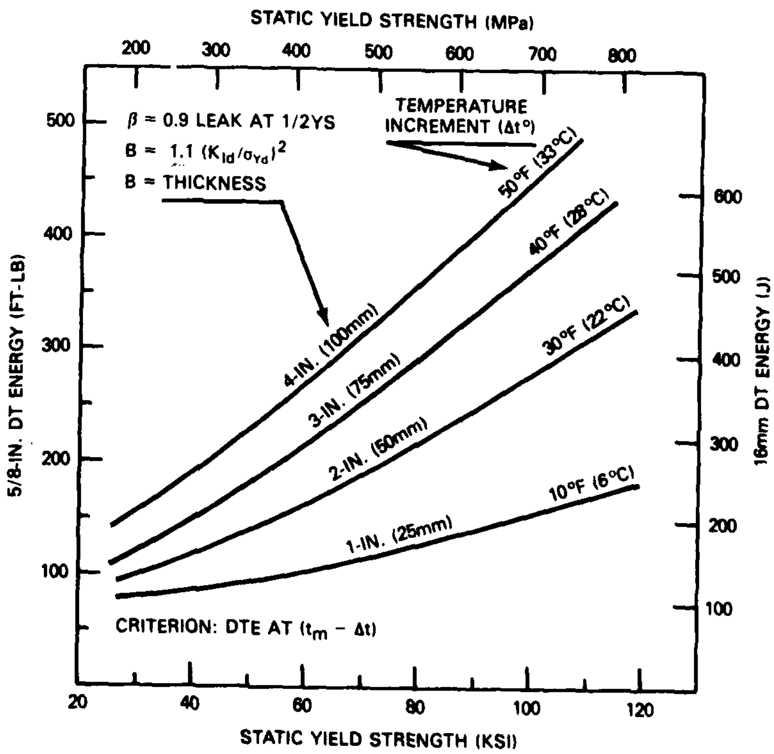
Operating welded structures below the transition region of the material is hazardous, because of the small size of critical pop-in flaws. Therefore, a good minimum level for toughness in highly stressed but not fracture-critical structural members is the dynamic plane-strain limit. For example, this means the NDT temperature of the steel should be below the minimum service temperature when sections are between 5/8 in. (16 mm) and 1.5 in. (38 mm) in thickness. For thicker sections with potentially larger pop-in cracks, the plane-strain limit is some increment above the NDT temperature. The DT energy that corresponds to the plane-strain limit (β = 0.4) for the conventional structural steels is shown in Fig. 5(a). The DT values were obtained from an empirical relationship between K_{Id} and DT energy [8]. The applicability of these relationships for HSLA steels has not been investigated, but they can serve as a guide where specific correlations are not available.

For fracture-critical members, the index of performance should be higher than the plane-strain limit, for example, a β = 0.9 level. This criterion has been recommended because it provides better protection from undetectable flaws, and it is a readily understandable structural-performance criterion [1]. This criterion implies that under a tensile load with nominal stress at 1/2 σ_{ys} a flaw can grow until it penetrates the section before it becomes critical. This large a flaw should be detected before it becomes critical and initiates an unstable fracture, and any small pop-in flaw will be arrested. For complex structural details, such as welded intersections, the thickest section should be considered as the controlling thickness.

The DT energy values for conventional steels that provide a β = 0.9 level of performance are shown in Fig. 5(b). Note that the DT energy index for sections thicker than 5/8 in. (16 mm) requires an adjustment in temperature as well as increased DT energy. The reason



(a)



(b)

Fig. 5 — Relationship between Dynamic Tear energy and structural performance at $\beta = 0.4$ (a) and $\beta = 0.9$ (b) levels for steels ranging in yield strength from 30 to 110 ksi (210 to 760 MPa)

for the temperature adjustment is that the $\beta = 0.9$ index is in the upper portion of the elastic-plastic regime where the fracture mode is affected by the constraint condition. Therefore, for the same *relative* performance a thick section must have a higher level of toughness than a thin section. The requirements of this index will not be met by conventional, normalized structural steels in sections thicker than 2 in. (50 mm) at -40°F (-40°C), but it is hoped that the HSLA steels with finer grain size from processing will have improved low-temperature properties. The HSLA steels have great potential for fracture-critical applications, because the alternative is to use more highly alloyed Q&T steels with sufficient hardenability to quench to a martensitic microstructure.

SUMMARY

Fracture-mechanics technology and the critical features of the ASTM standardized test methods for toughness measurements have been reviewed. Accurate toughness characterization is needed for a structural-integrity analysis, and the relationship of the results from Dynamic-Tear tests to linear-elastic-fracture-mechanics parameters and other performance criteria was given. Toughness criteria used in material specifications do not necessarily relate to structural performance, but the application requires a certified level of performance. Certification of a high level of structural performance will justify the use of high-quality materials.

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