

FRACTURE TOUGHNESS IN RELATION TO STEEL CASTINGS DESIGN AND APPLICATION

by

W. J . Jackson

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ABSTRACT

The purpose of this paper is to demonstrate the value of fracture mechanics in steel casting design and material selection, and to point out the significance of defects, especially with regard to brittle fracture and fatigue crack growth. While it has been necessary to include some background theory and mathematical concepts, these have been kept to a minimum; emphasis is placed on the practical use of fracture toughness criteria for establishing safety levels for particular service applications and on the implications of the fracture mechanics approach for the steel founder.

INTRODUCTION

Castings are individual products; they are inspected individually for discontinuities which must be repaired or the casting rejected. In many engineering applications castings tend to be "over designed", i .e. the safety factors are unnecessarily generous where it can be shown that any defects present are not critical. Design rules, to avoid the possibility of fast fracture, are not the only constraints on total castings design, but they are often the greatest constraint and the least quantitative. A successful fracture mechanics approach to design would encourage production of castings of better fitness for purpose, and generally lighter section, if this were desirable for other than safety reasons.

FACTORS OF SAFETY AND BRITTLE FRACTURE

Traditionally, design calculations are based on the theory of elasticity, and therefore utilize standard formulae, which assume that the material is elastic, homogeneous and isotropic. For non-critical components, it is usually sufficient to base the design on average stresses, but with critical components it may be necessary to take account of severe stress service conditions, and obtain the local stress distributions by theoretical or experimental stress analysis techniques. The design stress is related to either the yield stress, or the U.T.S., by means of a factor of safety. This single factor which is usually a product of several contributory factors, accounts for local stress fluctuations, variations of service loading conditions, scatter in material properties and environmental effects. The choice of the factor of safety depends on the experience and judgement of the designer unless it is implicitly stated in a relevant specification or design code.

For ductile materials and static loading conditions, the factor is related to the yield of 0.2% proof stress. Local stress concentrations may usually be ignored, because they are relieved by plastic deformation. The minimum safety factor for steel castings based on the U.T.S. is usually taken as 4, but design engineers, uncertain of the quality of the steel and unfamiliar with the reliability of steel castings, have in the past used additional safety factors of 2 to 5 or more. These exaggerated safety factors are rendered largely unnecessary by the wide range of non-destructive tests which can be applied to steel castings and by the data

now available, even ignoring recent fracture toughness data. This is reflected in the magnitude of the quality factors applied to steel castings to modify the safety factors for boilers and pressure vessels.

The essence of the fracture toughness approach is to quantify an acceptable degree of unsoundness in a steel casting for a given application and not to attempt to agree on what constitutes complete soundness. A fracture toughness approach offers the possibility of distinguishing the ability to resist fast fracture from other constraints such as plastic collapse and, sometimes, buckling.

Not all ductile failures involve fracture. The ductile failure is predictable because the necessary load required for a ductile fracture can be calculated or estimated. From a macroscopic viewpoint, a ductile fracture exhibits the following characteristics:

- a) a large amount of plastic deformation precedes the fracture
- b) shear lips may be present;
- c) the fracture may appear to be fibrous, or have a matte or silky texture;
- e) the cross section at the fracture may be reduced by necking; and crack growth will be slow.

Brittle failures cannot be predicted by simple engineering calculations. Because of their catastrophic and unexpected nature, much research has been done in trying to control this problem. From a macroscopic standpoint, brittle fractures are characterized by the following:

- a) little or no plastic deformation precedes the fracture;
- b) the fracture is generally flat and perpendicular to the surface of the component;
- c) the fracture may appear granular or crystalline and is often highly reflective to light. Facets may also be observed, especially in coarse-grained steels; and
- d) herringbone, or chevron, patterns may be present and cracks propagate rapidly.

When notched, mild steel can be made to fracture in either a brittle or a ductile manner merely by altering the temperature. Even if a notch is not made deliberately, a small crack can be initiated within a metal, as in the case of a polished fatigue specimen, by a process of grain boundary movement or slip. Cracks are also initiated at elevated temperatures when a steel is under creep conditions. Such cracks may be very small but will have extremely sharp extremities. With steels generally, initiation of brittle fracture is more difficult than propagation, given the same operating conditions. Most structures, such as bridges, ships, storage tanks, pressure vessels, are designed on the basis of defect-free materials, with appropriate factors of safety based mainly on past experience. By applying fracture mechanics a more realistic approach can be made, accepting that no metal is defect-free and calculating the size of defect that can be tolerated without it propagating in a brittle manner. The toughness of the steel obviously influences the propagation or arrest of a crack and in practice the problem is one of defining toughness, deciding by which tests it should be assessed and what level should be specified.

The Charpy V-notch impact test has had considerable success in providing the designer with some idea of the relative notch-toughness of various materials. The main advantage of this test is that the specimen used is relatively small, but it has the disadvantage that a measure of transition temperature is obtained only for the prevailing conditions. The Charpy V-notch transition temperature can also be shifted by a change in specimen size, a change in notch configuration and a change in the rate of loading. It follows that the Charpy V-notch test has the following disadvantages when the results are applied to practical design:

- a) The Charpy V-notch impact test does not reproduce the triaxiality that occurs in thicknesses greater than 10 mm (.39 in.);
- b) the notch is blunt by comparison with natural cracks;
- c) it is an impact test, and the majority of brittle failures in service occur under static conditions; and
- d) the material tested is usually taken from a test sample that is not always entirely representative of the material as a whole.

Consequently, Charpy test results cannot be used to determine a safe working temperature for service application, or safe design against brittle fracture. More sophisticated types of test are required and linear elastic fracture mechanics (LEFM) has been found useful for predicting, in terms of a single parameter, the fracture stress of components containing sharp flaws.

FRACTURE MECHANICS

Fracture mechanics is a useful method of characterizing fracture toughness, fatigue crack growth, or stress-corrosion crack growth behavior in terms of structural design parameters familiar to the engineer, namely stress and flaw size. Fracture mechanics is based on a stress analysis and does not depend on the use of service experience to translate laboratory results into practical design information (as does the Charpy V-notch test, for example).

The theory of linear elastic fracture mechanics (LEFM) has been developed in terms of a stress intensity factor (K) determined by stress analysis, and expressed as a function of stress and crack size, namely $(\text{stress}) \times (\text{length})^{1/2}$. The basic assumption is that crack propagation will occur when the strain energy release rate, or the stress intensity at the crack tip (K_c), reaches a critical value. There are three modes of fracture, mode I being identified as the opening mode, in which the crack surfaces move opposite and perpendicular to each other (as when opening by driving in a wedge). This mode is the most important from the low stress fracture point of view and has been studied more extensively than modes II and III, which involve sliding and lateral tearing respectively.

Plane strain is defined as a state of two dimensional strain, there being no strain in the through-thickness direction, that is, it is a state of triaxial stress. The ideal conditions of stress are not usually realized in practice and a mixed mode state of stress exists. Even in very brittle fractures, some plastic flow may occur at the tip of a sharp defect. In order to establish the critical stress intensity by linear elastic fracture mechanics, the plastic zone must be kept small in comparison to the other dimensions of the specimen. For essentially plane strain conditions, the inherent fracture toughness of a material can be expressed in terms of the critical value of the stress intensity factor

K_{IC} at which crack instability occurs. The value of K_{IC} has to be determined experimentally but, once properly determined under one set of conditions, it is equally applicable to other conditions. The value of K_{IC} does, of course, vary markedly with metallurgical variables, such as steelmaking practice and inclusions, heat treatment and microstructure, but it can be used to compare steels of different strength levels by use of the parameter

$$\left(\frac{K_{IC}}{\sigma_y} \right)^2$$

which is not possible in the case of approaches based on transition temperature.

To summarize:

K_C = Critical stress intensity factor for static loading and plane stress conditions of variable constraint. Thus, this value depends on specimen thickness or shape.

K_{IC} = Critical stress intensity factor for static loading and plane strain conditions of maximum constraint. Thus this value is at a minimum for thick sections.

K_Q = A provisional value of K_{IC} before all compliance tests have been applied.

It is emphasized that the preceding discussion has been confined to linear elastic fracture mechanics (LEFM), in which the fracture resistance of a material is defined in terms of the elastic stress field intensity near the tip of a crack. In fact, the fracture toughness parameter K_{IC} is valid only when determined under conditions which prevent significant yielding at the crack tip. Such conditions are difficult to achieve in practice for the lower strength steels commonly used for structural purposes. It is usual, therefore, in these steels which exhibit yielding at a crack tip before fracture occurs, to speak in terms of yielding fracture mechanics (YFM); the concept of crack opening displacement has been introduced as a measure of toughness in these circumstances. The crack opening displacement (COD or δ) is the actual distance that the two opposite faces of the crack tip move apart before failure occurs and the critical value is referred to as δ_c . The relationship to critical flaw size (a_{crit}) is given by the equation:

$$a_{crit} = c \cdot \frac{\delta_c}{e_y}$$

where e_y is the strain at yield and c is a material constant.

Another method of treating YFM is called the J-integral, which is the average measure of the elastic-plastic stress/strain field ahead of a crack. For elastic behavior (i.e. plane strain), the J-integral is represented as the energy release rate (J_{IC}) per unit crack extension, thus

$$J_{IC} = \frac{(1 - \nu^2) K_{IC}^2}{E}$$

where E is Young's Modulus and ν is Poisson's ratio. The relationship between J-integral, and δ may be expressed as follows:

$$\delta = \frac{J_{IC}}{\sigma_y}$$

For steels which are on the borderline for treatment by either LEFM or YFM, a unified test technique can be used to determine K_{IC} or δ_c from a single test piece. For elastic behavior, the following relationship has been developed:

$$\frac{\delta_c}{e_y} = \left(\frac{K_{IC}}{\sigma_y} \right)^2$$

Thus, the ratio $\frac{\delta_c}{e_y}$ in YFM is comparable to

$$\left(\frac{K_{IC}}{\delta_y} \right)^2$$

in LEFM, i.e. it is a measure of the defect tolerance of a steel. The COD test, whilst preferred in the UK for welds, is not universally acceptable and for low strength, tough cast steels, the NDTT approach using the drop-weight test (ASTM E208) is preferred.

In an article of this nature, it is not necessary to describe the detailed techniques of testing to determine K_{IC} and δ_c . Standard methods are available^{1,2} and an extensive literature exists giving practical and theoretical details concerning the testing parameters³⁻¹⁰. The tests are expensive to carry out because of the machining and preparation of the test pieces and also because of the precise instrumentation needed to measure the test parameters. A view of the servohydraulic machine used at SCRATA to carry out fracture toughness tests is shown in Fig. 1.

Research work is currently in progress at SCRATA to establish for cast steels the compatibility between K_{IC} , δ_c , J and other fracture parameters, which allow for a direct extension of LEFM concepts to YFM behavior. Some results from recent work are shown in Fig. 2 for a 0.34%C plain carbon steel and in Fig. 3 for 0.54%C plain carbon steel. It can be seen that the J-integral analysis gave toughness values far in excess of the K_Q values.⁽¹¹⁾

In the case of low-alloy steels, where the advantage of using J-integral only lay in the use of smaller specimens, there was closer correspondence of results⁽¹²⁾.

Calculation of Critical Flaw Size

Critical flaw sizes can be calculated with reasonable accuracy using experimentally determined fracture toughness (K_{IC}) values. The critical size will also depend on the flaw shape and location, and, additionally, the applied or working stress (σ_w) must be known. For surface flaws, the equation is:

$$a_{crit} = K_{IC}^2 \left[\frac{\phi^2 - 0.212 \left(\frac{\sigma_w}{\sigma_y} \right)^2}{1.21 \pi \sigma_w^2} \right]$$

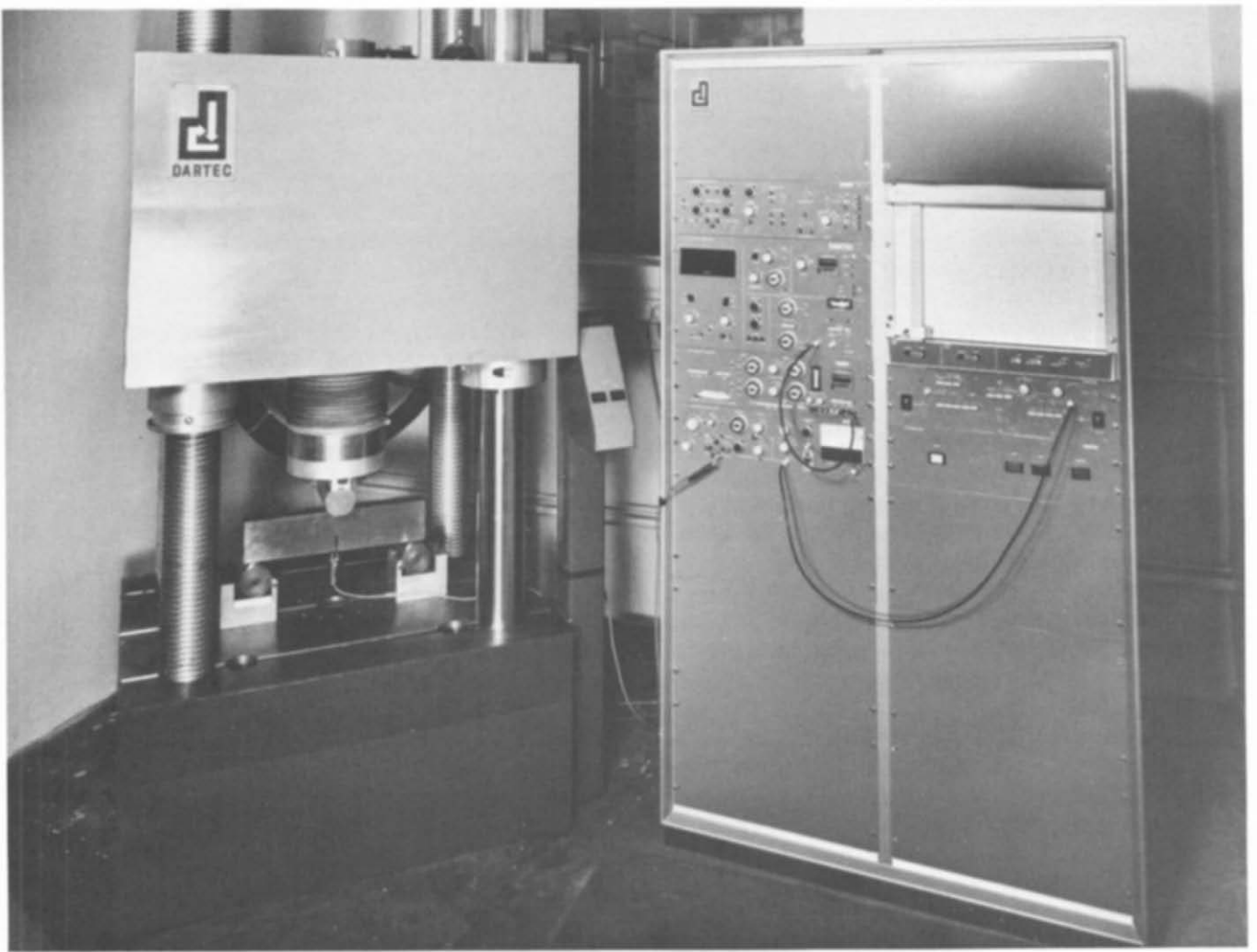


Figure 1—Servo-hydraulic fracture toughness testing at SCRATA

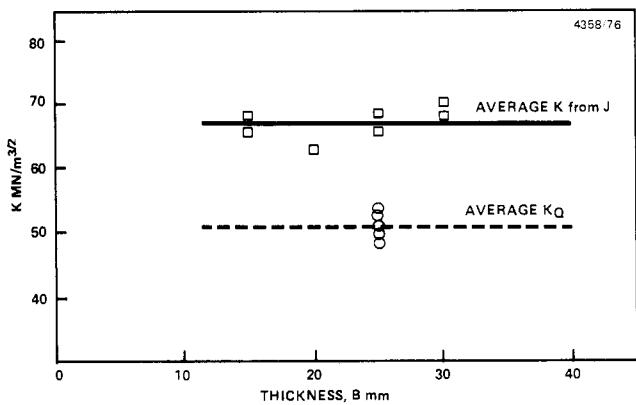


Figure 2— K_{Ic} values derived from J at fracture initiation for a 0.34%C steel, compared with K_Q values

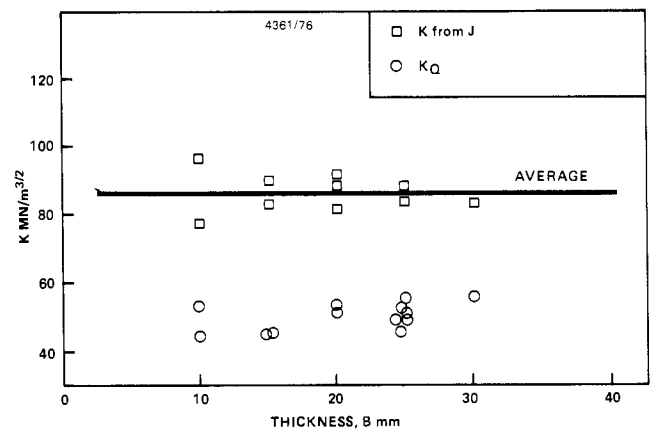


Figure 3— K_{Ic} values derived from J at fracture initiation for a 0.54%C steel, compared with K_Q values

For internal or embedded flaws, the coefficient 1.21 is taken as unity, i.e. internal flaws are less severe than surface flaws. Basic relationships for various crack geometries are given in Fig. 4. A sample calculation for determining the critical flaw size in a casting is given in Appendix I. Typical values of critical flaw size for widely differing types of cast steel have been calculated in Table IA for a range of flaw geometries and typical working stresses expressed as fractions of the actual yield or (0.2% proof) stress of the steel.*

These results have been plotted to show graphically some important features of the data, In Fig. 5, for a range of critical flaw sizes from sharp to rounded, it can be seen that at low working stresses flaws may be relatively large before they become of critical size and that a fully rounded flaw of nearly twice the size of a sharp flaw can be tolerated. At higher stresses, however, (e.g. 0.8 x yield stress) critical flaw sizes become very small, in fact less than 10 mm (.39 in.) for the steels illustrated, but the statement is generally true for cast steels which are amenable to the linear elastic fracture mechanics (LEFM) approach.

Subcritical Flaw Growth by Fatigue and Stress Corrosion

Fatigue failure is a three-stage process of initiation, propagation and fast fracture. The latter occurs when a crack has reached a critical defect size for the stress level applied. In the absence of defects, the initiation stage may occupy a large percentage of a component's life. When defects are present, the crack initiation stage becomes relatively unimportant since most of the life will be spent in the crack propagation stage.

The flaw growth rate, da/dN , under conditions of fluctuating working stress, may be measured in terms of the increase in length per cycle. This allows prediction of the number of cycles necessary to grow the initial flaw (a_i) to the critical flaw size (a_{crit}).

The rate of fatigue crack propagation is related to K by:

$$\frac{da}{dN} = c \cdot \Delta K^n$$

where c and n are material constants ⁽¹⁴⁾. The latter have been determined for a number of cast steels with both machined and cast-to-shape notches (Table IB) ^(15,16). Curves for the crack propagation rate of several steels are given in Fig. 6; one of the steels, represented by a dotted curve, contained Type II sulphide inclusions and the increased rate of crack propagation is clearly seen.

In general, it is not possible to predict the life between a_i and a_c unless the initial flaw is sharp. If it has a finite radius, p, then there is a dwell time, i.e. a number of cycles elapse before commencement of growth. The number of cycles to crack initiation, N_i , may be calculated from the following expression

$$N_i = B \left(\frac{\Delta K}{\rho^{\frac{1}{2}}} \right)^m$$

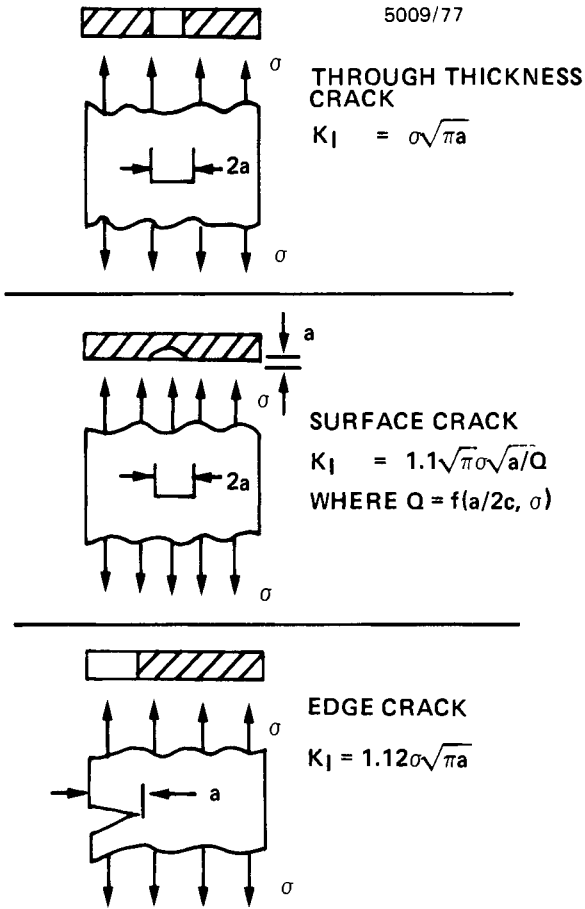


Figure 4— K_I values for various crack geometries

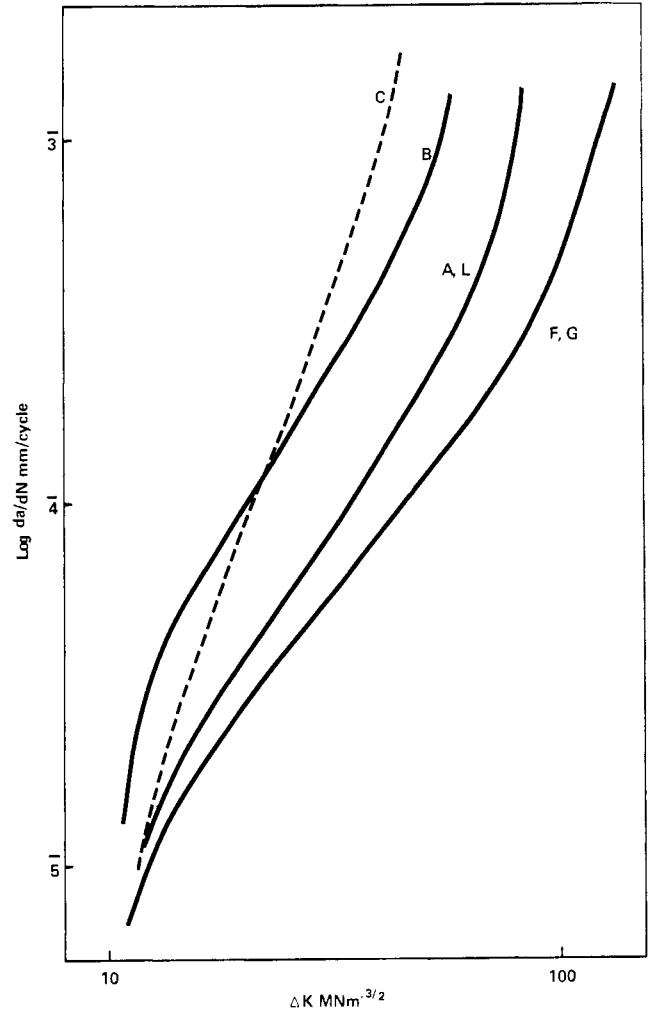


Figure 6—Fatigue crack propagation curves for six steels (A= 1 1/2% Mn, B= 1/2% Cr-1/2% Mo-1/4% V, C= 1 1/2% Mn-3/4% Ni-1/2% Cr-Mo, F= 1 1/2% Mn-Mo, G= 1 1/2% Ni-Cr-Mo, L= 0.54% C)

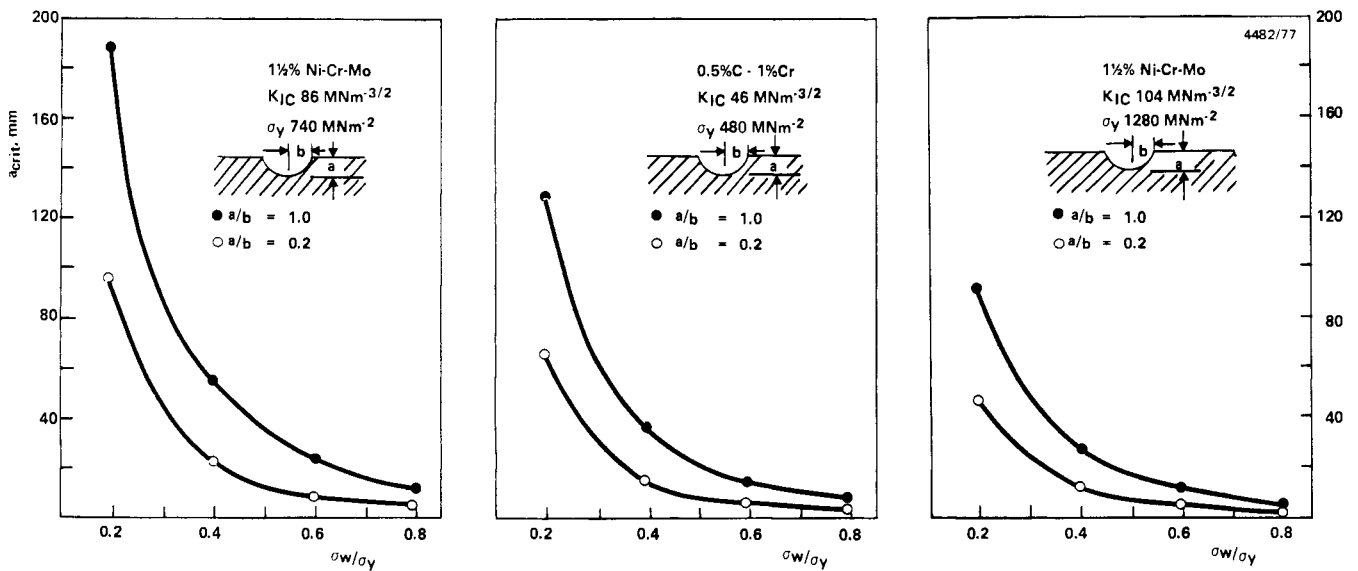


Figure 5—Effect of working stress/yield ratio on critical size of surface defect for three steels of different fracture toughness (K_{Ic})

TABLE 1A—CRITICAL FLAW SIZES FOR THREE CAST STEELS

Position of flaw	Flaw aspect ratio a/b	0.5% C - 1% Cr steel $K_{Ic} 46 \text{ MNm}^{-3/2}$ $\sigma_y 480 \text{ MNm}^{-2}$ $a_{crit}, \text{ mm}$ for σ_w/σ_y of:-				1 1/2 Ni-Cr-Mo steel $K_{Ic} 86 \text{ MNm}^{-3/2}$ $\sigma_y 740 \text{ MNm}^{-2}$ $a_{crit}, \text{ mm}$ for σ_w/σ_y of:-				1 1/2 Ni-Cr-Mo steel* $K_{Ic} 104 \text{ MNm}^{-3/2}$ $\sigma_y 1280 \text{ MNm}^{-2}$ $a_{crit}, \text{ mm}$ for σ_w/σ_y of:-			
		0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8
Surface	0.2	67	16.3	6.9	3.7	98	23.9	10.2	5.4	48	11.6	5.0	2.6
	0.4	79	19.4	8.3	4.5	116	28.6	12.3	6.5	57	13.9	6.0	3.2
	0.5	88	21.5	9.3	5.0	129	31.8	13.7	7.3	63	15.4	6.7	3.6
	0.6	101	25.0	10.5	5.8	149	36.6	15.4	8.5	73	17.8	7.5	4.2
	0.8	121	30.0	13.0	7.0	178	44.0	19.1	10.3	87	21.4	10.0	5.1
	1.0	129	37.0	16.3	9.0	190	54.3	24.0	13.2	93	26.4	11.7	6.4
Embedded	0.2	81	19.5	8.4	4.4	118	28.9	12.4	6.5	58	14.1	6.0	3.2
	0.4	96	23.5	10.1	5.4	128	34.5	14.9	8.0	69	16.9	7.2	3.9
	0.5	106	26.2	11.2	6.1	156	38.4	16.6	8.9	76	19.0	8.1	4.4
	0.6	122	30.2	12.7	7.1	180	44.3	18.6	10.4	88	21.6	9.1	5.1
	0.8	145	36.3	15.7	8.6	216	53.2	23.1	12.6	105	26.0	11.3	6.2
	1.0	157	44.7	19.7	10.8	230	65.7	29.0	16.0	113	32.0	14.1	7.8

* Vacuum melted.

TABLE 1B—'c' AND 'n' VALUES FOR FATIGUE PROPAGATION FOR NOTCHED CAST STEELS

Steel type	'c'		'n'	
	Machined	Cast	Machined	Cast
1 1/2% Mn	10 ^{-7.0}	10 ^{-7.0}	2.07	2.07
1/2% Cr-1/2% Mo-1/4% V	10 ^{-6.5}	10 ^{-6.55}	2.11	2.11
Mn-Ni-Cr-Mo	—	10 ^{-6.7}	—	1.98
1 1/2% Mn-Mo	10 ^{-7.1}	10 ^{-6.6}	1.94	2.00
1 1/2% Ni-Cr-Mo	10 ^{-6.7}	10 ^{-6.7}	1.80	1.80
0.5% C	10 ^{-6.9}	10 ^{-6.9}	2.09	2.09

where B and m are material constants. Values for cast steels have been determined^(15,16).

In addition to subcritical crack growth by fatigue, growth can occur by stress-corrosion. Again there is the problem of separating initiation and propagation, but this can be overcome in the laboratory by testing pre-cracked samples. A stress-corrosion stress intensity limit K_{ISCC} can be determined and used in place of K_{IC} to calculate the critical crack size below which stress-corrosion may be ignored.

APPLICATION OF FRACTURE MECHANICS

The elements of fracture mechanics may be summarized in the form of a triangle having at its apexes the parameters: working stress (σ_w), fracture toughness (K_{IC}) and critical flaw size (a_{crit}). If two of the three parameters are known, the third can be calculated; this simple concept emphasizes the importance of being able to accurately measure the size of a discontinuity. Furthermore, the designer does not always know exactly the magnitude and distribution of the stresses in a component and it is obvious why a safety factor has to be applied. But residual stresses in a casting can be of a surprisingly high order before the working stress is applied. Consequently, some knowledge of the magnitude of possible residual stresses is essential.

In many heavy engineering applications steel castings tend to be "over-designed", unnecessarily high safety factors being specified when it can be shown that the discontinuities present are not critical. In this event, discontinuities of certain sizes can be tolerated but the smaller the factor of safety, the smaller will be the acceptable discontinuity size. In many cases it is more economical to use thinner sections and put a limit on the size of the discontinuity; in other cases, if a critical flaw size is known, it may be more economical to select thicker sections and to leave subcritical discontinuities rather than to excavate and weld. Due consideration must be given at all times to the type of service for which the casting is destined, e.g. static or dynamic stress, temperature of operation, neutral or hostile environments, and the possibility of misuse during service. No more than the desired quality need be "built in" and this is the basis of the concept "fitness for purpose". For this concept to be operated properly, the relevant factors must be quantified, and this is the underlying aim of the work being carried out at SCRATA in this field at the present time. It is apparent that fracture mechanics can be used in three major areas: (i) design; (ii) material selection and alloy development; and (iii) determining the significance of defects. Ancillary areas are (iv) monitoring and control, and failure analysis. Each of these items will be enlarged upon.

Design

Conventional design procedures are based upon the yield strength or ultimate tensile strength. This approach was considered to be relatively safe when appropriate safety factors were used. Instances where unstable fracture occurred at stresses below the yield stress however necessitated making provision for such circumstances. Fracture mechanics provides this alternative in terms of the K_{IC} value, but cyclic stressing and fatigue crack growth rate also have to be taken into account. Factors of safety can then be used on the initial defect size, the working stress, and/or the anticipated number of loading cycles.

An example of the practical application to design may be given in the main structural framework of the Beaubourg Centre, Paris, France⁽¹⁷⁾. The design of the Beaubourg Centre was the subject of an international architectural competition, launched in 1971. Of the 681 schemes submitted, the winning architects were Piano and Rogers, and the winning engineering design was that of Ove Arup and Partners. The latter were inspired to use steel castings in their design following a visit to Japan, where they saw spherical cast steel nodes in the three dimensional structures at "Osaka 1970" which possessed a clean simplicity rarely found elsewhere.

The Beaubourg building has six floors and is divided lengthwise into 13 bays, each measuring 12.8 x 48 m (42 x 157.5 ft.) and are uninterrupted by internal load-carrying columns. The floors are suspended externally by cantilever beams (steel castings) which hinge on to the main columns (see Fig. 7). Because cast steel was a new material to the design engineers, it was necessary to devise, in collaboration with the constructional engineers, new methods for testing and inspection. Ultrasonic testing of the nodes for the main girders is shown in progress in the production stage (Fig. 8). It was appreciated that some defects were inevitable in cast and welded components and that non-destructive tests could not be relied upon to reveal every shortcoming. The engineers decided, therefore, to base their specifications on fracture toughness tests using LFM (K_{IC}) and YFM (COD) where applicable. Moreover, it was appreciated that these were expensive tests and the decision was taken that results should be used to establish the order of quality of the materials at the start of production. The fracture toughness tests showed the cast steel exhibited the required standards of quality. After preliminary welding tests had indicated the correct welding procedures, ultimate tests to collapse proved that it was possible to attain satisfactory and, in some cases, excellent results.

Another example is the design against brittle fracture of a main coolant pump in a nuclear reactor primary circuit⁽¹⁸⁾. The housing was constructed from three C-1/2%Mo steel castings which were welded together to form a casing having wall thickness from 4 in. to 22 in. and weighing about 32 tons, after internal surfaces had been clad with stainless steel. Because of the high toughness of the steel, an LFM approach was not valid and COD and J-integral tests were carried out over a range of temperatures (-50 to +70°C) (-58 to +158°F). A good correlation between these parameters was found.

The finite element method was used to determine the stress fields for proof test loading and three service conditions, start, running and stop. An additional 10 N/mm² (1450 psi) was taken into account as a conservative estimate of residual stress. Critical defect sizes were calculated from COD, J and the non-valid K_Q the COD-derived values were considerably larger than those calculated from K_Q . It was apparent that K_Q was unable to take advantage of the extra ductility available in and beyond the transition temperature range and it was considered that for this application the tolerable defect sizes defined on the basis of K_Q were much too stringent.

The analysis carried out provided valuable information for design engineers, on the stress distribution and critical defect sizes in the castings. Charpy V-notch and drop-weight tests were also made and will be used in the future for quality control purposes.



Figure 7—Structure at the top of the Beaubourg Centre in Paris, showing cast steel nodes (Courtesy of Ove Arup and Partners).



Figure 8—Ultrasonic testing of nodes of main girders in the Beaubourg Centre

A further example of the fracture mechanics approach to design is in the field of power generation. In 1975, the London firm Boving & Co. Limited received an order from the Central Electricity Generating Board (UK) for six 300 MW reversible pump turbines to work under a head of 540 m (1771.7 ft.). The machines were to work in various modes, as pumps, turbines, and also to run with the runners blow down as spinning reserve. A life of 55 years with 15,000 mode changes each year was specified. Since many mode changes involved opening or closing the main inlet valve, this valve, the stay ring spiral casing, and the top and bottom covers were designed for 400,000 cycles, with a stress range corresponding to the pressure change when the valve opens to when the valve closes, equal to 575 m (1886.5 ft.). It is believed that this was the first time such a rigorous specification for fatigue design had been applied to a water turbine.

The original design at the tender stage was based on conventional methods of water turbine design but the stress level adopted was adjusted to take account of the fatigue requirement. Some calculations were done at this stage to assess the sensitivity of the design to the expected size of defects and a casting acceptance standard was written. This allowed 20% wall thickness defects in the middle third of the section thickness, but only very small defects in the two outer thirds. For the final design an accurate stress pattern was required and this was obtained using the photo-elastic method for the valve body and rotor and finite element analysis for the top and bottom covers and stay ring. The main components of the machine, the valve body and rotor, the stay ring, the top and bottom covers were cast in carbon-manganese steel. The spiral casing was fabricated from steel plate, and welded to the cast steel stay ring. The fracture toughness of the materials was determined by plane strain fracture toughness testing.

After the components were cast a careful ultrasonic inspection was made, and all defects were numbered and their size and position tabulated. The size was determined by probe movement technique. The defects were then plotted on to drawings of the components, so that the stress in that position could be found. On each defect, whether inside or outside the defect acceptance standard, a fracture mechanics assessment was made. The crack growth in 400,000 cycles was estimated, and the K_I was checked using this enhanced crack size and a stress equal to the maximum that could occur in operation (during load rejection). The possibility of plastic collapse occurring in these conditions was also checked. As a result of these calculations a decision was taken whether to accept or repair the defect. In the case of defects in close proximity to one another, the rules given in a draft specification were used to determine any inter-action ⁽¹⁹⁾. It is believed that this approach to design ensures a machine of adequate life, and minimizes the amount of casting weld repairs required.

Material Selection

The first step in applying fracture mechanics to material selection is to obtain the value of K_{IC} (or K_C) for the materials under consideration. For plain carbon and lower strength steels auxiliary test methods must be used to estimate the K_C or K_{IC} , or a COD test should be carried out and δ_c determined. Next, assess the type of flaw that will most likely occur in the casting being analyzed (e.g. surface, edge or through-thickness, see Fig. 4) and estimate the range of flaw sizes that could possibly be

encountered. Then, plot a_{crit} versus gross working stress calculated, as a particular fraction of the yield stress of the steel. Such a diagram (Fig. 9) represents the order of the steels according to their ability to carry working stresses in the presence of flaws of certain sizes, without giving rise to fast propagation of those flaws. Such a diagram for each material can be used to select the optimum material, to establish design stress levels, and to form the basis for inspection requirements. It must be borne in mind that the stresses plotted are actual stresses, which, in the area of the defect, could be higher than the average design stress; and that a discontinuity which is below the critical size under static conditions will grow under the action of repeated stress, that is, by a mechanism of fatigue. Furthermore, since

$$\left(\frac{K_{IC}}{\sigma_y} \right)^2$$

is a measure of the defect tolerance of a steel, increasing the yield strength without proportionate increase in toughness is detrimental to the flaw tolerance. Thus, steels with the same

$$\left(\frac{K_{IC}}{\sigma_y} \right)^2$$

ratio will have the same critical discontinuity sizes at the same fraction of their yield stresses but the absolute working stresses can be very different.

Significance of Discontinuities

Discontinuity size is one parameter of the fracture triangle and the significance of discontinuities in relation to the other two parameters, working stress and K_{IC} , has already been discussed under the previous headings of design and material selection. The factors to be taken into account when considering acceptance standards for the maximum size and number of flaws that can be tolerated in a given component are:

- a) mechanical properties, including fracture toughness;
- b) applied stress level (including residual stress if any);
- c) cyclic nature of the stress;
- d) temperature;
- e) environment;
- f) degree of uncertainty of foregoing data; and
- g) potential consequence of failure.

Discontinuities in steel castings may be classified into two categories: (1) linear or crack-like (which includes cold cracks, hot tears, fine (interdendritic) and filamentary shrinkage); and (2) rounded (which includes gas porosity in the form of discrete near-spherical holes, entrapped air, pinholes, wormholes, and also exogenous inclusions which consist of nonmetallic matter arising from sand and/or slag). Apart from cold cracks, which are stress cracks occurring after the completion of

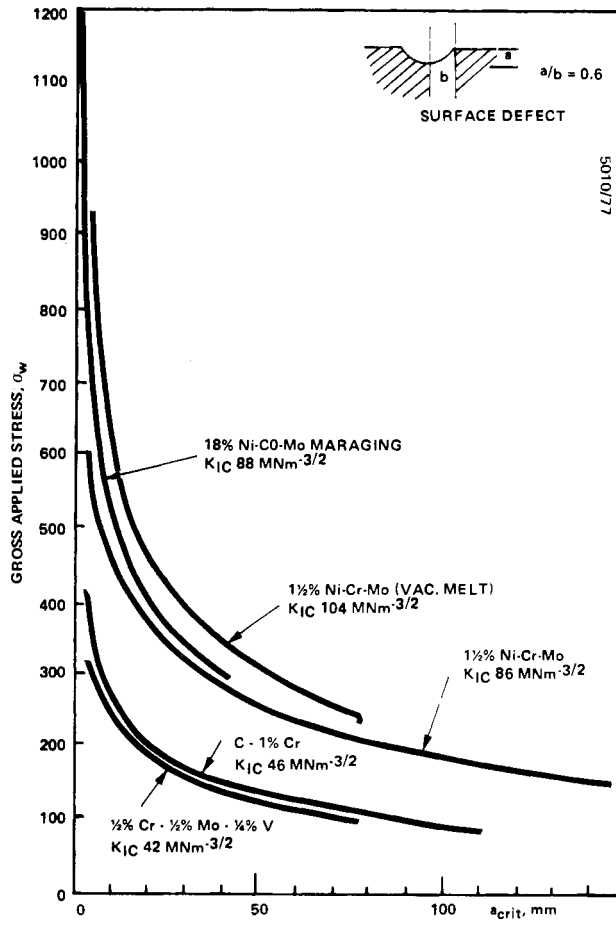


Figure 9—Effect of fracture toughness and working stress on critical size of defects

solidification, steel castings, at the time of commencement of service, rarely exhibit single internal flaws of the exemplary type used in fracture toughness calculations. Flaw tips are unlikely to be as sharp as the fatigue crack tip used in fracture toughness test specimens. It is likely that a dwell time under cyclic stressing would be necessary to initiate sharp crack. Again, apart from the cold crack, other flaws almost certainly consist of multiples or groups. Embedded flaws are less innocuous than surface flaws, and, at present, until research shows how to treat flaws of complex shape, a conservative approach is adopted; all flaws are assumed to have a sharp tip and three-dimensional groups of flaws are taken to be equivalent to one flaw having the size of the envelope encompassing the smaller ones.

Monitoring, Control and Failure Analysis

The use of fracture mechanics in the monitoring of equipment in service is dependent mainly upon a knowledge of the fracture toughness of the material and the exact applied stress, be it static or cyclic. Without this knowledge, it cannot be predicted when a discontinuity will reach a critical size. Furthermore, because of access difficulties, flaw location and sizing becomes more difficult in situ. Nevertheless, provided that all the limitations are understood, monitoring of critical equipment can be worthwhile. An example applied to steel castings is provided by the Central Electricity Generating Board (UK).

During an inspection of an I.P. cylinder of a power station turbine, extensive cracking of the inlet steam belt was found. Several regions of shallow cracking were eliminated by grinding out, but one extensive crack gave cause for concern because of its depth and position. A repair by welding was ruled out because of possible distortion and a replacement casting was not available. A fracture mechanics assessment was therefore undertaken to determine whether or not the cracked casing was acceptable for further service. The 120 MW turbine unit, of which the 1/2%Mo-1/3%V steel casing was part, had been installed and commissioned in 1959/60, and up to 1970 had operated as a base load machine with very few hot and cold starts. From 1970 onwards, the unit was used predominantly for two-shift operation and therefore subjected to a large number of hot and cold starts; there seemed little doubt that cracking in the casing was associated with the large temperature differentials set up during start-ups and shut-downs.

The analysis of the crack behavior fell into three parts: (1) the analysis of the operational stresses in the casing, (2) the derivation of stress intensity factors corresponding to those stresses, and (3) the application of the calculated stress intensity factors to the mechanical property data.

Operational Stresses - The stress experienced by the casing for any operational condition was taken as the sum of thermal, pressure and residual stresses. The thermal stress was evaluated from the product of the nominal stress and the concentration due to the local geometry. The pressure stresses were neglected during a start until the turbine came on load; thereafter, the stresses were determined by taking the product of the nominal stress in a uniform cylinder and the concentration due to the local geometry. With regard to residual stress, no measurements had been made on castings in 1/2%Mo-1/3%V steel, but previous stress relaxation data

for cast 1%Cr-Mo-V steel at 550°C (1022°F) subjected to repeated straining, indicated that an equilibrium value of about 75 N/mm² (10875 psi) was reached. This indication was supported by other work on 1%Cr-Mo-V cracked castings. A residual stress of 75 N/mm² (10875 psi) was, therefore, assumed to act as a uniform tension across the uncracked portion of the casing, normal to the plane of the crack.

Stress Intensity Factors - Estimates were based upon the simple double-edge cracked plate geometry, a solution relating stress intensity factor to crack size, and applied stress being already available. An estimate was made of the variation of stress intensity factor through the thickness of the casing by taking the stress and crack length at each position through the wall, and assuming that these did not vary through the thickness. It was found that, for two starts and the steady state on-load condition, the maximum stress intensity factor occurred at the outer surface and for shut-down at the inner surface.

Crack Growth Predictions - Figure 10 shows the variation of stress intensity factor with outside surface steel temperatures for a cold start which imposes rates of heating similar to those previously observed. Also shown in this figure is the K_{IC} temperature dependency determined in earlier studies. It can immediately be seen that brittle fracture may occur over the temperature range 30° to 130°C (86° to 266°F). Brittle fracture can of course be avoided if the steel temperature differentials are limited to produce stress intensity factors which fall below K_{IC} at all temperatures.

Tolerable Through Wall Temperature Differentials - The need to avoid brittle fracture during start-up and shut-down and the requirement for restriction of stable growth by fatigue and creep permitted an operational pattern to be defined, as shown in Fig. 11. Regions A and B represent the limitations on the temperature differentials, as a function of the outside steel surface temperature which should be followed for the avoidance of brittle fracture during start-up and shut-down. It should be noted that a positive temperature differential means that the inner surface of the casing is hotter than the outside, and a negative differential means that the outer surface is hotter than the inner. The limitation of the through wall differential in region C of Fig. 11, resulted from the requirement to limit stable growth during Winter 1974/75. Assuming that the machine was to operate on a 5-day week, and run for 3000 hours over this period, the crack would grow by 6 mm (.24 in.) if the maximum differential of region C is sustained on each start-up and shut-down. Alternatively, the growth could be reduced to a negligible value by operating the machine continuously, i.e. a 7-day week.

It was emphasized during this study that many assumptions had been made in arriving at values for pressure, residual and thermal stresses during start-up, operation and shut-down, and that the fracture mechanics assessment could not provide a guarantee for the safety of the machine. Furthermore, it was recommended that in the event of a steam leak, an observed crack extension or any circumstance which indicated that crack growth may have occurred, the unit should be shut down immediately, adhering to the restrictions of area B in Fig. 11. Additional instrumentation was installed in the casing and the precautions stated were adhered to, with the result that since Winter 1974/75 the unit has continued to operate satisfactorily.

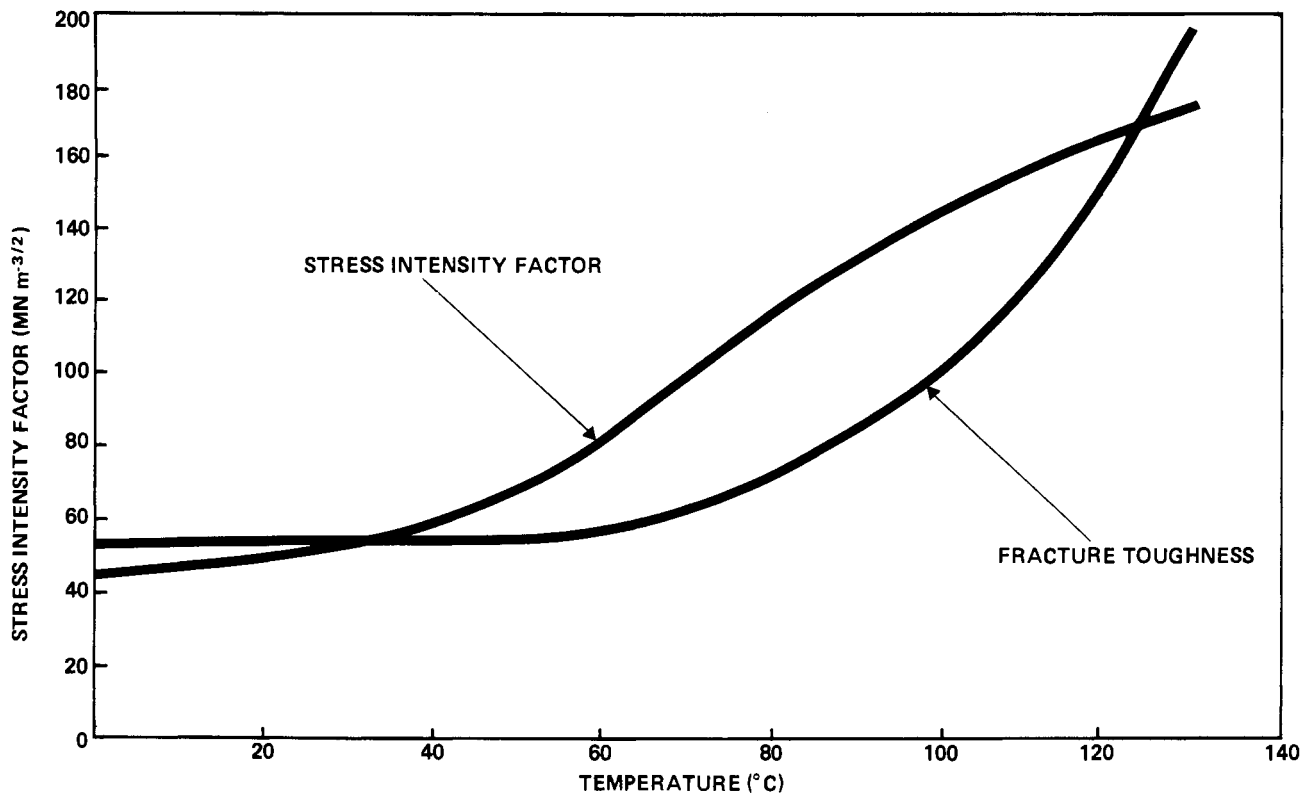


Figure 10—Variation of stress intensity factor with temperature for a cold start, also showing fracture toughness variation of the steel (1/2% Mo-1/2% V)

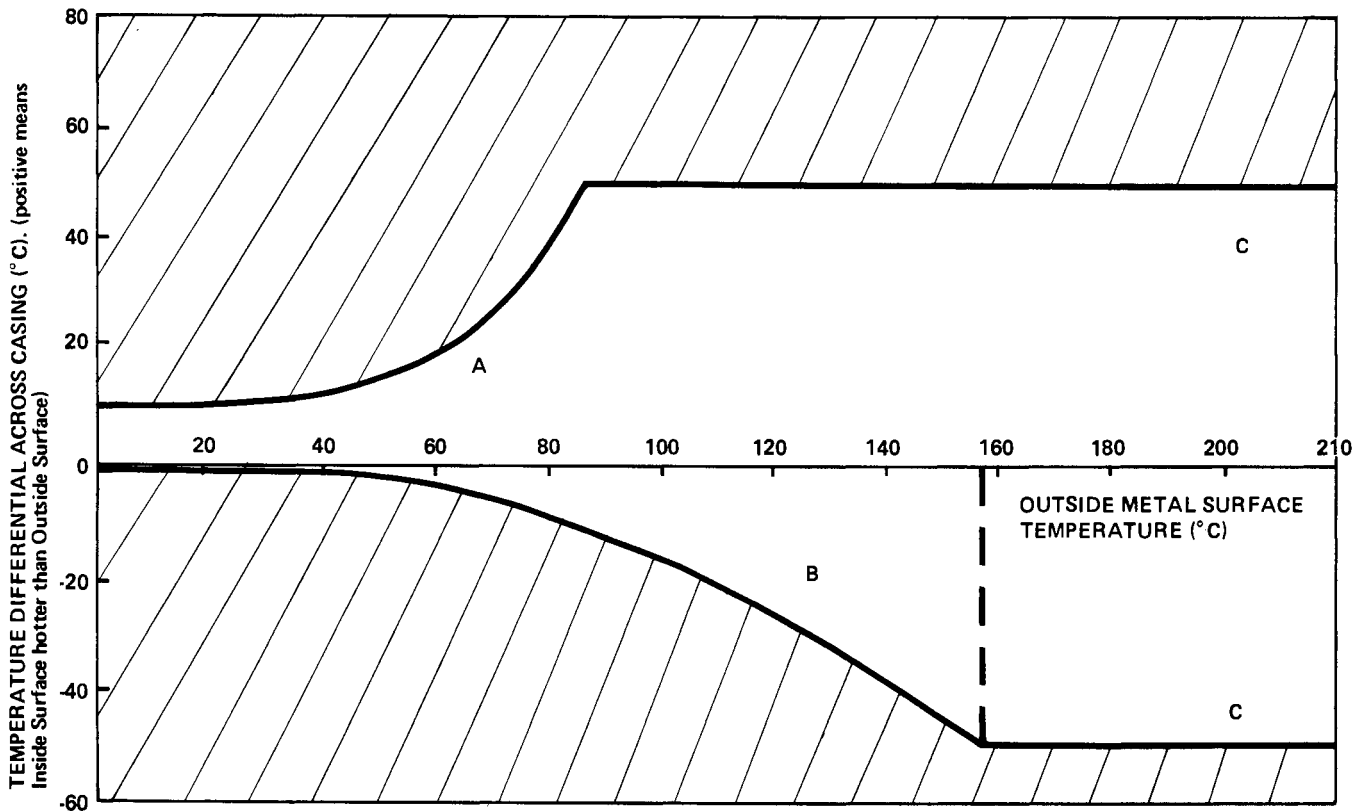


Figure 11—Recommended temperature differentials for the turbine casing, arising from a fracture mechanics assessment

In addition to monitoring, failure analysis is extremely important, for only by doing this can fracture mechanics be shown to be a viable technique. Unfortunately, no reports exist in the literature of this having been applied to steel castings, although investigations using fracture mechanics have been made on welded joints between forged and cast components in power generating plant ⁽²⁰⁾. It has also been applied to a forged rotor shaft, In this case the damage was complex and related to discs which failed in service; the damage was extensive and it was difficult to ascertain which cracks had initiated the failure and which were consequential damage. Fracture mechanics was used to test the hypothesis that the failure was due to the bursting of one of the low pressure discs during rotation. It also indicated that the failure could have been postponed or even avoided by the use of material of higher fracture toughness. The investigation allowed appropriate methods to be developed to prevent such failures in the future ⁽²¹⁾.

Accuracy of Flaw Size Measurement

Four main non-destructive testing techniques are used in steel foundries at the present time: magnetic particle and penetrant methods for surface inspection; radiography and ultrasonic inspection for internal examination. It can be seen from Table IA that, typically, the smallest surface defect dimension that needs to be measured is of the order of 2.5 mm (.10 in.) and 3.0 mm (.12 in.) for internal flaws (assuming that design stresses greater than $0.8\sigma_y$ are not used). An examination of existing standards incorporating NDT methods shows that the smallest defects that must be measured for acceptance purposes are as shown in Table II. The values quoted in ASTM and other standards have been evolved from experience in examining steel castings and it is hoped that the application of fracture mechanics will help to rationalize the difference between existing NDT standards.

If we accept these data as truly representing the present day situation, it would appear that radiography is an inaccurate technique for measuring flaw sizes. For the steel with the lowest flaw tolerance in Table IA, embedded rounded flaws ($a/b=1$) of 15.6 mm (.61 in.) (i.e. 7.8 mm (.31 in.) radius) can be tolerated even at high design stresses ($0.8\sigma_y$); consequently the fact that the ASTM radiographic standard E280 restricts rounded flaws to 1.0 mm (.04 in.) does not seem particularly relevant. Whittaker ⁽²²⁾ confirms this viewpoint by saying "It remains a sad fact that, in general, radiography is able to detect the defects which fracture mechanics show to be of only secondary importance, whilst it fails to detect adequately the really important defects".

It is shown in Table II that the minimum flaw size detectable by ultrasonic methods is 10 mm (.39 in.) for a linear flaw. The ultrasonic method should be able to detect flaw sizes with an accuracy of ± 20 per cent, i.e. between 8 and 12 mm (.31 and .47 in.) for linear and 3 to 5 mm (.12 to .20 in.) for 4 mm (.16 in.) rounded flaws. Whether or not a 20 per cent accuracy is achieved is difficult to assess, since the accuracy of the techniques used (either maximum amplitude or beam spread) depends mainly on the structure of the steel and its ultrasonic attenuation, which in turn determines the usable test frequency and the resolving power of the method. Other important factors to be considered are the equipment characteristics, setting sensitivity, frequency and diameter of the probe crystal, surface roughness of the casting, shape of the casting and very importantly, the skill and ability of the operator. Consequently, a factor

**TABLE II—AVERAGE MINIMUM FLAW SIZES REQUIRED
TO BE DETECTED BY NON-DESTRUCTIVE TESTING
TECHNIQUES**

Magnetic particle	Linear 4mm, round 2mm
Dye penetrant	Linear 4mm, spherical 3.5mm
Radiographic	
Linear flaws	E446, no linear flaws; E186 Grade 1, 17mm; E280 Grade 4, 80mm.
Spherical flaws	E446, 0.5mm; E186, 1.0mm; E280, 1.0mm.
Shrinkage	E446, 3mm long; E186, 10mm long; E280, 30mm long.
Ultrasonics	Linear 10mm long. Round (midwall) 8% of wall thickness. Round (outerwall) 5% of wall thickness.

of safety of 100 per cent is suggested. It would appear prudent, from a fracture mechanics point of view, not to use steels of such low toughness that at the design or working stress a rounded critical defect size is less than 6 mm (.24 in.) (i.e. 3 mm (.12 in.) x 2) when ultrasonic inspection is employed.

Surface or near surface flaws can be detected by penetrant and magnetic particle methods, but only the length, and not the depth* of flaw can be determined. The suggested capability of these methods is for measuring lengths down to 0.25 mm (.01 in.). Comparison with Table IA shows that this is a satisfactory accuracy for a range of steels having widely differing properties.

A comparison of the efficiency of various NDT techniques has been made for surface fatigue cracks in heat treated low-alloy wrought steel⁽²³⁾. Fig. 12 shows that cracks were 100 per cent detected by ultrasonics when 6 mm (.24 in.) long, by the magnetic particle method when 9 mm (.35 in.) long and by penetrants when 10 mm (.39 in.) long. Even when they were 13 mm (.51 in.) long, radiography could only detect them every 65 shots in 100. The accuracy achieved in measuring these cracks is illustrated by Fig. 13 which shows that magnetic particle achieves an accuracy of 80 per cent for cracks 4 mm (.16 in.) long. The data, although not obtained from steel castings, indicate the difficulties in finding surface cracks and measuring their lengths. Furthermore, of these methods, only ultrasonics can measure the depth of a flaw (and this not at all accurately) which fracture mechanics shows to be much more important than the length. Foundries and steel casting users should therefore satisfy themselves that they know the minimum size of flaw that can be consistently detected, taking all variables into account. There is little virtue in being able to detect flaws if their size, and hence their significance with regard to failure by brittle fracture, can not be determined.

The application of fracture mechanics principles assumes ideal conditions for theoretical manipulation (i.e. discrete discontinuities either at the surface or totally embedded) but in the practical case of castings, discontinuities occur irregularly in shape and distribution. Ways of dealing with such situations have been suggested⁽²⁴⁾ but two very important points remain: (i) NDT techniques are not sufficiently advanced to give accurately the size, shape and location of individual and groups of flaws; and (ii) more case histories are needed involving the application of fracture mechanics to steel castings to dispel any doubts concerning its application.

METALLURGICAL FACTORS AFFECTING FRACTURE TOUGHNESS

For a given structure, higher toughness is associated with lower strength levels. The microstructure itself influences toughness to a considerable degree. Bainite, at a given strength level, exhibits better impact toughness than ferrite, upper bainite generally having higher impact transition temperatures than lower bainite (25). Tempered martensite exhibits the highest toughness.

Carbon steels and most commercial low-alloy steels exhibit ferritic or ferritic/pearlitic microstructures in the normalized and tempered condition, whilst quenching produces bainitic or martensitic structures

* Depth here means the minor axis in a roughly elliptical shape, and not depth below the surface.

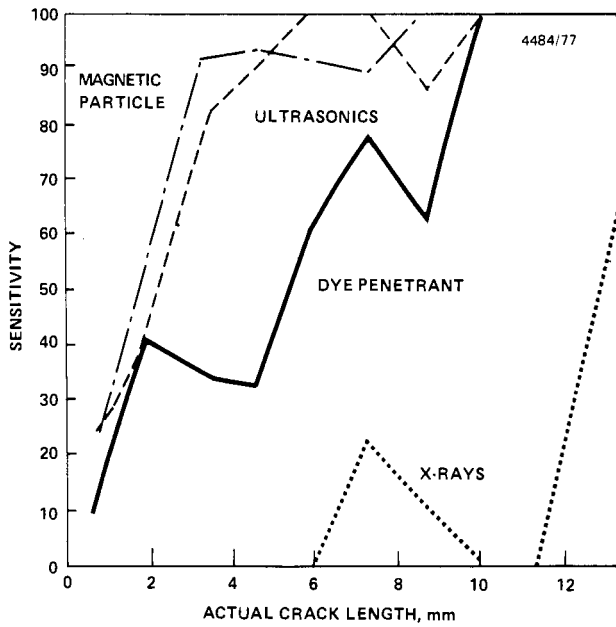


Figure 12—Sensitivity of NDT methods in detecting surface cracks in low-alloy steels

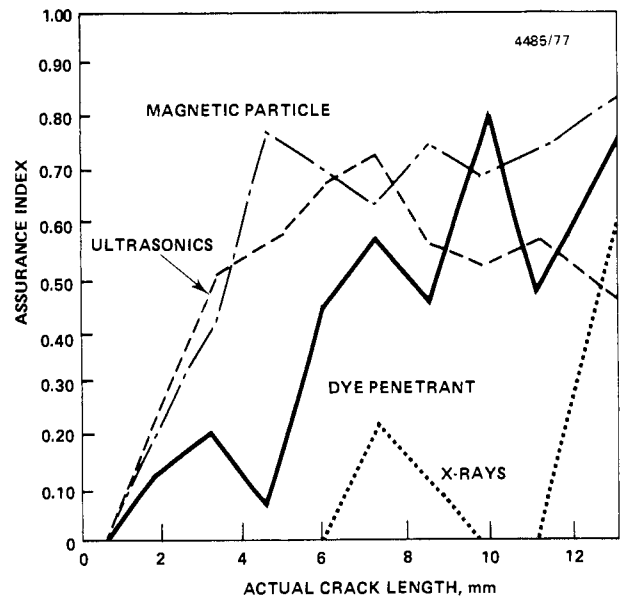


Figure 13—Accuracy of crack length indication by different NDT methods

in low-alloy steel. Significant differences in toughness-strength relationships are evident when quenched and tempered steel castings are compared with those in the normalized and tempered condition⁽²⁶⁾. Increasing the tempering temperature, which lowers the strength, has the effect of increasing the K_{IC} value (Fig. 14).

As may be expected, decreasing the sulphur content increases the fracture toughness. Increasing sulphur and phosphorus together has a marked effect on lowering the fracture toughness⁽²⁷⁾. In test blocks castings, however, it was found that fracture toughness did not necessarily correlate with sulphur and phosphorus (Fig. 15); fracture toughness varied with position in the top half but not in the bottom half of the block. This result indicated that the casting was not adequately fed and that underhead microshrinkage was occurring. The question of porosity is one which requires much further work and closer definition of the type, extent, shape, size and interaction of the pores.

Another point of which further data are required is concerned with grains and grain boundary effects. In SCRATA work where intergranular fracture was encountered, no correlation could be found between the amount of I.F. on the fracture surfaces and the corresponding K_{IC} value. The reason for this is that the fracture toughness test does not measure the toughness of the whole area of the uncracked ligament but measures the toughness of a relatively small zone at the tip of the fatigue pre-crack. It was calculated for the steel in question that the distance that this zone extended ahead of the crack tip was approximately 0.5 mm (.02 in.). Virtually none of the I.F. areas of the fracture were within this distance of the initial crack tip, thus explaining the lack of correlation between percentage I.F. and K_{IC} .

A similar example may be quoted even though it relates to wrought steels⁽²⁸⁾. It has been shown that for an AISI 4340 steel containing 0.8%Mn, austenitizing at 1200°C (2192°F) can increase the fracture toughness (K_{IC}) by a factor of two without reducing the yield strength. At the same time however, Charpy V-notch values are lowered. It is possible therefore, that grain coarsening has taken place and the pre-crack tip was in each test within a grain, remote from a grain boundary. By comparison, a Charpy test having a blunt notch requires more energy for crack initiation but far less for crack propagation through a coarse grained steel. Observations made on the two foregoing examples could well explain the scatter which occurs between test pieces taken from adjacent positions.

Microshrinkage is another phenomenon which needs further study in relation to fracture toughness. In one investigation, Ni-Cr-Mo steel test pieces showed interaction between the microshrinkage and the fatigue pre-cracking, a typical example of which is shown in Fig. 16. The conclusion from this particular study was that porosity effectively raised the measured toughness, because multi-planar crack fronts, rather than single cracks, were being tested. Thus, mixed mode deformation characteristics were induced which involved more energy absorption. There was no evidence to suggest that minimum levels of toughness were affected by microshrinkage.

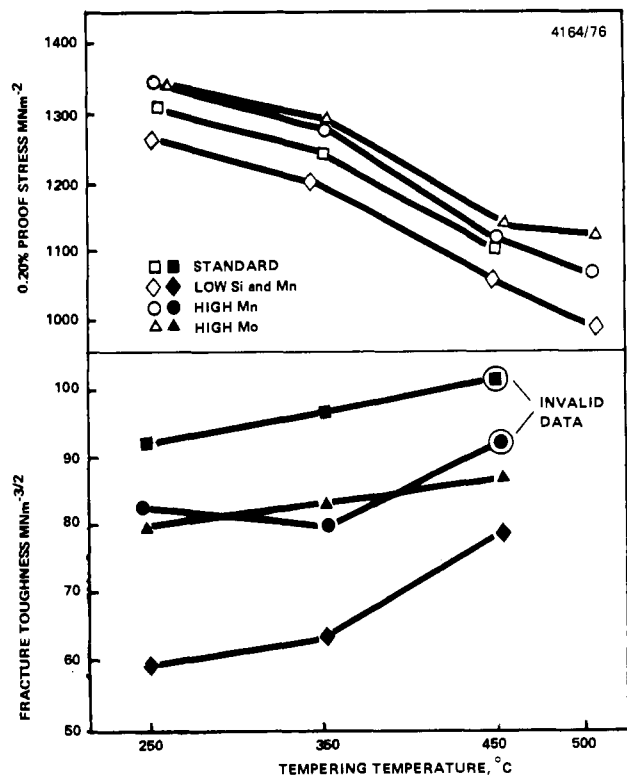


Figure 14—The effect of tempering temperature on four heats of 1½% Ni-Cr-Mo steel after water quenching

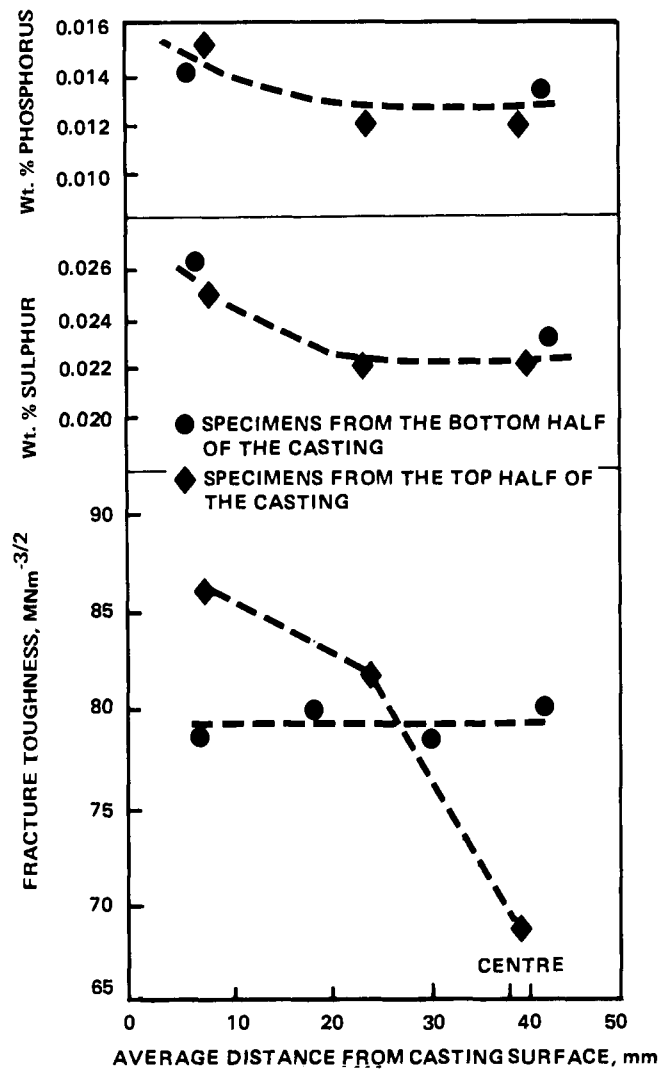


Figure 15—Variation of fracture toughness, sulphur and phosphorus contents with specimen position in a quenched and tempered 1½% Ni-Cr-Mo steel

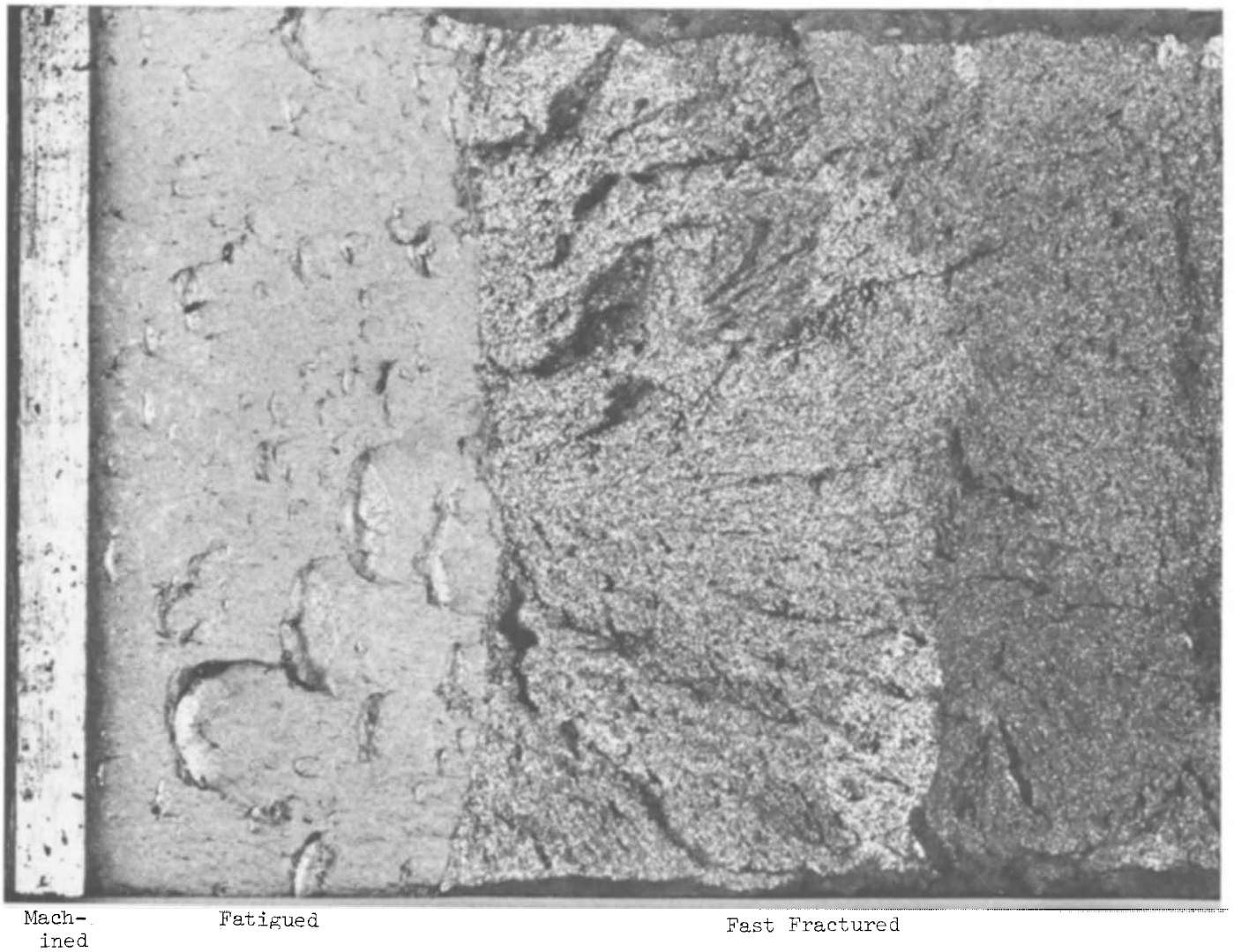


Figure 16—Fracture surface of a single edge-notched fracture toughness test piece showing "Horse shoe" markings in the pre-fatigued zone

ALTERNATIVE DATA

The advantage of the fracture mechanics tests over more conventional toughness tests lies in the fact that material values are obtained that can be used in design equations. Nevertheless, the tests are expensive to carry out and if the results of cheaper and quicker tests can be empirically correlated with K_{IC} or δ_c values, then the cheaper tests may be performed, and the derived value of K_{IC} or δ_c can be used in the design equations. It is important to remember, however, that the toughness of most steels decreases with decreasing temperature and increased loading rate (i.e. time taken to reach maximum load). Behavior can change very rapidly at intermediate positions between slow loading (static for K_{IC}) to rapid loading (dynamic or impact for K_{ID}). Furthermore, increasing the thickness of the material being tested decreases K_C values to a constant value, K_{IC} . Different tests may do no more than show empirical correlations and it would be unwise to apply a correlation for one material to another.

The Charpy V-notch test is widely used as a quality control test and correlations with K_{IC} have been sought ⁽²⁹⁾. For certain wrought steels, the upper shelf K_{IC}/CVN (Barsom and Rolfe) correlation ⁽³⁰⁾ has been found to be acceptable, whilst for forged rotor steels a rather similar correlation has been found (Bengley and Logsdon) ⁽³¹⁾. In general, these methods apply to wrought steels which exhibit a well-defined Charpy energy and fracture appearance transition curve and are not markedly sensitive to strain rate.

Work on cast steels has been carried out for the Steel Founders' Society of America revealed several correlations for cast 1 1/2%Ni-Cr-Mo and 1 1/2% Mn-Ni-Cr-Mo steels ⁽³²⁾. Using room temperature values of K_{IC} and Charpy V-notch absorbed energy, a plot of crack size factor $(K_{IC}/\sigma_y)^2$ versus CVN/σ_y gave a line of best fit having the equation:

$$\left(\frac{K_{IC}}{\sigma_y}\right)^2 = 2.786 \left(\frac{CVN}{\sigma_y}\right) + 0.090$$

The relationship gave a correlation coefficient of 0.855 and although the slope of the line was slightly less than that of Barsom and Rolfe, the agreement was fairly good.

Dynamic tear tests were also carried out in the SFSA program, since this form of test has been advocated as a less costly substitute for plane strain fracture toughness testing. In these tests higher strength test pieces had a fatigue pre-cracked notch instead of the more usual brittle weld bead as a crack starter. The lower strength specimens had a machined notch, sharpened at the bottom by pressing in a knife-edge. The tests were performed in a 2000 ft. lb. capacity double-pendulum impact machine. A plot of crack size factor $(K_{IC}/\sigma_y)^2$ versus $DTTE/\sigma_y$ gave an equation for the relationship:

$$\left(\frac{K_{IC}}{\sigma_y}\right)^2 = 0.775 \left(\frac{DTTE}{\sigma_y}\right)^{\frac{1}{2}} - 0.279$$

where DTTE is the dynamic tear test energy in ft. lb. The correlation was similar to the one for Charpy V-notch energy, despite the greater degree of constraint and sharper notches used in the DT test.

ACCEPTABLE FLAW SIZE

From previously mentioned "fracture triangle" it can be seen that in order to calculate the critical discontinuity size, the applied or working stress must be known; ideally, residual stress in the casting should be taken into account. Furthermore, the manner of applying load to the casting must be known (static or cyclic), and the environment in which it is to be used (neutral, corrosive, subzero temperature etc.). Clearly, the founder and engineering designer must work closely together for the use of fracture mechanics to be successful.

What discontinuity size must be detected? The answer depends upon the fracture toughness of the material and the working stress, but some answers are given for plain carbon steel castings in Table III ⁽³⁴⁾. Very few castings ever have flaws of the magnitudes shown in this Table; however, it may be possible for a smaller crack to extend to a critical size as a result of cyclic loading. This assumes that on cyclic loading a defect propagates instantaneously, i.e. no account is taken of the number of cycles required to initiate the crack. (This is another way of incorporating a factor of safety). Assuming that the cyclic load range varies from zero to a maximum of 1/2 YS, 2/3 YS and YS, a calculation may be carried out to give the results in Table IV. These flaw sizes indicate the initial surface crack size which will grow to 125 mm (4.92 in.) deep at the three maximum applied stresses; it will be seen that even for 10,000 cycles at the yield stress the initial critical flaw size is 23 mm (.91 in.) deep and 230 mm (9.06 in.) long ⁽³⁴⁾. Clearly, very large crack sizes can be tolerated in carbon steels.

Curves giving critical defect sizes for several medium- to high-strength cast steels, for applied stresses ranging from approximately one-fifth yield stress to four-fifths yield stress, are shown in Fig. 9. Thus, for an applied stress of 300 N/mm² (43500 psi), the size of a critical surface flaw (depth x length ratio 1:3) would be 9 mm (.35 in.) for C-1%Cr and 1/2%Cr-1/2%Mo-1/4%V steels, 35 mm (1.38 in.) for a 1 1/2%Ni-Cr-Mo steel, 38 mm (1.50 in.) for a maraging steel and 55 mm (2.17 in.) for a vacuum-melted 1 1/2%Ni-Cr-Mo steel. For very sharp cracks at working stresses near the yield, critical flaw sizes become 2 to 3 mm (.08 to .12 in.) for medium-alloy steels but design parameters rarely approach this. In normal circumstances, 10 mm (.39 in.) is probably the smallest flaw that will be required to be detected.

It follows that situations could arise where a flaw is purposely left in a casting, when otherwise, on the basis of intuition, it would have been gouged out. On the other hand a small flaw (say 10 mm (.39 in.)) may have to be gouged out (because the critical size is, say 6 mm (.24 in.) by calculation). It is impossible to generalize as to whether the use of fracture mechanics will increase or decrease work in the fettling shop, but flaws of a very large size will doubtless become tolerable in low-carbon, un-alloyed cast steels. Whether or not we deliberately leave in those flaws that otherwise would have been removed depends upon the acceptance of the fracture mechanics approach. Further work is needed to indicate the importance of different types and groupings of flaws and their arithmetical treatment.

TABLE III—CRITICAL FLAW SIZES FOR AN ANNEALED AND STRESS RELIEVED
0.24%C-1.15%Mn STEEL CASTING SUBJECTED TO A SINGLE
APPLICATION OF LOAD

Temperature C°	YS N/mm ²	K _{1c} MNm ^{-3/2}	Depth x length, mm 1:4 ratio		
			at 1/2YS	at 2/3YS	at YS
-45	378	66	80 x 320	50 x 200	15 x 60
-17.5	364	121	300 x 1200	140 x 560	50 x 200
10	344	165	400 x 1600	300 x 1200	150 x 600
Depth x length, mm 1:10 ratio					
-45	378	66	62 x 620	35 x 350	12 x 120
-17.5	364	121	230 x 2300	100 x 1000	38 x 380
-10	344	165	300 x 3000	230 x 2300	125 x 1250

TABLE IV—INITIAL SURFACE FLAW SIZES WHICH WILL GROW TO A DEPTH OF
125MM IN THE STEEL REFERRED TO IN TABLE III AS A RESULT OF
CYCLE STRESS AT ROOM TEMPERATURE

Cyclic stress (0 to max.)	Initial flaw size, depth x length, mm 1:10 ratio			
	No. of cycles			
	100	1000	10,000	100,000
1/2YS (145 N/mm ²)	127 x 1270	127 x 1270	92 x 920	16 x 160
2/3YS (185 N/mm ²)	127 x 1270	125 x 1250	60 x 600	4 x 40
YS (280 N/mm ²)	125 x 1250	120 x 1200	23 x 230	0.5 x 5

DETERMINATION OF FLAW SIZE

Are the flaw sizes arising from fracture mechanics considerations large enough to be detected or sized by non-destructive flaw detection methods? For surface flaws, which are normally found by magnetic particle or dye penetrant methods, linear flaws of about 4 mm (.16 in.) represent the limit, the sizing of smaller flaws being too inaccurate to be meaningful. For measuring internal flaws by ultrasonics, linear flaws of about 10 mm (.39 in.) may be measured but for smaller flaws, sensitivity is not good enough for them to be accurately sized. With ultrasonics, measurement of defect length is much dependent upon the size of probe used; the smaller the flaw, the smaller must be the probe, because a flaw cannot be sized accurately if it is smaller than the crystal size. The depth of a flaw also becomes more difficult to measure accurately when depth is small in relation to the cross section of the ultrasonic beam. Unfortunately, it is the depth of a surface flaw which is important in fracture mechanics assessment and depth is the most difficult dimension to measure by ultrasonics. It cannot be measured at all by magnetic particle or dye penetrant methods. Radiography is no better where small flaws are concerned.

It appears that we are in a grey area when fracture mechanics indicates the critical flaw size is 10 to 15 mm (.39 to .60 in.) or less. Founders and engineers, therefore, should satisfy themselves that they know the minimum size of flaw that can be measured under a given set of circumstances; there is little virtue in being able to detect flaws if their size, and hence significance with regard to failure by brittle fracture, cannot be determined. In practice, the calculated critical flaw size should be substantially larger than the actual flaw size that might escape detection. An alternative procedure is to estimate conservatively the size of the smallest flaw that can be detected by the NDT techniques available and to select a steel having a higher K_{IC} value and hence a larger critical flaw size than that calculated.

FLAWS IN RELATION TO QUALITY

A "no detectable discontinuity" criterion implies that all cast steels have the same resistance to fracture. Whilst fracture may be controlled by plastic collapse in relatively thin sections, the output of castings with relatively large section thickness is high enough to ensure that fracture resistance should be calculated according to the principles of LEFM. There are several ways of defining quality, but the most apt is that which relates quality to fitness for purpose; if the casting properly does the job it is intended to do, then it is of satisfactory quality. How is it possible to determine what level of, say, porosity, according to reference radiographs, is acceptable for the casting to be of adequate quality? Reference radiographs are composed of a series of typical radiographs in order of increasing severity of the specific discontinuity, so that radiographs of other flaws may be compared with them; they are not directly related to load carrying ability. The first radiographic standard, adopted as E71 by ASTM in 1947, was prepared by experts to illustrate various severities in arbitrary progressions. This specification and others that followed had no technical basis in relation to design, although they have been tremendously useful when service records of suitability and unsuitability have been kept. Their shortcomings become evident with new designs, where there is no background experience.

They raise unnecessary constraints in non-critical applications, where a flaw normally considered to be severe by radiographic standards can be quite harmless in a region of low stress⁽³⁵⁾.

Radiographic standards, therefore, should be used more sensibly in relation to modern design criteria based on fracture mechanics. The same remark applies to other NDT acceptance standards for steel castings which may be issued in the future. It must be acknowledged, however, that much more research needs to be done into the accuracy of sizing flaws, the behavior in practice of actual flaws in various stress systems, the interaction of groups of flaws, the distribution of stress within a component, the effect of residual stress and the effect of metallurgical variables. Most important, convincing proof is required that fracture mechanics theory does work in practice, because, after all, no failure may be consequent upon factors of safety having been too high.

All this is not likely to happen during the course of any single research program; it will evolve as any other technology has, by trial, observation, deduction, refined trial, and so on. A start has been made by BSI and ASTM, who have meticulously described and defined the methods of fracture toughness testing, so that all results from whatever source should be comparable. Next will be the examination of casualty material, to try to work out retrospectively why failure occurred. Simultaneously, fracture toughness data will be requested in specifications, in the first instance only for large, complex, high integrity castings. Useful experience will accrue from work already done on wrought steels, and welds, where in the latter case a specification for acceptance based on fracture mechanics principles has already been proposed⁽¹⁹⁾. In the future, a sufficiently large body of fracture mechanics data will be generated for steel castings, so that specification minimum requirements can be based on statistically derived values, as is the case for other material properties. Typical values for K_{IC} and COD for cast steels are given in Table V.

Until this information becomes available, the following guide may be used when designing "fracture critical" steel castings to ensure that the quality of the castings is adequate.

1. Safety factors should be put on both the gross working stress and on the calculated critical flaw size. Since the exact ligament stresses are not always known with accuracy, particularly in the case of complex-shaped castings, it is essential to put a safety factor on the gross stress. Also, in order not to approach the a_{crit} , a factor of safety must be put on the calculated value.
2. For a given K_{IC} value, flaw tolerance can be good or bad, depending on the yield strength of the steel, so the parameter:

$$\left(\frac{K_{IC}}{\sigma_y} \right)^2$$

is a better representation of the flaw tolerance of a steel.

TABLE V—TYPICAL ROOM TEMPERATURE FRACTURE TOUGHNESS VALUES (K_{IC} AND COD) FOR CAST STEELS

Steel type and description	0.2% Proof stress MNm ⁻²	Initiation COD mm	" K_{IC} from COD MNm ^{-3/2}	Valid K_{IC} MNm ^{-3/2}
1.5%Ni, 1%Cr, 0.3%Mo, 0.25%C Quenched and tempered	1216-1310	—	—	78-86
As above, but vacuum melted	1280	—	—	104
2%Ni, 0.8%Cr, 0.35%Mo, 0.35%C Normalized, quenched and tempered. Martensitic. Low sulphur and phosphorus.	1134	—	—	100
As above, but slack quenched, giving a mixed microstructure	747	—	—	69
As above, martensitic, but higher sulphur and phosphorus	1065	—	—	65
0.6%Ni, 0.7%Cr, 0.4%Mo, 0.35%C Normalized and tempered	683	—	—	64
1%Ni, 1%Cr, 0.3%Mo, 0.3%C Normalized and tempered	787	—	—	66
0.5%Cr, 0.5%Mo, 0.25%V Normalized and tempered	367	—	—	55
0.5%C, 1%Cr Normalized and tempered	412-425	—	—	55-62
1½Mn Normalized	412	0.95-0.160	94-122	—
0.5%C Normalized	425	—	—	65
13%Cr Normalized and tempered	366-446	0.04-0.08	61-92	—
37%Ni, 18%Cr, 0.5%C As cast	247	0.076	—	—
As above, aged 100h at 750°C	386	0.025	—	—
25%Cr, 20%Ni, 0.5%C As cast	225	0.102	—	—
As above, aged 100h at 750°C	241	0.025	—	—

3. A steel should be chosen having a large critical flaw size (a_{crit}) which can be measured more accurately.
4. If the working load is fluctuating it is necessary to calculate from crack propagation rate curves the time for a flaw (a_i) to grow to a critical size (a_{crit}). This can then be compared with the design life of the component.
5. A steel should be chosen that is amenable to ultrasonic examination, since this is the best single method for detecting flaws and estimating their size.
6. It should be assumed that a string of cracks is one long crack, that a group of flaws is one large flaw of size comparable to the envelope that circumscribes them, that, unless clearly otherwise, all flaws have a sharp aspect ratio and that they reside on the surface.

A steel selected on this basis is likely to be overdesigned but perhaps not so much as if there had been no awareness of fracture mechanics principles. Other design criteria remain unaltered, as do other considerations such as weldability.

WELDING OF STEEL CASTINGS

How will welds affect the critical flaw size and fracture toughness of the casting? A word of caution and more research is needed on this subject. In an investigation into the fracture toughness of weld-repaired 2 1/2%Ni-Cr-Mo castings, the toughness of two weld deposits was measured, the results being summarized in Table VI⁽³⁶⁾. Calculations for "allowable"* flaw sizes were made, assuming an applied stress of two-thirds that of the yield strength of the casting and a flaw shape (aspect ratio) of 4:1 in a 100 mm (3.93 in.) thick section. It can be seen that the "allowable" flaw depth of 70 mm (2.76 in.) in the casting is reduced to 52 mm (2.05 in.) in one weld deposit and to 38 mm (1.50 in.) in the other (31 mm (1.22 in.) after stress relieving). In the worst case, assuming that the residual stress is equal to and acts additively to the yield stress, the allowable flaw depth is reduced to 5 mm (.20 in.). This example illustrates that welding the casting and leaving in a flaw of 5 mm (.20 in.) is no better than leaving in the original 70 mm (2.76 in.) flaw in the casting. Fracture toughness values of the heat affected zones were not determined but they would almost certainly have been lower than in the parent metal. In cast C-Mn steels the HAZ's were found to have lower COD values than the parent metal, as shown in Table VII⁽¹³⁾. This emphasizes the fact that toughness considerations of welded steel castings (both repair welded and cast/weld assemblies) should be based on the properties of the welded areas, as is the case for welded structure in wrought products.

*The application of a factor of safety (usually 2) to the critical defect size gives rise to the concept of an "allowable" defect size in fusion welded joints, for a single application of load; it does not, however, take into account cyclic loading effects.

TABLE VI—ALLOWABLE DEFECT SIZES IN 2½% NI-CR-MO STEEL CASTING AND WELD METALS

Material	0.2% proof stress N/mm ²	Design stress* Proof stress	Fracture parameter		"Allowable" defect in 100mm thickness	
			Applicable criterion	Value	Depth, mm	Length, mm
2½% Ni-Cr-Mo casting	601	0.66	δmax.	0.72mm	70	280
Metrode 3% Ni-Cr-Mo B welded metal	575	0.70	δmax.	0.44mm	52	208
Jetweld LH110 weld metal						
- stress relieved	676	0.59	Kpop-in	167MNm ^{-3/2}	31	124
- as welded	676	0.59	Kpop-in	189MNm ^{-3/2}	38	152
- as welded	676	1.59†	Kpop-in	189MNm ^{-3/2}	5	20

* Design stress = 400N/mm². † Assuming yield point residual stress.

TABLE VII—COD AND ALLOWABLE FLAW SIZES IN
NORMALIZED C-MN STEEL CASTINGS

Steel*	Notch location	Test temper- ature, °C	COD (δ _c) mm x 10 ⁻²	a _{max} at 2/3σ _y	"Allow- able" flaw size
1	Casting	+10	10	27	13
			27	35	17
2	HAZ	+10	7.1	32	16
			12	54	27
	Casting	-10	12	54	27
			5	20	10

* Chemical composition:

Steel 1 - 0.20%C, 0.48%Si, 1.03%Mn, 0.010%P, 0.013%S.

Steel 2 - 0.21%C, 0.52%Si, 1.26%Mn, 0.060%P, 0.031%S.

SPECIFICATIONS

Will fracture mechanics tests become mandatory in specifications? There is considerable activity in the compiling and revising of both national and international standard specifications relating to steel castings. SCRATA has contributed a lot by way of draft preparation, collating comments, and carrying out statistical surveys of mechanical properties. SCRATA is also becoming increasingly involved, mainly in an advisory capacity, in the compilation of private standards. These arise mainly from Government or nationalized bodies who find that their demands and requirements for steel castings are sharply increasing and feel the need to write their own standard specifications in view of the specific nature of their own engineering requirements. In nearly all specifications arising in this area, the emphasis is on non-destructive testing and quality, the material and its mechanical properties often being covered by quoting a British Standard. Thus, as engineering requirements become more stringent, the definition of defect criticality becomes more important.

In the ASME Boiler and Pressure Vessel Code, Sections III and VIII, Summer 1972 Addenda, drop weight tests on cast material made in accordance with ASTM E208-69 are now mandatory. This type of test, used to determine the nil ductility transition temperature, could well receive more prominence in the future, particularly for the tough structural steels which are not conveniently treatable by fracture mechanics.

Activity in defining national and international standard specifications is increasing rapidly and the steelfounder can expect to see more precise standards for steel castings. This is a reflection of the continually improving technology of manufacture and will increase the confidence shown by the engineer-user in employing steel castings in his designs for plant and equipment.

CONCLUSIONS

Fracture mechanics is a comparatively new subject that has already shown its usefulness to engineers in design, steel development and failure analysis. It has proved useful in the understanding of brittle fracture and in the analysis of problems involving fatigue crack growth. A simple calculation will determine the order of magnitude of a critical flaw size, but in such calculations, assumptions have to be made concerning the accuracy of flaw sizing by commercially used NDT methods and also concerning the exact stress in the locality of the flaw. Nevertheless, it is essential that the foundryman knows the "bare necessities" of fracture mechanics, since his customer will ask about it and expect replies. It is unlikely that the foundryman will get involved in routine fracture toughness testing, for steels once proved will be henceforth accepted on the basis of a simpler routine test.

The fracture toughness of cast steels is comparable to that of similar wrought steels and, at lower strengths and applied stresses, very large flaws can be tolerated. Under more stringent conditions, critical flaw sizes can be very small. In the latter case, the limiting factor will be NDT and it will be prudent to select a steel of sufficiently high fracture toughness to obtain a crack size that is detectable under the given conditions. More research is needed to quantify and

understand the effects of the various flaws that occur in steel castings.

The adoption of more critical design policies is important to steel-founders and casting users. The advantageous combination of high strength, adequate ductility, stiffness and considerable toughness in a wide range of carbon and alloy cast steels usually ranks them ahead of other cast metals for arduous applications, particularly when cost is taken into account. If the practice is continued of incorporating large safety factors into design calculations, the relative advantage of cast steels compared with other cast metals is severely reduced. The use of fracture mechanics should help in overcoming this outmoded approach to design.

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APPENDIX I - SAMPLE CALCULATION

Assume a casting made in 1 1/2%Ni-Cr-Mo steel is to be operated at half of its yield stress (740 N/mm²) (107300 psi) and one application of load, and that it has a surface crack the major axis of which is ~1 1/2 times the length of the minor axis. The fracture toughness (K_{IC}) of the steel is measured at 86 MNm^{-3/2} (78 ksi in.^{1/2}).

The critical defect size may be calculated as follows:

$$a_{cr} = K_{IC}^2 \left[\frac{\phi - 0.212 \left(\frac{\sigma_w}{\sigma_y} \right)^2}{1.21 \pi \sigma_w^2} \right] \dots (1)$$

where K_{IC} = plane strain fracture toughness.

σ_w = gross working stress normal to major axis of the flaw.

a_{cr} = critical depth of a surface flaw (i.e. half the width of an embedded flaw)

σ = 0.2 per cent proof stress.

ϕ = double elliptical integral.

$$\text{Let } Q = \left[\phi^2 - 0.212 \left(\frac{\sigma_w}{\sigma_y} \right)^2 \right]$$

$$\text{Then } \left(\frac{a}{Q} \right)_{cr} = \frac{K_{IC}^2}{1.21 \pi \sigma_w^2} \dots (2)$$

(For embedded flaws the coefficient on the denominator is taken as unity).

To define the shape of the flaw, a/b can be considered to represent the flaw size aspect ratio, where 2a is the minor and 2b is the major axis of an ellipse (i.e. when a/b = 1 the ellipse becomes a circle). The relationship between ϕ and a/b is given in Fig. 17 for easy reference. In this example, a/b = 0.2 and $\sigma_w = 740/2$. Using these values in equation (2),

$$\begin{aligned} \left(\frac{a}{Q} \right)_{cr} &= \frac{K_{IC}^2}{\sigma_w^2} \times \frac{1}{1.21 \pi} \\ &= \frac{(86)^2}{(370)^2} \times \frac{1}{3.80} \\ &= \frac{7396}{136900} \times 0.263 \\ &= 0.0540 \times 0.263 \end{aligned}$$

$$\text{i.e. } a_{cr} = Q \times 14.2 \text{ mm (.56 in.)} \dots (3)$$

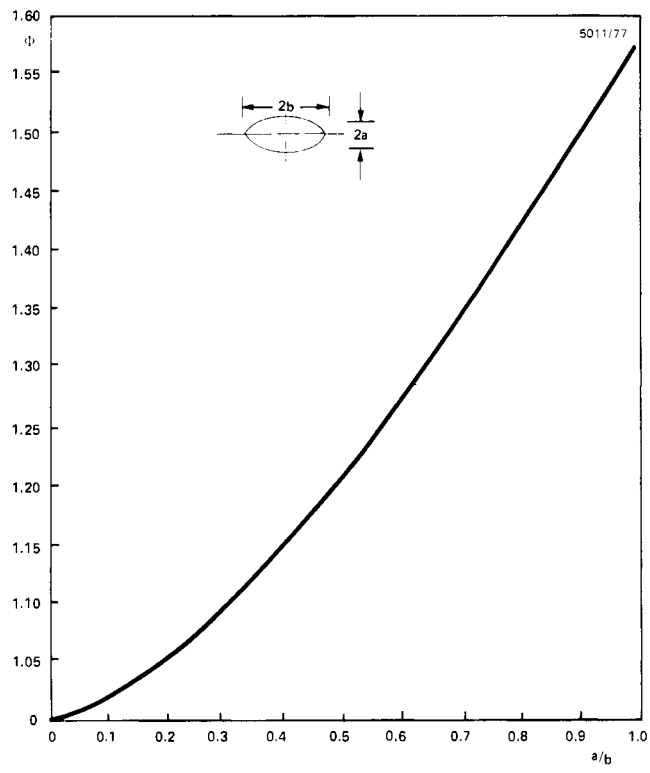


Figure 17—Elliptical function versus aspect ratio

Now, for $a/b = 0.7$, from Fig. 17, $\phi = 1.34$

$$\text{and } Q = \phi^2 - 0.212 \left(\frac{\sigma_w}{\sigma_y} \right)^2$$

$$= (1.34)^2 - 0.212 (0.5)^2$$

$$Q = 1.743 \quad \dots\dots (4)$$

Inserting this value for Q in equation (3)

$$a_{cr} = 1.743 \times 14.2$$

$$a_{cr} = 24.75 \text{ mm (.97 in.)} \quad \dots\dots (5)$$

In a fatigue situation:

$$\frac{da}{dN} = C \cdot (\Delta K)^n \quad \dots\dots (6)$$

where da/dN = rate of crack growth

$$\Delta K = \Delta\sigma (Ma)^{\frac{1}{2}}$$

where ΔK = stress intensity factor range

and $M = 1.21 \frac{\pi}{Q}$ for surface defects

C, n = material constants (typical values relating to cast steels are given in Table IB.

i.e. $\Delta K = \Delta\sigma \left(1.21 \frac{a}{Q} \right)^{\frac{1}{2}}$

$$\frac{da}{dN} = c \left\{ \Delta\sigma \left(1.21 \pi \frac{a}{Q} \right)^{\frac{1}{2}} \right\}^n$$

$$= c \left\{ \Delta\sigma \left(1.21 \frac{\pi}{Q} \right)^{\frac{1}{2}} \right\}^n \cdot a^{n/2}$$

$$\text{Inverting } \frac{dN}{da} = \frac{a^{-n/2}}{C \left\{ \Delta\sigma \left(1.21 \frac{\pi}{Q} \right)^{\frac{1}{2}} \right\}^n}$$

$$N = \int_{a_i}^{a_{cr}} \frac{a^{-n/2}}{c \left\{ \Delta\sigma \left(1.21 \frac{\pi}{Q} \right)^{\frac{1}{2}} \right\}^n} \cdot da$$

$$= \left[\frac{a(1-n/2)}{1-n/2} \cdot \frac{1}{\left\{ \Delta\sigma \left(1.21 \frac{\pi}{Q} \right)^{\frac{1}{2}} \right\}^n} \right]_{a_i}^{a_{cr}}$$

(Equation continued)

$$= \left[\frac{a_{cr}^{(1-n/2)} - a_i^{(1-n/2)}}{1 - n/2} \right] \cdot \left[\frac{1}{c \left\{ \Delta\sigma \left(1.21 \frac{\pi}{Q} \right)^{\frac{1}{2}} \right\}^n} \right] \dots (7)$$

We have the following values for insertion in equation (7):

$$a_{cr} = 24.75 \text{ mm } (.97 \text{ in.})$$

$$a_i = 5.0 \text{ mm } (.20 \text{ in.}) \text{ (i.e. assuming the starting crack size is } 5 \text{ mm } (.20 \text{ in.))}$$

$$Q = 1.06$$

$$c = 10^{-6.96}$$

$$n = 1.75$$

$$M = 1.21 \frac{\pi}{Q} = 2.18$$

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \left(\text{assuming } R = \frac{\sigma_{min}}{\sigma_{max}} = 0.5 \right)$$

$$= \frac{740}{2} - 0.5 \left(\frac{740}{2} \right)$$

$$= 370 - 185$$

$$\Delta\sigma = 185 \text{ MNm}^{-2} \text{ (26825 psi)}$$

Inserting these values in equation (7),

$$N = \left[\frac{24.75 \left(1 - \frac{1.75}{2} \right)^{-5} \left(1 - \frac{1.75}{2} \right)}{1 - \left(\frac{1.75}{2} \right)} \right] \cdot \left[\frac{1}{10^{-6.96} (185 \times \sqrt{2.18})^{1.75}} \right]$$

$$= \left[\frac{1.493 - 1.223}{0.125} \right] \cdot \left[178.53 \right]$$

$$= 2.163 \times 178.53$$

$$\underline{N = 386 \text{ cycles.}}$$

This is the number of cycles that will grow an initial surface crack of 5 mm (.20 in.) depth to 24.75 mm (.97 in.), the critical size, when operating at half the yield stress. By comparison with Table IV for plain carbon steel, a crack of 16 mm (.63 in.) depth will grow to 125 mm (4.92 in.) in 100,000 cycles at half the yield stress. Whilst the operating conditions are not identical, the order of magnitude difference is great and illustrates the point that higher strength steels do not operate well under conditions of cyclic stress.

WRITTEN DISCUSSION by L. Venne, ESCO Corporation

We would like to compliment Dr. Jackson upon his excellent paper on "Fracture Toughness in Relation to Steel Castings Design and Application".

It is evident that the work of SCRATA and some applications in the U.K. are well advanced in relation to the American Foundry Industry in the area of fracture mechanics. Most of us have been taking a "wait and see" attitude to determine what the future requirements of industry would be before committing ourselves in the area of fracture toughness.

We have for many years been depending upon the "v" notch charpy impact test to determine the relative toughness of a given steel but it now appears that this test has a number of shortcomings and we will need to develop additional data for the future.

In this regard I would like to ask Dr. Jackson how he feels we should proceed as an individual company or as an industry to begin obtaining information on our steel in a fracture toughness program.

Dr. Jackson refers to the work of R. O. Ritchie in examining the relationship between charpy impact and fracture toughness. This work shows that the relatively blunt notch of the charpy specimen tends to give results rather opposite to the very sharp radius of the fracture toughness specimen under certain conditions and it would seem that both have significance in determining the effect of critical defects in castings.

Would it be a logical step to work with instrumented charpy testing to obtain dynamic charpy information or should the approach be to LEFM?

Dr. Jackson refers to Crack Growth by fatigue and by stress corrosion. I would ask if Dr. Jackson could comment on the significance of hydrogen in crack growth by stress corrosion cracking especially when studying steels of high yield strength.

AUTHOR'S REPLY

Fracture mechanics involves costly testing and I consider it to be unlikely that K_{IC} or COD testing will ever be written into steel castings specifications as an acceptance test. The day may come, however, when design engineers make increased use of fracture mechanics principles and write specific tests into their own purchasing specifications. I feel more confident in saying that, even if this does not happen, designers will want to know the order of fracture toughness parameters for the more commonly used cast steels. Both SCRATA and the SFSA have carried out work that fulfills the initial needs of the designer.

The SFSA have also related LEFM data to Charpy V-notch data and I think that this will be the approach made with regards to standard specifications. That is, Charpy V-notch parameters (probably FATT) will be included in the specification for a steel, and the designer will know from accumulated data on that steel a value for fracture toughness, at least within a certain scatter band, and will be able to use that value for design and NDT specification purposes.

I believe that the fracture mechanics parameters to be first used in this way will be K_{IC} for LEFM and COD for YFM. As mentioned previously, a fairly substantial body of data exists for these parameters in relation to cast steel. Furthermore, standard specifications for these parameters exist or are in preparation in both the USA and UK. By comparison, more work has to be done on instrumental Charpy testing and the interpretation of results for use in design. The test is cheaper and far quicker of course, and could become, under appropriate circumstances, the alternative acceptance test to Charpy V-notch FATT.

Very little attention has been given to the fracture mechanics approach to cast steels under conditions of stress corrosion. Opinions have been given, for wrought steels, that hydrogen plays an important role in stress corrosion cracking in steels of high yield strength ⁽¹⁾. The importance of hydrogen in HAZ and SCC situations has also been recognized, in so far as hydrogen will induce cracking and correlations between

$$\left(\frac{K_{Q,SCC}}{\sigma_y} \right)^2$$

and hardness and microstructure have been proposed. ⁽²⁾

The mode of microscopic fracture under varying conditions of electrode potential can under go a transition depending on initial K level relative to K_Q in air ⁽³⁾. At intermediate K levels, however, stress corrosion crack growth rates are essentially independent of K and the tendency for stress corrosion cracks to branch are electrochemically, as well as mechanically, controlled. It is apparent that conditions at the crack tip have an important bearing on the mode and kinetics of crack propagation in steels of high yield strength, but no specific work has been carried out on cast steels. Stress corrosion behavior of cast stainless steels has however, been studied in relation to delta-ferrite content and sensitization⁽⁴⁾.

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