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DUCTILE FRACTURE OF TI-5AL-2.5SN AT LOW TEMPERATURES

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INTRODUCTION

The ductile fracture of titanium in tension at temperatures below about $0.4T_m$ has recently been investigated by Conrad et al [1]. Special attention was given to Bridgman's necking analysis [2], Cockcroft's fracture criterion [3], growth of voids according to McClintock [4], the relation between fracture stress and dimple size proposed by Hahn and Rosenfield [5] and the computation of fracture toughness from the measured dimple size using the model of Krafft [6]. The present paper presents a similar study into the ductile fracture of the α-alloy Ti-5Al-2.5Sn.

MATERIALS AND PROCEDURE

Composition of the alloy is given in Table 1. Tensile specimens of 5 cm gage length were cut from 0.16 cm dia. swaged and annealed wire with a mean linear intercept grain size of 19 μm. Texture studies indicated that the basal planes were approximately 15° from the wire axis. No second phase β particles were detected by optical microscopy.

Following annealing and subsequent chemical polishing, the wire specimens were held in clamp-type grips (giving a 2.5 cm gage length) and strained to fracture in an Instron machine at a nominal strain rate of $3.3 \times 10^{-4}s^{-1}$ from 4.2 to 800 K. The testing procedure and experimental measurement techniques were similar to those described in [1].

RESULTS AND DISCUSSION

1. Fracture Stress and Strain

The effects of temperature on the average fracture stress $\sigma_f(= L_f/A_f$ where L_f is the load and A_f the cross sectional area at fracture) and on the true strain at fracture $\varepsilon_f(= \ln(A_o/A_f))$ are given in Figure 1. The variation of σ_f with temperature is similar to that for the yield stress [7]. ε_f is relatively independent of temperature between 800 and 200 K and then decreases with further lowering of the temperature.

2. Necking

At the lowest temperatures, the radius of curvature of the neck was fairly large; it decreased only slightly with temperature over the range considered. The ratio of the radius of the specimen cross section at fracture, r_f, to

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the radius of curvature of the neck, R, was between 0.5 and 08. The variation of this ratio (r_f/R) with the true fracture strain ε_f could be considered to be in accord with the curve proposed by Bridgman [2]; however, the present results exhibited considerable scatter about Bridgman's curve. Using Bridgman's equation [2], the present data yielded correction factors between 0.85 and 0.90 for converting the average fracture stress to the "true corrected" plastic flow stress at fracture.

3. Fracture Criterion

To take into account the effect of the tensile stress, Cockcroft [3] proposed a modified work done fracture

$$W = \int_{o}^{\varepsilon_f} \bar{\sigma}\left(\frac{\sigma_1}{\bar{\sigma}}\right) d\bar{\varepsilon} = \text{Const.} \ , \qquad (1)$$

where σ_1 is the maximum tensile stress, $\bar{\sigma}$ is the equivalent flow stress and ε_f is the equivalent strain to fracture. A plot of W obtained from the area under the true stress-true strain curve versus temperature is given in Figure 2. W increases with decrease in temperature to about 100 - 200 K and then decrease again as the temperature is further lowered to 4.2 K. Thus, the constant of Cockcroft's equation is temperature dependent, which was also found to be the case for titanium-interstitial alloys [1]. Also included in Figure 2 is W*, the contribution to W of the thermal component of the flow stress σ^* [1].

4. Fracture Surface Appearance and Dimple Size

The mode of fracture in all cases was cup-cone. Scanning electron microscopy (SEM) studies revealed that the fracture surfaces had the dimpled appearance characteristic of ductile fracture; see Figure 3. The mean linear intercept dimple size D determined from SEM micrographs ranged between 7 and 15 μm; tending to increase slightly with increase in temperature. Dark spots or inclusions were often observed within the dimples, indicating that they were caused by the presence of fine precipitates or inclusions. Only very rarely was there any indication of a twin within a dimple.

Hahn and Rosenfield [5] proposed the following modification of McClintock's [4] equation for the growth of voids in tensile tests

$$\ell nD = \left\{\frac{\sqrt{3}}{2(1-n)} \sinh\left[\frac{\sqrt{3}(1-n)}{2}\left(\frac{2\sigma_r}{\bar{\sigma}_f} + 1\right)\right] + \frac{3}{4}\right\} \varepsilon_f \ , \qquad (2)$$

where D is the void size, n = dlogσ/dlogε the strain hardening exponent, $\sigma_r = \sigma_f \ell n(1+r_f/2R)$ the radial stress component in the neck. A comparison of the measured dimple size (mean linear intercept) with that predicted by equation (2) is given in Figure 4. Reasonable agreement appears to occur to about 15 μm; for larger dimple sizes the measured values are less than those predicted. This suggests that the McClintock analysis is valid for the growth of voids to the grain boundaries, but not beyond. This was also the case for titanium-interstitial alloys [1].

5. Fracture Stress and Dimple Size

Hahn and Rosenfield [5] suggested that the dimple size and fracture stress may be related through an equation similar to that for fracture toughness, namely $\sigma_f D^{1/2} = K_D$, where K_D is some "fracture toughness" constant. K_D was calculated from the present data and found to decrease linearly with temperature, yielding $K_D = 31 - 1.5 \times 10^{-2}\ T\ (10^5 N/m^{3/2})$. These values of K_D are about two orders of magnitude lower than K_{I_c} for titanium alloys [1]. Also, the increase in K_D with decrease in temperature is not in accord with the usual behaviour of K_{I_c}.

6. Fracture Toughness and Dimple Size

Krafft [6] proposed that K_{I_c} correlates with the plastic flow properties of a given material through

$$K_{I_c} = E\ n\sqrt{2\pi d_T} \ , \qquad (3)$$

where d_T is the process zone size, E is Young's modulus and n = dlogσ/dlogε. A plot of $K_{I_c}{}^2/\sigma_{ys}{}^2$ versus σ_{ys}/E for the present Ti-5Al-2.5Sn alloy using the values of K_{I_c} calculated through equation (3) and taking d_T = D is presented in Figure 5. σ_{ys} is the 0.2% yield stress. The ratio $K_{I_c}{}^2/\sigma_{ys}{}^2$ is an index of the crack size tolerance under plane strain conditions [8].

Also depicted in Figure 5 is the band representing the range of values reported in the literature [1] for titanium alloys, including results obtained using standard plane strain fracture toughness specimens. It is seen from Figure 5 that the present results for the most part fall within the band for titanium alloys. The fact that they lie on the low side of the band is probably not due to the use of equation (5) to calculate K_{I_c}, for K_{I_c} values derived in a similar manner for titanium-interstitial alloys did not exhibit this tendency.

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Table 1 Composition of the Ti-5Al-2.5Sn Alloy in wt.%

C	N	O	H	Fe	Mn	Al	Sn	O_{eq}† at.%
0.022	0.010	0.150	0.015	0.16	0.001	5.0	2.2	0.56

†O_{eq} = O (at.%) + 2N (at.%) + 0.75C (at.%)

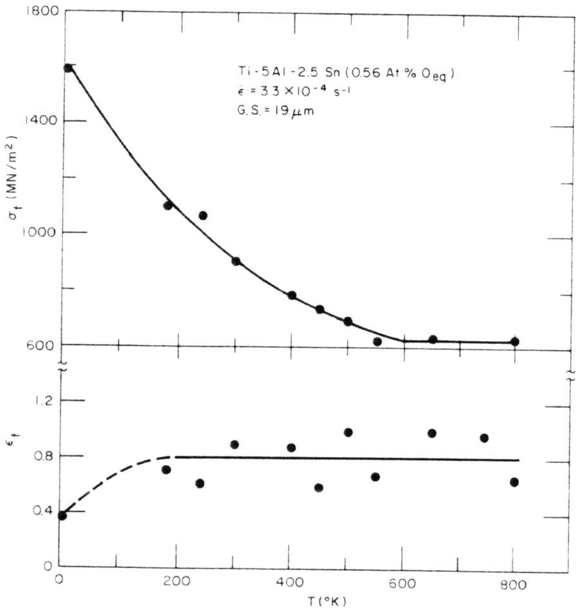

Figure 1 Effects of Temperature on the Average True Fracture Stress σ_f and on the True Fracture Strain ε_f

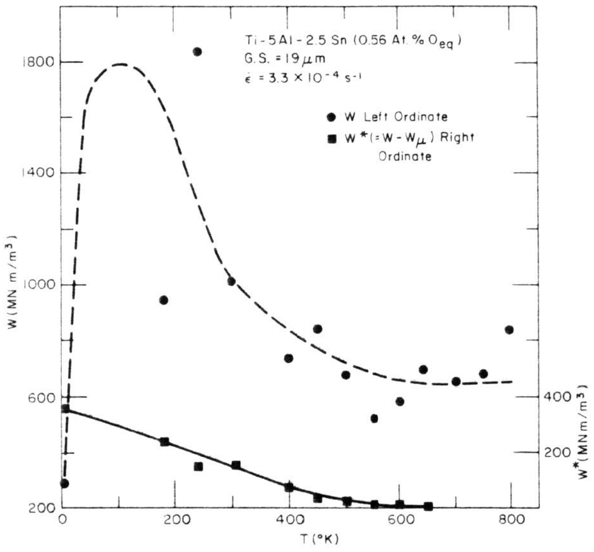

Figure 2 Effects of Temperature on the Total Work Done to Fracture W and on that Associated with the Thermal Component of the Flow Stress W*

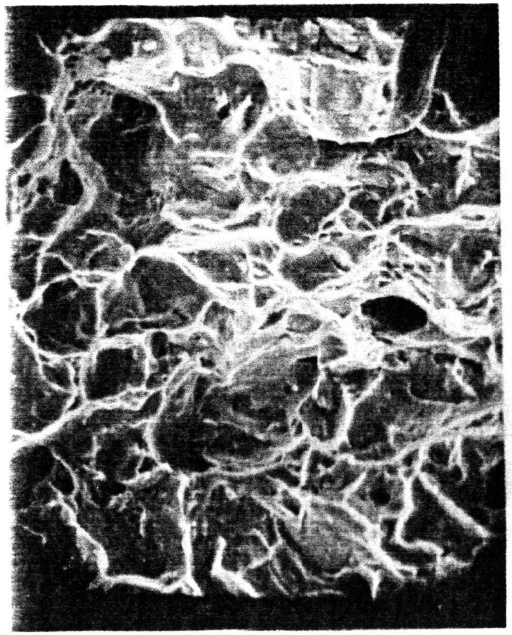

Figure 3 SEM Photomicrograph of the Fracture Surface of a Ti-5Al-2.5Sn Alloy Specimen Tested at 300K. Original Magnification 650X

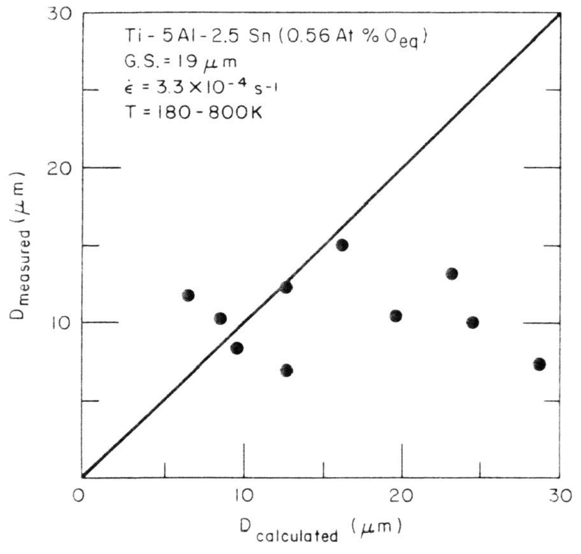

Figure 4 The Measured Dimple Size versus that Calculated from McClintock's Equation [4]

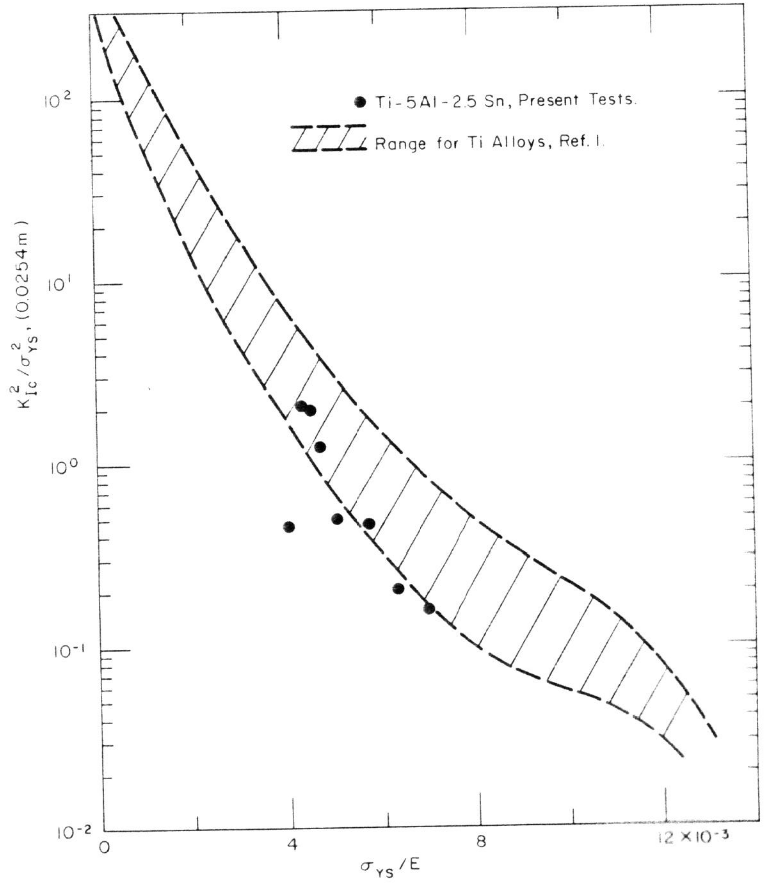

Figure 5 $K_{I_c}{}^{2}/\sigma_{ys}{}^{2}$ versus σ_{ys}/E Calculated for the Present Ti-5Al-2.5Sn Alloy using Krafft's Equation [6] to Compute K_{I_c}