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Fundamental Considerations of Fatigue, Stress-Corrosion Cracking and Fracture in Advanced Ship Structures

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ABSTRACT

The ship structure community today stands on the brink of encountering the occurrence of fatigue, stress-corrosion cracking, and fracture heretofore considered solely the burden of the aerospace community. These problems arise out of the fundamental nature of high-strength alloys. However, the prospects for successfully dealing with these phenomena in ship structures are far better today than was the situation when such difficulties arose in aerospace structures in the past. The potential for fatigue, stress-corrosion cracking and fracture in high-strength alloys is well recognized and varying degrees of technology are currently available for analytical treatment and control. This paper describes the basic tendencies of high-strength alloys toward susceptibility to fatigue, stress-corrosion cracking, and fracture with increasing strength level. Quantitative approaches for assuring structural integrity are presented.

INTRODUCTION

Advanced ship structures which are presently emerging, such as high-performance hydrofoil craft and surface effect ships, involve the use of structural alloys significantly higher in strength/density properties than the steels familiar to the ship building industry. These new ship designs contemplate the structural application of alloys such as 17-4 precipitation-hardening stainless steels, HY-130 steel, 5000-series marine aluminum, and perhaps even titanium. However diverse these various materials may appear to be, they share certain common fundamentals which bear upon their safe and reliable use in naval structures. By necessarily moving towards the use of these higher strength/density alloys, ship designers have inherently escalated the risks of fatigue, stress-corrosion cracking (SCC) and fracture in advanced ship structures.

With the notable exception of well documented temperature-induced brittle fracture problems in low and intermediate strength ship steels, the ship building industry has largely avoided the types of serious fatigue, SCC, and fracture problems which have plagued the aerospace industry for more than 30 years. However, the evolution of a new generation of high-performance ships threatens to disrupt this favorable status quo. The ship structure community today stands on the brink of encountering the occurrence of fatigue, SCC and fracture problems heretofore considered soley the burden of the aerospace community. However, the prospects for successfully recognizing and dealing with these phenomena in ship structures are far better than was the situation when such difficulties arose in aerospace structures in the past.

The evolution of a comprehensive structural integrity technology today offers a rational means of integrating materials characterization and selection, structural design and testing, fabrication and nondestructive inspection technologies into a unified effort capable of achieving safe and reliable high-strength structures. This paper offers an introduction to the fundamentals of fatigue, SCC and fracture as they relate to the structural integrity of advanced ships.

DESCRIPTION OF PHENOMENA

Fatigue

Metal fatigue involves the initiation and growth of cracks under the action of cyclic stresses caused by repeated application of service loads. Residual stresses remaining from fabrication also play an important role in aggravating metal fatigue. In ship structures, particular emphasis is placed on the crack growth stage of fatigue because of the significant probability of defects being introduced into critical regions of the structure during fabrication. This concept of the preexisting flaw which escapes detection during nondestructive inspection is one which the aerospace community has adopted after experiencing disastrous failures, a lesson which has not escaped the notice of Navy ship designers.

Metal fatigue takes on greater importance with increasing yield strength level because higher strength alloys seldom, if ever, offer superior fatigue crack growth resistance as compared to lower strength materials, yet are expected to sustain higher working stresses in service. The result of this fact is a tendency to "overwork" high-strength alloys in fatigue situations, thus hastening fatigue failure.

Another factor which serves to complicate the use of high-strength alloys in fatigue is corrosion. For most structural alloys, the presence of a seawater environment significantly accelerates fatigue crack growth. The effects of corrosion-fatigue tend to be greater in high-strength materials, especially if coupled with stress-corrosion cracking. Fatigue and corrosion-fatigue pose long-term threats to the reliability and life-cycle costs of advanced high-strength ship structures.

Stress-Corrosion Cracking

Stress-corrosion cracking (SCC) is the growth of cracks under the combined influences of sustained tensile stress and a seawater environment. It is a particular hazard to welded structures which contain tensile residual fabrication stresses and weld defects where cracks can readily nucleate. However, unlike metal fatigue which occurs in all classes of materials, many structural alloys are virtually immune to SCC. The primary determining factor in SCC immunity is yield strength level. As yield strength is increased, SCC sensitivity also tends to increase. Based on present knowledge, there appears to be a minimum yield strength level below which SCC does not occur in structural metals. For steel base plate this is approximately 120 ksi (84.4 kg/mm^2); however, for ferrous weld metals it may be as low as 80 ksi (56.2 kg/mm^2).

Metallurgy and electrochemistry play important roles in both SCC and corrosion-fatigue. At any given yield strength level, the sensitivities of various alloys to these environmental crack growth phenomena vary widely depending upon metallurgical and electrochemical factors. As yet, there are few scientific principles for metallurgically designing alloys to resist environmental crack growth, so definitive testing must be pursued. However, certain alloys have been found to be notably superior or inferior in this regard, and such testing is necessary to assure that the particular chemical composition/processing/heat treatment combination intended for a marine material offers adequate properties.

Electrochemistry has a very pronounced effect on environmental crack growth. Sources of electrochemical effects can be the unintentional coupling of dissimilar metals, such as steel hydrofoils to an aluminum hull, or sacrificial anodes, such as zinc, intentionally placed on a structure to prevent surface corrosion. One of the major complexities of dealing with environmental crack growth is that electrochemical conditions which suppress general surface corrosion (pitting) promote SCC and corrosion-fatigue crack growth. The overall problem of environmental crack growth is exceedingly complex and represents a threat to the uninformed ship designer venturing into the application of unfamiliar materials.

Fracture

Fracture, of course, is a well known phenomenon to ship designers. However, the problem as it applies to advanced ships is one of brittleness associated with increasing yield strength, rather than brittleness associated with decreasing service temperature, as has been experienced in the past. Here, metallurgical and geometric factors become of paramount concern. The embrittling effects of higher yield strength can be offset through metallurgical control, and the thinner section sizes associated with high-performance ships are less prone to brittle fracture than ordinary heavy section ship materials because of their greater ability for localized plastic deformation around crack tips. The goal of fracture control in advanced ships is largely attainable with present technology, but requires complex trade-off decisions between yield strength, thickness, and metallurgy which must be based on quantitative fracture criteria.

METHODS FOR CHARACTERIZATION

Fracture Mechanics Concepts

Quantitative methods for the engineering characterization of fatigue and corrosion-fatigue crack growth, stress-corrosion cracking and fracture rely both directly and indirectly upon linear elastic fracture mechanics. Pertinent parameters such as the rate of fatigue crack growth per cycle of repeated load, the threshold conditions for SCC crack growth to initiate, and the conditions for unstable fracture initiation to occur correlate with the fracture mechanics crack-tip stress-intensity factor (K).

The traditional schematic illustration of the fracture mechanics crack-tip model is shown in Fig. 1. It shows that in metals under tensile stress which contain a sharp crack, a small zone of plastically strained material occurs at the crack tip. Events in this microscopic region at the tip of a single crack can control the performance of an entire structure.

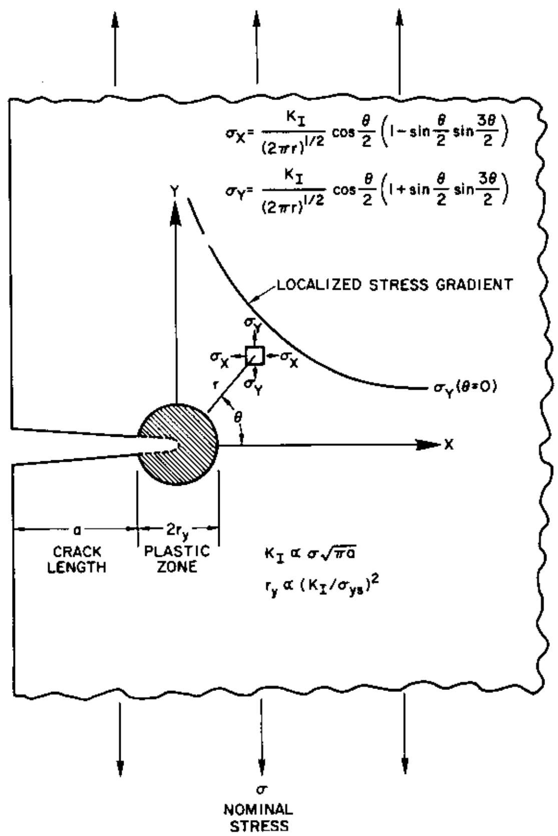


Fig. 1 Fracture mechanics model for a sharp crack in metals under applied stress. The stress-intensity factor (K) defines the stress gradient ahead of the crack tip and also defines the size of the plastic zone (r_y).

The crack and its plastic zone at the tip cause an abrupt rise in stress as this vicinity is approached. The parameter which describes this abrupt rise in stress, from elastic nominal stress levels remote from the crack tip to levels above yield within the plastic zone, is called the stress-intensity factor (K).

Dimensionally, K is directly proportional to the product of nominal stress (σ) and the square root of crack size (a)

$$K \propto \sigma\sqrt{\pi a} \qquad (1)$$

and has units of psi$\sqrt{in}$. The exact expression of proportionality is dependent upon geometry. Numerous expressions for calculating K in various geometries can be found in handbooks on the subject [1,2].

However, once a value of K is established by calculation, its significance is geometry-independent. Therein lies the importance of linear-elastic fracture mechanics. K values measured in laboratory characterization specimens, using established engineering principles, can be directly meaningful to calculated K values which are found to exist in structures. In fact, there exists no alternative technology for dealing with cracks in structures. Despite well recognized limitations, fracture mechanics remains a vital key to the overall problem of structural integrity in advanced ship structures.

Fatigue Crack Growth

The engineering technology for dealing with fatigue crack growth in structural alloys rests on an empirical correlation between the rate of crack extension per cycle of repeated load (da/dN) and the crack-tip stress-intensity factor range ($K_{max} - K_{min} = \Delta K$). This relationship takes the form of a power law

$$da/dN = A\ (\Delta K)^m \qquad (2)$$

where A and m are material constants. An example of this type of characterization data is shown in Fig. 2; which is a log-log plot of da/dN vs. ΔK for 5Ni-Cr-Mo-V steel using results from tests on three specimen types of differing geometries.

Crack growth rate data does not define "fatigue life" per se. Rather, it provides an analytical basis for calculating the cyclic life interval between "initial" and "terminal" crack sizes, as illustrated schematically in Fig. 3. Such calculations can serve as the basis for establishing inspection intervals for critical components of structures which undergo repeated service stresses. Crack growth rate data also serve to determine the anticipated overall service life of structural components which are non-inspectable and known to be prone to cracking (e.g., blind welds).

In actual practice, the analysis of fatigue crack growth in structural situations is considerably more complex than what has been presented here, and involves consideration of such aspects

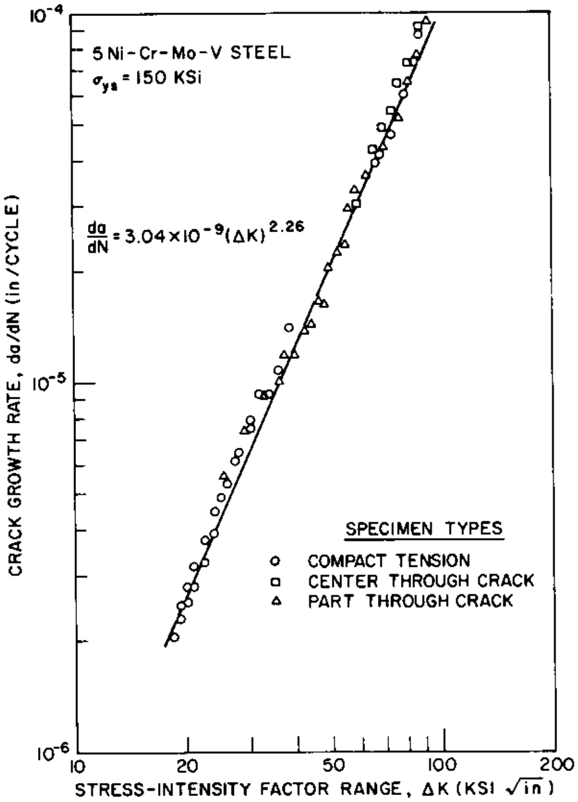


Fig. 2 Relationship between fatigue crack growth rate (da/dN) and crack tip stress-intensity factor range (ΔK) for a high-strength steel as determined from tests on three types of fracture mechanics specimens.

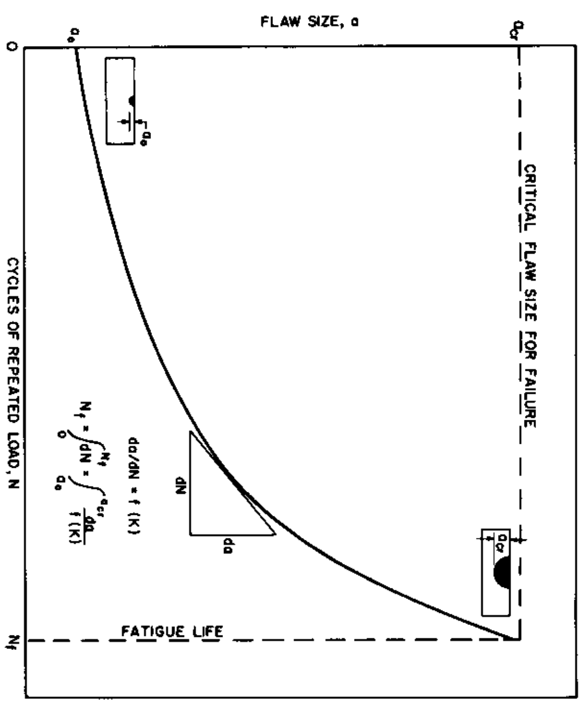


Fig. 3 Methodology for using fracture mechanics based crack growth rate data to predict the fatigue life of structural components.

as environment, residual stresses and loading spectra [3]. However, this discussion has provided an introduction to the fundamentals of fatigue crack growth characterization. This type of materials testing is currently in the process of being standardized both by the ASTM and in Military Standards [4,5]. Standardized fatigue and corrosion-fatigue crack growth rate data will be one of the major sources of engineering input for structural integrity plans for future advanced ships.

Stress-Corrosion Cracking

The engineering technology for dealing with SCC in structural alloys is based upon the existence of a stress-intensity threshold (K_{Iscc}) below which SCC does not occur. That is, like fracture control, it is based on a prevention concept, whereas fatigue crack growth is based more on inspection and repair concepts, except in special situations involving non-inspectable components.

SCC tests are conducted with tensile-loaded precracked specimens which are exposed to seawater or laboratory salt solution for extended periods of time, up to several thousand hours in some cases. An example of the type of data obtained in these tests is shown in Fig. 4. The objective here is to maintain the test for a sufficient period of time to assure that a threshold has been reached (at least 1000 hours for steels and at least 100 hours for titanium alloys).

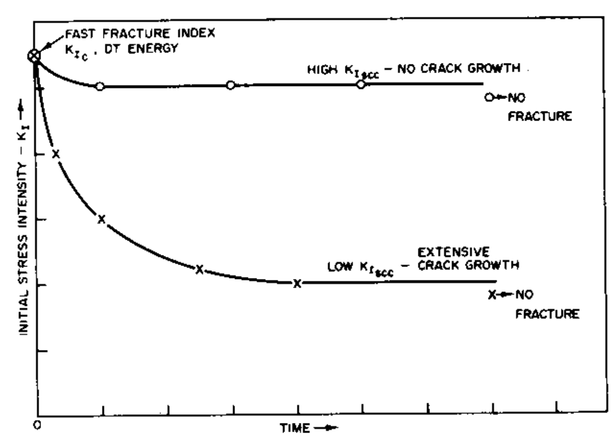


Fig. 4 Typical stress-corrosion cracking test results used to determine K_{Iscc} threshold levels in structural alloys.

The measured value of K_{Iscc}, which in all cases be less than the fracture toughness level of the material, then serves as a maximum permissable stress-intensity for sustained loads in structural components which may contain cracks and are exposed to seawater. If K levels in excess of K_{Iscc} cannot be avoided where seawater is present, then stress-corrosion crack growth can be expected to occur. At present, there are no design criteria for dealing with stress-corrosion crack growth on a basis similar to fatigue crack growth, which is much more difficult than SCC to approach on a prevention basis. At present, SCC test methods are being standardized by both the Navy and the ASTM [6].

Fracture

Following the widespread occurrence of brittle fracture in ship structures which began during World War II, a wide variety of fracture tests came into existence. The problem in selecting an appropriate fracture test for use in relation to advanced ships is twofold: (i) the test must adequately characterize the fracture resistances of a broad range of materials and (ii) the test data must correlate with a fracture mechanics parameter, where applicable, and also with structural prototype element test results and with service experience.

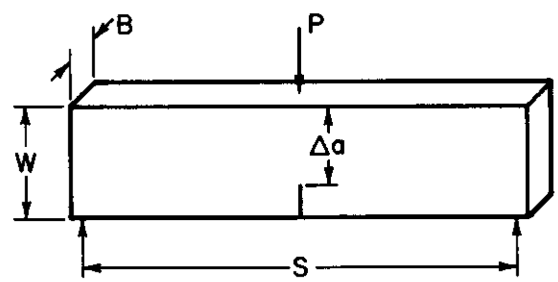
The Navy approach to this problem has been the development of the Dynamic Tear (DT) test. The salient features of this test are the use of simple notched specimens readily fractured in drop-weight machines, without expensive specimen preparation or elaborate test procedures. The fracture energy value obtained from this test can be empirically correlated with the plane strain fracture toughness (K_{Ic}) for steels [7], titanium alloys [8] and aluminum alloys [9], thus permitting fracture mechanics data to be obtained from DT test results. More importantly, the DT test can be utilized for quantitative measurement of high levels of plastic fracture resistance in structural metals, which are beyond the current measurement capabilities of linear elastic fracture mechanics. Such DT fracture resistance measurements provide a background of knowledge that is useful for the classes of materials which comprises the vast majority of Navy structures, both present and future.

The DT test has been developed in two sizes, 1-in. and 5/8-in., with the 5/8-in. being standardized by the Navy and the ASTM [10,11]. Work has also been done to adapt the DT test to thinner section materials which are of interest to high-performance ships [12]. Size effects in DT test results [8] can be rationalized through the equation

$$E = R_p\ (\Delta a)^x (B)^y \qquad (3)$$

where E is the fracture energy, Δa is the length of crack run in the specimen (Fig. 5), B is the specimen thickness, and R_p is a characteristic fracture parameter which remains constant for any given material, regardless of DT specimen size. The DT test has proven to be an invaluable Navy tool in materials selection, fabrication development, and quality control procedures for assuring structural integrity of advanced ship structures.

DYNAMIC TEAR TEST



$$\text{ENERGY} = R_p\ B^X\ \Delta a^Y$$
$$\text{WHERE } R_P = \text{CONSTANT}$$

STANDARD SPECIMENS

B		Δa		W		S	
(IN.)	(CM)	(IN.)	(CM)	(IN.)	(CM)	(IN.)	(CM)
0.63	1.6	1.125	2.9	1.625	4.1	6.5	16.5
1.0	2.5	3	7.6	4.75	12.1	16	41

Fig. 5 Dimensions of standard Dynamic Tear (DT) specimens.

PRINCIPLES FOR APPLICATION TO STRUCTURAL INTEGRITY

Fracture mechanics characterization data, per se, are of nominal value to ship designers without the aid engineering principles, procedures and criteria for their application to problems of structural integrity [13,14]. Among the phenomena discussed in this paper, principles for the application of fracture technology are the most highly developed and will be discussed in some detail. Also, fracture is the only phenomenon where a substantial amount of correlation between characterization tests and service experience exists at the present time.

Principles and criteria for dealing with crack growth phenomena (fatigue, corrosion-fatigue and SCC) are far more rudimentary at this stage of development. However, that does not imply that engineering procedures for dealing with these phenomena do not exist, but rather that such knowledge has not yet evolved into general engineering principles which can be summarized for broad application. For instance, one of the steps in establishing the structural integrity of the PHM fast craft strut/foil structure system has been a detailed comprehensive flaw growth analysis. The fundamental basis for this analysis was the type of fatigue technology which has been presented in this paper. However, application of this fatigue technology to specific problem areas remains arcane at the present state of development. Therefore the remainder of this paper will concentrate on a discussion of well established procedures for applying fracture control technology and the gradually evolving extension of these principles into the area of SCC prevention.

Prevention and/or control of rapid fracture extension for any specific structure involves simultaneous consideration of three factors - the thickness, (B) the yield strength, (σ_{ys}) and the intrinsic fracture resistance of the material used in the structure. As with any design process, fracture prevention consists of assessing the structural requirements in terms of minimum allowable fracture resistance for the material, plus any margin of safety that may be deemed necessary. For many structures, the mere avoidance of brittle fracture (i.e., plane strain crack-tip conditions) is a sufficient design objective; for many others, however, higher levels of tolerance for high stresses and large cracks are necessary.

To understand the trade-offs between thickness, yield strength, and fracture resistance necessary for fracture prevention, one must comprehend the three fundamental fracture states (plane strain, elastic-plastic, fully plastic) which describe failure conditions for metals, and the rationale for defining the differences between them. Plane strain (i.e., brittle) fracture occurs in that group of materials, usually at very high strength levels, for which unstable crack propagation can be initiated from relatively small flaws and elastic stresses; the self-propagating nature of the fracture process renders such materials useful only for application where a strong benefit of the high strength property is realized or where redundancy can be designed into the structure. Linear elastic fracture mechanics was developed to describe brittle fracture, and in fact, strict quantitative description of fracture remains limited to the brittle plane strain mode. The parameter K_{Ic} is a property of brittle materials which defines the point of unstable crack initiation. Linear elastic-fracture mechanics is applied to design problems by use of a group of equations relating the parameter K_{Ic} to applied stress flaw size, and geometry factors. By including the material yield strength in these equations, the ratio K_{Ic}/σ_{ys} then defines the resistance to brittle crack extension in a fully rational manner.

The majority of materials that are used in Naval construction are of the plastic or elastic-plastic fracture resistance type. Materials which exhibit plastic fracture characteristically deform beyond yield under high stress in the presence of a sharp crack, and require a large expenditure of energy to sustain the fracturing process. DT test methods are used to measure the fracture properties of these materials and interpretations to structural design are made through comparisons to larger structural element test results and/or to service experience. The fully plastic and the plane strain fracture modes represent the extremes of a smooth spectrum of properties that varies with yield strength; a relatively sharp transition region between these two fracture states is termed elastic-plastic fracture. The locus of separation lines between the fracture states vary systematically according to thickness as defined by generally accepted criteria.

The above discussion can be summarized on the Ratio Analysis Diagram (RAD), Fig. 6, which is a "plotting board" format for analyzing materials properties and structural requirements. The important details of the RAD are the envelope of data defining available materials properties and the lines of constant K_{Ic}/σ_{ys} ratio, which define the separations of fracture mode in terms of thickness. The elastic-plastic "slice" is bounded by the ASTM defined plane-strain limit [15] and the generally accepted yield criteria limit [13].

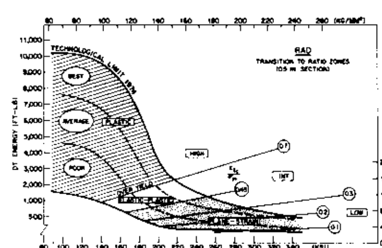


Fig. 6 NRL Ratio Analysis Diagram (RAD) for steels showing metal quality corridors. The plane strain, elastic-plastic and fully plastic zones are defined for 0.5in. thick section sizes.

The RAD is utilized for material trade-off studies by plotting values of K_{Ic} or DT energy vs. σ_{ys} on a diagram scaled for the correct thickness; the effects of many such variables as heat-treatment, chemistry, material quality, etc., can be readily analyzed by the use of the RAD. It is worth observing at this point that fracture data, like most other materials property data, are statistical in nature and therefore most materials are represented by ranges of properties rather than single data points, as is illustrated in Fig. 7. The RAD concept has been well established for analysis of fracture in steel, aluminum and titanium alloy systems and is currently being verified for analysis of potential crack growth in SCC.

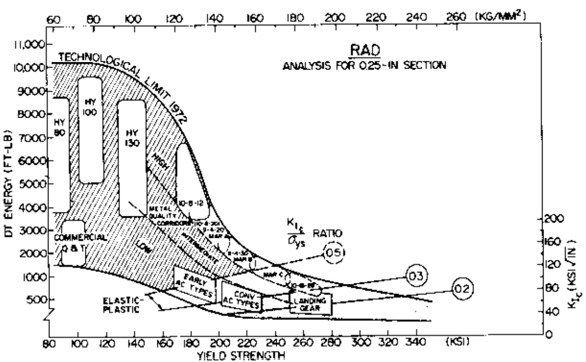


Fig. 7 RAD zoned for 0.25-in. thick steels showing the loci of data for particular structural steels and determined from test results.

Extension of the RAD [16] concept to examine the propensity of materials for crack growth by SCC, and to compare SCC and fracture properties in a given alloy depends on entering the K_{Ic} scale. Equations for relating K, σ, and geometry can be employed to predict growth of cracks as a function of applied stress and crack size; this format is identical to that defined on the RAD for fracture. A plot of SCC data for steels on the RAD is shown in Fig. 8. The SCC RAD is arbitrarily divided into regions of "high," "intermediate" and "low" resistance to crack growth as a first-order ranking criterion for SCC resistance in steels.

These data only define the necessary threshold conditions for initiation of SCC crack growth. K_{Iscc} values do not infer the rate at which SCC cracks will grow once initiated. Such crack growth rates vary widely among structural alloys. Final failure, however, is not influenced by a sea-water environment, and fracture toughness values obtained from standard K_{Ic} or DT tests irrespective of environment are subject to the same interpretation.

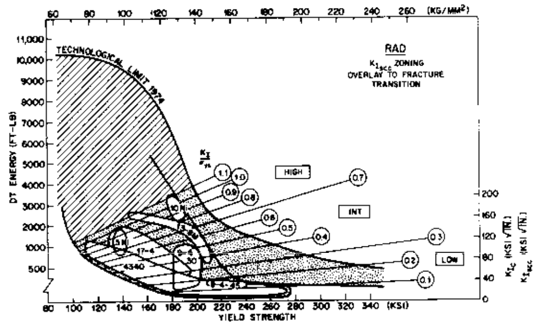


Fig. 8 K_{Iscc} threshold levels for steels plotted on the RAD format.

SUMMARY

The overall long-term stuctural integrity of the new generation of high-performance ship structures will, to a large extent, be determined by crack growth and fracture performance. Ship designers who are venturing into these uncharted areas must gain an understanding of crack growth and fracture technology. This paper has presented and reviewed the fundamental aspects of these topics. Although much remains to be accomplished, particularly in translating fundamental materials characteristics into engineering principles, the general outlines of the problem are well established and engineering methods for achieving structural integrity have been initiated.

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