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FRACTURE OF STRUCTURAL ALLOYS AT TEMPERATURES APPROACHING ABSOLUTE ZERO*

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INTRODUCTION

Plastic deformation and fracture are often viewed as competitive processes. Factors that increase an alloy's resistance to slip usually tend to enhance the probability of brittle fracture. Temperature reductions can lead to pronounced increases of yield strength, while ductility may be decreased, resulting in flaw-sensitive mechanical behaviour. For this reason, alloys employed at normal temperatures may be unusable at low temperatures, and the fracture toughness of candidate alloys for extreme cryogenic service is a vital design consideration.

With the advent of superconducting electrical machinery we face for the first time a demand for fail-safe, efficiently designed structures that must be cooled with liquid helium to temperatures as low as 4 K. Fracture data are urgently needed to enable judicious material selection for a temperature extreme that previously was rarely experienced. Due to its inertness and proximity to absolute zero, liquid helium at 4 K provides a unique environment where the thermally-activated deformation processes of materials are suppressed, and lattice friction stresses are nearly maximized. Therefore, fracture tests in this environment should provide information of current scientific interest as well as data of engineering utility.

Previous studies of low temperature fracture were hampered by the lack of a quantitative parameter that could be applied to a broad range of material/temperature combinations. The traditional notched tensile and Charpy tests provide only qualitative indications of crack tolerance, while the K_{IC} test applies only to high strength alloys, which fail in the elastic range. None of these parameters are well suited for characterizing the ductile and tough austenitic alloys which offer maximum fracture resistance at cryogenic temperatures.

In this study, J-integral and K_{IC} tests were used to characterize the fracture behaviour of 14 alloys at temperatures from 295 to 4 K. The parameters measured, K_{IC} and J_{IC}, are complementary, being related in the linear-elastic case by the equation:

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

J_{IC} is believed to be a material constant, applicable in both the elastic and elastic-plastic cases. Thus, the newly developed J_{IC} criterion offers a method for comparing the fracture behaviour of low, medium, and high strength alloys - a task that was problemmatic in the past.

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EXPERIMENTAL PROCEDURES

The commercial alloys listed in Table 1 were tested using compact specimens 20 to 38 mm thick. Where possible, K_{IC} was measured and J_{IC} was obtained by equation (1). Otherwise, J_{IC} was obtained directly using the resistance curve method, which requires back extrapolation of J-vs-Δa data for a series of specimens [1]. Crack extension, Δa, was averaged at 25, 50, and 75% of specimen thickness, and the $J = 2A/Bb$ approximation was used. Although special cryostats were required to retain liquid helium, the test procedure at 4 K was similar to that at room (295 K) and intermediate temperatures.

The tensile properties of the alloys were also measured, following ASTM Method E8-69, and the elastic constants were obtained by Ledbetter et al, using ultrasonic methods [2]. The chemical analyses of these alloys and other procedural details are available in comprehensive reports [2].

RESULTS

Strength Level and Fracture Mode

Table 1 lists selected mechanical property results at 4 K. Following Tetelman and McEvily [3], it is convenient to classify these materials as

$$\text{low}\left(\frac{\sigma_y}{E} < 0.003\right),\quad \text{medium}\left(0.003 < \frac{\sigma_y}{E} < 0.006\right)$$
$$\text{and high strength}\left(\frac{\sigma_y}{E} > 0.006\right)$$

alloys. Decreasing the temperature from 295 K to 4 K serves to increase the strength level, with σ_y/E increasing by amounts ranging from 17% for 5083-0 aluminum to 245% for 21-6-9 stainless steel. Most of the alloys displayed plasticity when fractured at 295 K in the thickness stated, necessitating J tests. However, at 4 K the majority of alloys (all of the ferritic steels and titanium alloys, as well as several precipitation-hardened fcc alloys) were linear-elastic. It was noted that alloys having $\sigma_y/E > 0.006$ usually satisfied the ASTM E-399-74 specimen thickness requirement; exceptions were the ELI Ti-6Al-4V alloy at 295 K and the 21-6-9 stainless steel at 4 K.

Strength Versus Fracture Toughness

Although a combination of high yield strength and high fracture toughness would be ideal, in reality these properties are antithetical. It appears that designers must seek an alloy with the optimum combination of strength and toughness for a given application. An inverse relationship between σ_y and K_{IC} at room temperature has been demonstrated for steel, aluminum, and titanium alloys [4]. It must be appreciated that a similar trade-off exists for alloys at cryogenic temperatures, and for elastic-plastic fractures as well.

The J_{IC} and σ_y/E data at 295 and 4 K are plotted on logarithmic coordinates in Figure 1. These results show that the low strength alloys exhibit a wide variation in toughness, but the spread of observed J_{IC} values decreases with increasing σ_y/E, following a trend that holds for two orders of magnitude in J_{IC}. Thus, empirical results for technologically important materials support the following conclusion: relatively low fracture toughness values are possible at any strength level, but the maximum toughness attainable with commercial alloys is an inverse function of strength throughout the elastic and elastic-plastic ranges.

The Temperature Dependence of J_{IC}

Temperature effects on J_{IC} correlate well with crystal structure. Figure 2 illustrates three distinct trends for alloys having the fcc, bcc and hcp structures. The data presented in this figure are representative in that fcc alloys typically exhibit high toughness throughout the ambient-to-cryogenic range, while hcp alloys are noted for low toughness, and bcc alloys shown abrupt transitions to brittle fracture modes involving cleavage. Secondary metallurgical factors (composition, purity, heat treatment) can modify the fracture toughness of alloys within each crystal structure class considerably, as indicated by the following.

I. The fcc alloys can be categorized into three sub-groups:

1. Stable, annealed fcc alloys show sizable increases in toughness as temperature is reduced from 295 to 4 K. The AISI 310 stainless steel and 5083-0 aluminum alloys tested in this study show J_{IC} increases amounting to 55% and 175%, respectively.

2. Precipitation-hardened fcc alloys show mild temperature dependences. Included here are Inconel 750*, Inconel 718, A-286, and 2014-T652 aluminum. The toughness of these alloys either increased, decreased or remained constant, but the change in J_{IC} between 295 and 4 K never exceeded 30%.

3. Metastable austenitic alloys undergo martensitic phase transformations during tests at low temperatures. Two such alloys, AISI 316 and 21-6-9 stainless steels, were studied here. Martensitic phases were detected at the fracture surfaces of specimens tested at 4 K, but there was no evidence of transformations at 295 K. AISI 316 shows an increase in J_{IC} between 295 and 4 K, whereas 21-6-9 exhibits a sizable decrease. Thus, it is difficult to generalize on the effects of phase transformations; favourable as well as adverse effects are possible.

II. The bcc alloys including ferritic steels are of limited use due to their transitional behaviour. As a class, the 3.5, 5.5, and 9% Ni steels exhibited the largest J_{IC} decreases observed in this study. The transition for 9% Ni steel occurs at $76 > T > 4$ K, where J_{IC} is reduced by 82%. However, note that J_{IC} actually increases by 20% as temperature decreases from 295 to 111 K, just prior to the transition. Similar increases of J_{IC} in the "upper shelf" regions were observed for 3.5 and 5.5 Ni steels, but, due to lower Ni content, the transition temperature ranges for these steels were higher in comparison with 9% Ni steel.

III. Although the toughness attainable with hcp alloys is relatively low in comparison with austenitic alloys, some hcp titanium alloys offer unique physical properties, such as superior strength-to-weight and strength-to-thermal conductivity ratios, which guarantee their use in many applications. As indicated in Figure 2, a mildly adverse temperature dependence is accepted as the general trend for the Ti-5Al-2.5Sn and

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* Tradenames are used for the sake of clarity, and do not imply recommendation or endorsement by NBS.

Ti-6Al-4V alloys which are most favoured for cryogenic service. Nevertheless, many unalloyed hcp metals (Cd, Zn) display ductile-to-brittle transitions, and tests of an extra-low-interstitial, recrystallization annealed Ti-6Al-4V alloy revealled a sharp decline of K_{IC} in the relatively narrow interval $76 < T < 125$ K, [5]. A comparison of data for ELI and normal Ti-6Al-4V grades (Table 1) confirms that fracture results for these alloys are particularly sensitive to material condition and purity.

CONCLUSION

The J-integral was used to evaluate and compare the low temperature fracture behaviour of 14 commercial structural alloys. The results suggest several generalizations that should aid in predicting the behaviour of untested alloys. However, many factors affect fracture behaviour, and exceptions to the general trends noted here undoubtedly exist. Moreover, rankings of fracture toughness based on J_{IC}, a fracture initiation parameter, may not be equivalent to rankings based on initiation/propagation parameters as measured, for example, in dynamic tear tests.

ACKNOWLEDGEMENTS

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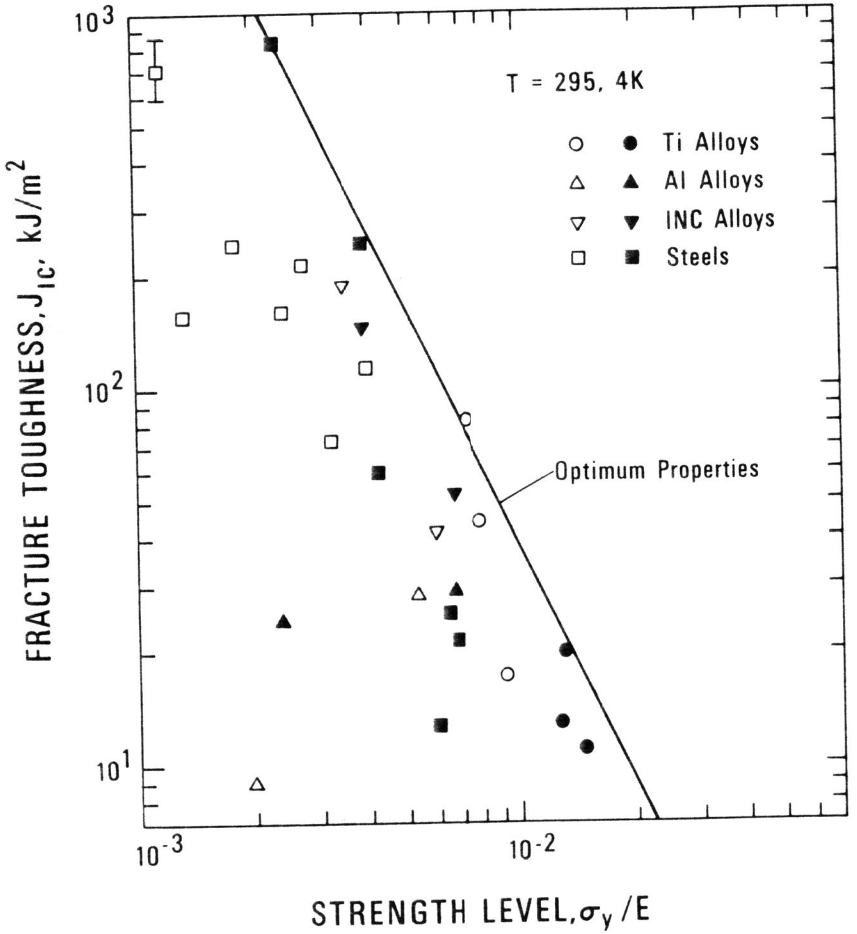

Figure 1 Fracture Toughness as a Function of σ_y/E for Commercial Alloys Tested at 295 and 4 K

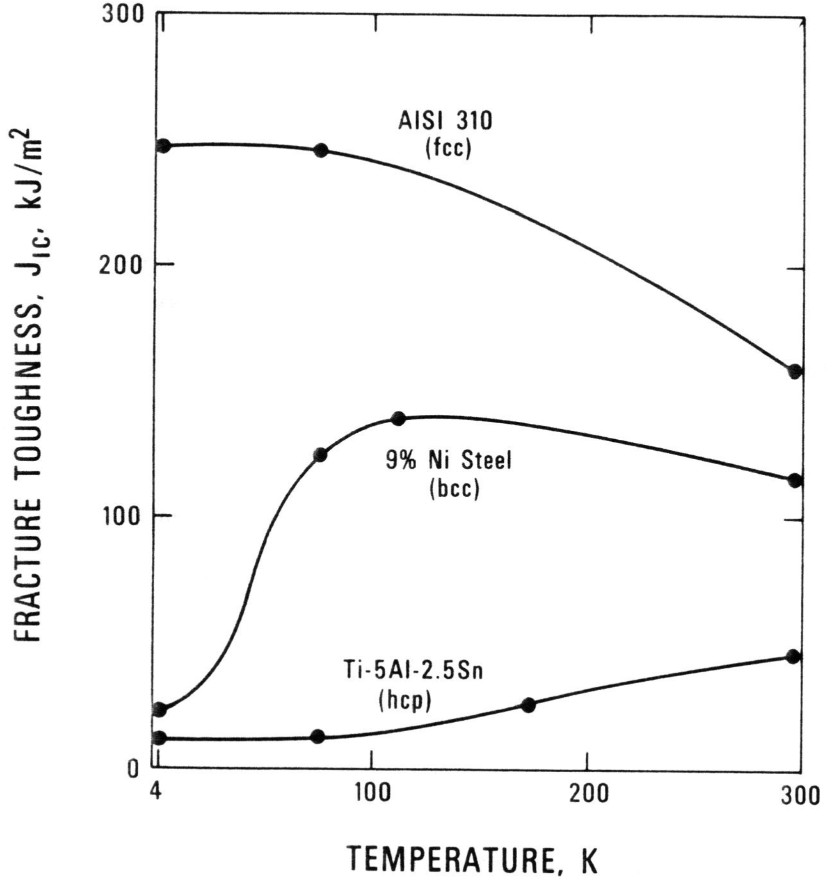

Figure 2 The Temperature Dependence of J_{IC} for Alloys Representing Three Crystal Structures

Table 1 Test Materials and Selected Results

Material and Condition	Spec. Thickness (cm) and Orientation	Yield Strength at 4K, σ_y (MPa)	Young's Modulus at 4K (GPa)	Poisson's Ratio at 4K, ν	K_{IC} (MPa·m$^{1/2}$) 295K	4K	J_{IC} (kJm^{-2}) 295K	4K
5083-O Aluminum (annealed)	3.2, TL	186	81.0	0.318	--	--	9.0	25.0
2014 Aluminum (T652 temper)	3.8, TL	547	83.8	0.330	50.0	53.4	29.2	30.3
Ti-6Al-4V, Normal (mill annealed)	2.5, TL	1792	122.0	0.309	47.0	38.5	17.8	11.0
Ti-6Al-4V, ELI (Recryst. annealed)	2.0, TL	1660	126.0	0.308	--	54.0	86.0	20.9
Ti-5Al-2.5Sn, Normal (annealed)	3.8, TS	1551	123.0	0.311	75.7	42.0	46.1	12.9
Inconel 718 (soln. treated & aged)	2.5, TS	1408	211.0	0.295	96.0	112.0	42.0	54.2
Inconel 750 (soln. treated & aged)	3.8, TS	869	219.0	0.296	--	--	193.0	149.0
A-286 (soln. treated & aged)	3.8, TS	889	212.0	0.281	--	--	74.5	61.2
AISI 310 (annealed)	3.8, TL	765	199.0	0.296	--	--	158.0	245.0
AISI 316 (annealed)	3.8, TL	545	234.0	0.281	--	--	∿740.0	875.0
21-6-9 Stainless (annealed)	3.8, TL	1240	--	--	--	--	∿245.0	26.3
A203-E (3.5% Ni Steel) (quenched & tempered)	2.5, TL	900	215.0	0.282	--	∿30.0	163.0	3.8
A645-74 (5.5% Ni Steel) (austenitized, temperized, & reversion annealed)	3.1, TL	1200	209.0	0.282	--	∿50.0	222.0	13.3
A553-72A (9% Ni Steel) (quenched & tempered)	3.1, TL	1329	202.0	0.285	--	∿73.0	117.0	23.2