The Fracture Toughness of Beryllium

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1. INTRODUCTION

This paper briefly surveys past work which has been carried out on applying the concepts of fracture mechanics to beryllium and summarises the author's work in this area.

2. NOTCHING AND PRE CRACKING METHODS

A data survey by Hurd (1) shows that fatigue pre cracking (2,3) generally produces lower Kc values than other methods. Stress arrested pre cracks(4) can give low Kc values but lead also to a large scatter in results. The author has discussed this problem elsewhere(5). The author's work on machined notch specimens shows that a heat treatment of 1h. 575°C causes a considerable decrease in the measured Kc value (figure 1). This is probably due to the relief of compressive stresses around the notch tip produced during machining. This is confirmed by tests on heat treated and re notched specimens (figure 1). By considering the ligament stresses at the crack tip the magnitude of the stress relief effect can be estimated to be $\frac{\text{Kcsr.}}{\text{Kc as mach.}} \simeq 0.5 - 0.7$

3. SPECIMEN SIZE EFFECTS

Hurd's data summary(1) shows some indication of the expected variation of Kc with specimen thickness, b. The scatter is however too great to enable one to establish the plane strain region. Beryllium is unusual in not exhibiting shear lips on fracture surfaces so that the degree of plane strain in a specimen cannot be estimated visually. This is presumably due to the metals limited capacity for shear at temperatures below 200°C. The author's experiments(5) show little variation of Kc with thickness for $b > 0.25$ in. Calculation of the required thickness for plane strain using the ASTM procedure is difficult because of the nature of the stress strain curve of beryllium and the uncertainty in assigning a yield stress. The author has carried out investigations of crack tip plastic zones using multiple beam interferometry(6) which show that in fact the 0.2% proof stress is probably the most appropriate value to choose on the grounds of overall plastic zone topography and of elastic stress re distribution around the plastic zone.

4. TEST PROCEDURE

Test records of (load, notch opening) for beryllium are almost always invalid according to ASTM criteria due to the trace departing from linear at too low a fraction of the ultimate load. This may be due to microplastic deformation at the crack tip. The problem has received little attention, the usual practice being to use the maximum load as the critical value for calculations. The purpose of the ASTM criteria is to ensure that a sufficient amount of slow crack growth with the development of an associated plastic zone occurs prior to fast fracture. Metallography of beryllium specimens(5) loaded to ~ 0.95 Kc and then unloaded shows that such crack growth has occurred so it is probably reasonable to take the maximum load as the critical value for calculation of Kc.

5. TYPICAL DATA FOR FULLY DENSE HOT PRESSED AND WROUGHT INGOT BERYLLIUM

Figure 2 shows data due to a number of authors on different breeds of beryllium. In some cases the data are considered unreliable by the author due to compressive stress effects etc. The general level for plane strain data is in the range 8-16 Kpsi with ingot material tending to be slightly less tough than hot pressed powder material.

6. THE FRACTURE TOUGHNESS OF POROUS BERYLLIUM

Figure 3 shows the variation of fracture toughness with porosity for hot pressed beryllium (stress relieved notched bend specimens). Slightly porous specimens carry a higher load and also crack more slowly with a greater notch opening and hence higher absorbed energy. Figure 4 shows the area under the (load, notch opening) curve as a function of porosity whilst figure 5 shows the effect of porosity on amount of intergranular failure. It can be seen that this increases monotonically with increasing porosity. The beneficial effect of a small amount of porosity on toughness is confirmed by notched Charpy measurements - see figure 6.

It is interesting to consider the effects of porosity on fracture toughness in more detail. The only recorded work which shows a beneficial effect of porosity on toughness(7) was carried out on NaCl

single crystals. Finely dispersed porosity caused profuse cleavage steps and retarded fracture. The effects of porosity on the mechanical properties of beryllium have been determined(8) and show that the elastic and strength properties all decrease monotonically with increasing porosity except for Poisson's ratio which is independent of porosity in the volume fraction range 0-0.2.

The present author and Dr S.R. Anthony(5) have developed a model based on the concept of the pores acting as crack blunting features which are spaced along the crack front. We have $Kc = \frac{1}{2}\sigma \max\sqrt{\pi\rho}$ where σ max is the maximum tensile stress in the region of the crack tip and ρ is the crack tip radius. Using the concept of a composite crack front partly of tip radius d and partly of the natural radius d_o one obtains finally $\frac{KICP}{KIC} = e^{-\alpha P}\left\{\left(\frac{d}{d_o}\right)^{\frac{1}{2}}\sqrt{\frac{6P}{\pi}} + 1 - \sqrt{\frac{6P}{\pi}}\right\}$

This expression gives fair agreement with the data in figure 3 for pore diameters in the range 7-15µm.

A model which is physically more realistic since it takes into account microstructural features such as grain boundaries is based on the concept of pores acting as flaws, fracture proceeding by the progressive linkage of these flaws(5). Consider a fracture surface of nominal area A_o but of true area A. Then $A(P)=A_o(P)A_1(P)A_2(P)$ where $A_1(P)$ is the normalised variation of surface area with porosity due to the intersection of pores and $A_2(P)$ is the normalised variation due to fracture surface topography (ie surface roughness), $A_1(P)$ is given by $A_1(P) = 1-P$. $A_2(P)$ will be a function of grain boundary strength, grain size, cleavage strength, preferred orientation etc ie a complicated function but the boundary conditions are $A_2(P) \simeq 1$ at $P = 0$ and $A_2(P) \rightarrow 1$ as $P \rightarrow 1$. Experimental observations suggest in addition that $A_2(P)$ reaches a maximum at $P \sim 0.07-0.10$.

Considering the fracture toughness KIC of the porous material we have $KIC(P) = \left\{E(P)\ G(P)\right\}^{\frac{1}{2}}$

and $Ep = Eo(1-2.4P)$(8)

whilst $G(P) = Go(P)\frac{A(P)}{Ao} = Go(P)\ A_2(P)\ (1-P)$

Assuming that Go(P) varies with porosity in the same way as does the ultimate strength of beryllium we have $Go(P) = Go\ e^{-4.5P}$

Thus we have $KIC(P) = KIC \left\{(1-2.4P)\,(1-P)e^{-4.5P}\,A_2(P)\right\}^{\frac{1}{2}}$

$$\approx KIC\,(1-3.95P)\,A_2^{\frac{1}{2}}(P)$$

This expression predicts qualitatively the behaviour shown in figure 3 and although not fully quantitative is considered physically more realistic than the crack blunting model.

Other possible explanations for the effects of porosity(5) are that the porous material could be acting as a series of ligaments all of which are in plane stress due to their small transverse dimensions or alternatively that the porous material has modified mechanical properties so that the application of relationships between fracture toughness and tensile properties(10,11) leads to a variation of toughness with porosity. Neither of these explanations can easily explain the maximum toughness at P ~ 0.05 however.

7. CONCLUSIONS

(1) The plane strain fracture toughness of fully dense beryllium lies in the range 8-16 Kpsi

(2) Compressive stresses due to notch machining can cause large errors in fracture toughness measurements.

(3) A small amount of porosity has a beneficial effect on the fracture toughness and Charpy impact properties of beryllium. A model in which the pores are regarded as flaws provides a semi quantitative explanation of the effects.

(4) The theoretical aspects of the effects of porosity on fracture toughness of brittle and semi brittle materials need further investigation.

8. REFERENCES

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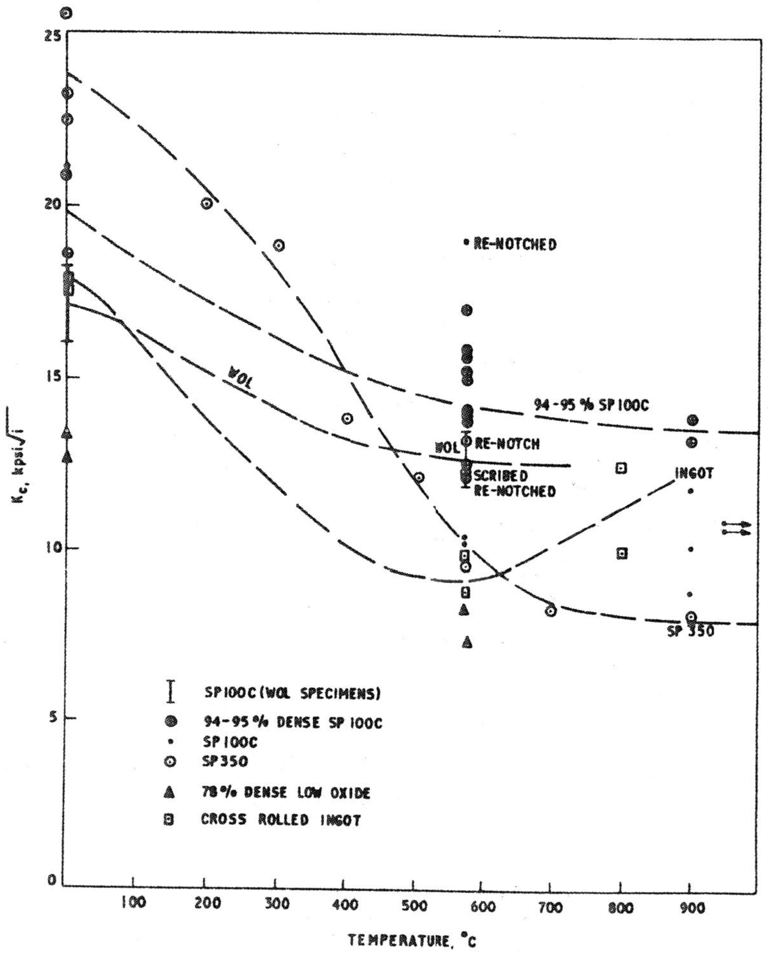
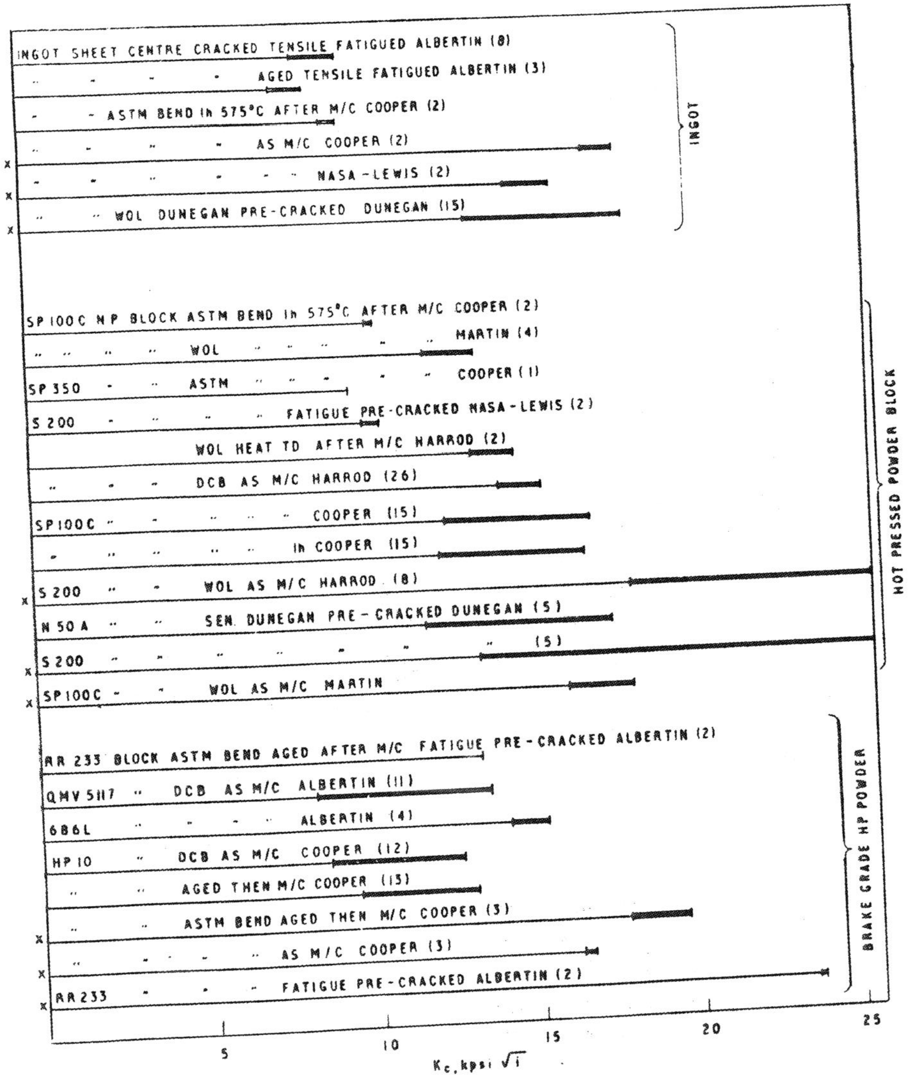


FIGURE 4 FRACTURE TOUGHNESS OF HEAT TREATED THREE POINT BEND SPECIMENS AS A FUNCTION OF HEAT TREATMENT TEMPERATURE — TREATMENT TIME 1 HOUR



* ONLY DATA FROM SPECIMENS WITH B ≥ 0.25 in. USED.

ie. FOR PLANE STRAIN IF $K_c = 15$ kpsi $\sqrt{i}$ $\sigma_{ys} \geq 45000$ psi

IF $K_c = 10$ kpsi $\sqrt{i}$ $\sigma_{ys} \geq 32000$ psi

x INDICATES RESULTS CONSIDERED DOUBTFUL BY PRESENT AUTHOR

FIGURE 2 PLANE STRAIN* FRACTURE TOUGHNESS OF FULLY DENSE BERYLLIUM

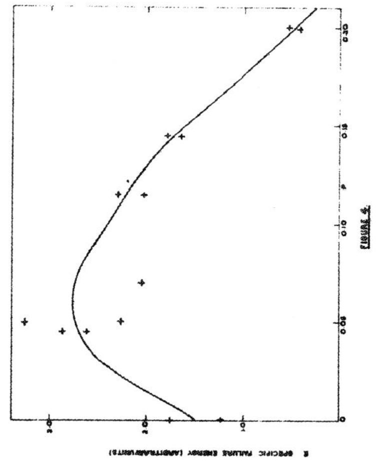
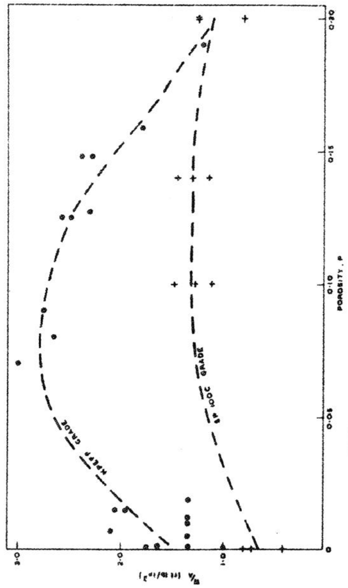


FIGURE 4



CHARPY V-NOTCH ABSORBED ENERGY FOR POROUS BERYLLIUM

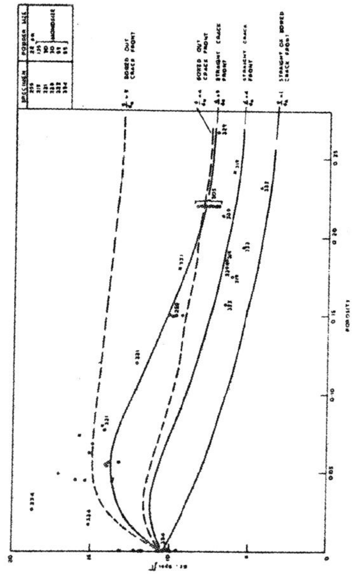


FIGURE 3 FRACTURE TOUGHNESS OF STRESS RELIEVED THREE POINT SPECIMENS AS A FUNCTION OF POROSITY

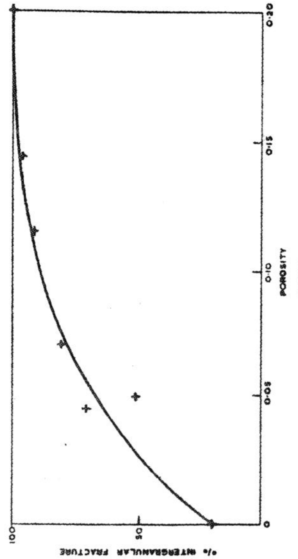


FIGURE 5