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**STUDIES OF THE EFFECT OF THICKNESS ON THE FRACTURE
TOUGHNESS OF GRADE 300 MARAGING STEEL, PART 2**

by

**C. DUKE
K.R. BROWN**

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ABSTRACT

The fracture toughness of samples of grade 300 maraging steel sheet of varying thickness was determined in tensile test specimens containing a spark machined slot. A maximum fracture toughness of $105 \text{ MPa m}^{\frac{1}{2}}$ was obtained in specimens in the thickness range 0.75 to 1.25 mm. The fracture surfaces of specimens over 0.5 mm thick contained both plane stress and plane strain areas, but below 0.5 mm fracture was entirely under plane stress conditions.

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FRACTURE PROPERTIES; MARAGING STEELS; THICKNESS; SHEETS

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INTRODUCTION

This report describes a part of a continuing study of the fracture toughness properties of grade 300 maraging steel [Smith & Brown 1977]. Maraging steels have outstanding degrees of strength, ductility and toughness, while still maintaining satisfactory corrosion resistance.

It has been shown [Knott 1973] that as the thickness of many alloys is decreased, the fracture toughness increases. The mode of fracture also varies with changes in thickness. In thin regions the fracture is by shear at approximately 45° to the tensile axis, while in thicker specimens the fracture is normal to the tensile axis. In specimens of intermediate thickness, the fracture is of mixed mode.

EXPERIMENTAL PROCEDURE

1. A series of unaged samples of commercial 18% Ni-Co-Mo grade 300 maraging sheet steel 1.65 mm thick were machined to the shape and dimensions as shown in Figure 1.
2. Transformation to martensite was carried out in a vacuum furnace by soaking for one hour at 815°C and air cooling. The samples were then age hardened by soaking at 482°C for three hours and then air cooling.
3. An artificial flaw was introduced into each specimen by spark machining a slot of the nominal dimensions 3 mm in length and 0.175 mm wide completely through the specimen. The ends of each slot had a radius of curvature of approximately 0.06 mm. Accurate dimensions of the slots were measured using a travelling microscope.
4. Where required, specimens were ground to varying thickness in the centre section as shown in Figure 1.
5. Each specimen was then loaded in an Instron universal testing machine and stressed to fracture at a cross head speed of $8.5 \times 10^{-3} \text{ mm s}^{-1}$. A standard Instron tension extensometer was attached to the specimen and a load-elongated curve plotted on an X-Y recorder.
6. The fracture surfaces were then examined using a scanning electron microscope (JSM).
7. To determine the critical stress intensity (K_C) the following relationship [Orange 1973] was used:

$$K_C = Y\sigma\sqrt{a+r} \quad (1)$$

where σ = failure stress (MPa)
 a = half crack-length (metres)
 K_C = critical stress intensity factor (MPa m^{1/2})
 Y = calibration factor
 $Y = (1 - 0.025\lambda^2 + 0.06\lambda^4) (\pi \secant \frac{\pi\lambda}{2})^{1/2}$
 r = plastic zone correction factor

$$r = \left(\frac{K}{\sigma_{ys}} \right)^2 / n\pi, \quad n = 2.83$$

$$\lambda = \frac{2a}{w}, \quad w = \text{width of specimen}$$

TABLE 1

Nominal Specimen Thickness (mm)	Failure Stress σ_F (MPa)	Fracture Toughness K_C (MPa m ^{1/2})
0.14	922.8	68.8
0.175	1170.6	87.1
0.30	1059.9	79.1
0.40	1320.5	97.7
0.40	1198.0	88.5
0.50	1196.1	87.5
0.50	1286.2	94.3
0.75	1293.1	99.0
0.75	1395.9	105.3
1.15	1371.4	102.4
1.15	1326.4	98.8
1.65	1324.4	98.8
1.65	1069.7	79.7
1.65	1231.4	92.2

Yield stress of unflawed specimen = 1900 MPa

Ultimate tensile strength of unflawed specimen = 1983 MPa

Average hardness of specimens = 550 VPN

Average length of machined slot = 2.9 mm

Average width of machined slot = 0.175 mm

RESULTS

Plots (Figure 2) of the fracture toughness, K_{IC} , as shown in Table 1, against specimen thickness suggest a distinct maximum fracture toughness of approximately $105 \text{ MPa m}^{1/2}$ for sample thicknesses in the range 0.75 mm to 1.15 mm.

Fractographic studies on the scanning electron microscope showed that all specimens of 0.75 mm thickness or greater, developed small regions of plane strain fracture near the machined slot. Small shear lips, 0.015 to 0.04 mm wide, were formed at the root of the machined flaw, indicating that a small degree of plasticity preceded plane strain fracture (Figure 3). As the fracture moved away from the slot, the plane strain fracture was replaced progressively by plane stress failure with the result that the plane strain areas were roughly triangular as shown in Figures 3 and 4.

At high magnification (Figures 5 and 6), both plane strain and shear areas could be seen to consist only of ductile tearing. Some delamination was noted around inclusions (Figure 5) but no brittle or intergranular failure was observed.

For thicknesses below 0.75 mm, no plane strain region developed and fracture was entirely by shear, Figure 7. Above 0.75 mm the relative amount of plane strain failure increased with increasing thickness. This is evident in Figure 8, where the area of the triangular plane strain fracture face relative to sheet thickness is plotted against specimen thickness. The region of maximum fracture toughness corresponds to mixed mode failures.

DISCUSSION

The plots of fracture toughness, K , against specimen thickness (Figure 2) suggest that thicknesses in the range 0.75 to 1.25 mm give an optimum fracture toughness. A peak value of approximately $105 \text{ MPa m}^{1/2}$ was obtained and the fracture toughnesses of comparable thickness specimens agree well with values determined by Smith & Brown [1977]. The peak value was obtained in this work when the fracture occurred by mixed mode, and is approximately double the plane strain fracture toughness K_{IC} obtained for fracture under entirely plane strain conditions [Smith & Brown 1977].

However, it should be noted that Smith & Brown [1977] used forged bar of the same grade but of different origin to the rolled sheet used in the present work. Although both materials were given similar heat treatments, a possible contributing effect of material property variation cannot be eliminated. The form of the curve is similar to those curves obtained

for other materials [Knott 1973, Sullivan, Stoop & Freed 1973] and agrees extremely well with the model described previously [Smith & Brown 1977]. The peak value of fracture toughness occurred at almost the same thickness (0.8 mm) as that for aluminium alloy sheet used to develop the model [Sullivan, Stoop & Freed 1973].

In the mixed mode failures, a plane strain fracture initiates at the notch, but as the crack propagates, it is rapidly replaced by a ductile shear failure, i.e. anti-plane strain. After propagating a distance about equal to sheet thickness, the fracture is entirely by shear. In the thinnest samples examined, the fracture initiated and propagated entirely by shear.

In mixed mode failures, the plane strain crack grows forward in the centre of the sheet thickness and propagates by dragging with it the shear lips. As it grows, the shear lips widen until they occupy the whole of the cross section of the sheet. The load used in the calculation of the fracture toughness was a maximum load and it is believed that this load was that in operation when the crack front was predominantly plane strain. It is conceivable, however, that the plane strain fracture could have occurred by slow crack growth that would not have been detected by our relatively insensitive extensometer, and therefore the load recorded, and consequently the fracture toughness calculated from it, would refer to plane stress failure. However, although satisfactory correlation was obtained with the results of Smith & Brown [1977], where some plane strain fracture was always present, it cannot be concluded positively that the measured toughness referred to plane strain. In future work this should be investigated using crack staining techniques and a more sensitive crack opening displacement gauge.

Note that none of the values of the fracture toughness determined in this work are 'valid' according to ASTM requirements [ASTM 1974]. The ASTM standard methods for plane strain fracture toughness determination require very specific specimen and notch geometry to ensure that fracture is by plane strain. In particular the specimen thickness must exceed $2.5 \left(\frac{K_{Ic}}{\sigma_{ys}} \right)^2$ which, for the present material, corresponds to approximately 2.5 mm. The fracture toughness measured in a valid ASTM test is therefore a minimum which can then be used in the design of components of section equal to or heavier than the test specimen.

For the design of thin wall pressure vessels and structures however, the valid plane strain fracture toughness is not applicable, for when the wall thickness is not large enough to develop high through-thickness restraint, fracture is not entirely by plane strain. Although the present results are 'invalid' by ASTM requirements, they are relevant to thin wall design.

The notch sharpness also differs from that required by the ASTM standards. Although the standards require the notch tip to be sharpened by fatigue, a spark machined slot of tip radius approximately 0.06 mm was used in the present work. The use of such a blunt notch should result in a higher fracture toughness value [Brown & Strawley 1966]; indeed for comparable specimen thicknesses, the present results are approximately 10% higher than those of Smith & Brown [1977], who used a fatigue sharpened notch. This possibility is supported by the presence in samples which failed, partially by plane strain, of small shear lips at the notch root. These were absent in the samples of Smith & Brown [1977]. Other work however [Sullivan, Stoop & Freed 1973] has shown that in some materials notch acuity has little effect on the measured fracture toughness. Until direct comparisons are made between spark machined and fatigue pre-cracked notches in the same material, it is not known whether the entire improvement in fracture toughness of 0.75 to 1.25 mm sheet stems from material differences, the sheet thickness effect, or differences in notch sharpness. Studies to investigate this aspect further are being conducted.

CONCLUSIONS

The fracture toughness of grade 300 maraging steel sheet is a maximum in the thickness range 0.75 to 1.25 mm. For spark machined flaws, the maximum value $105 \text{ MPa m}^{\frac{1}{2}}$ is almost twice the plane strain fracture toughness (K_{1c}) of heavy sections ($\sim 58 \text{ MPa m}^{\frac{1}{2}}$).

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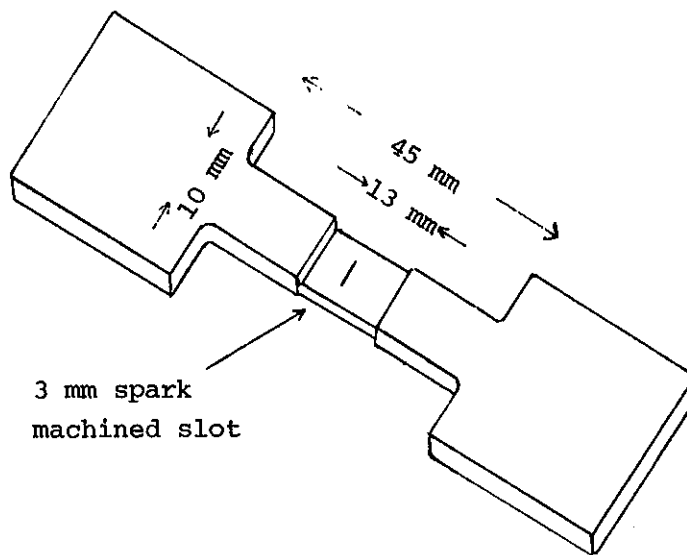


FIGURE 1 GEOMETRY AND DIMENSIONS OF SAMPLES USED FOR THE DETERMINATION OF FRACTURE TOUGHNESS. THE THICKNESS WAS VARIED BY GRINDING THE CENTRE SECTION OF THE SPECIMEN AS SHOWN

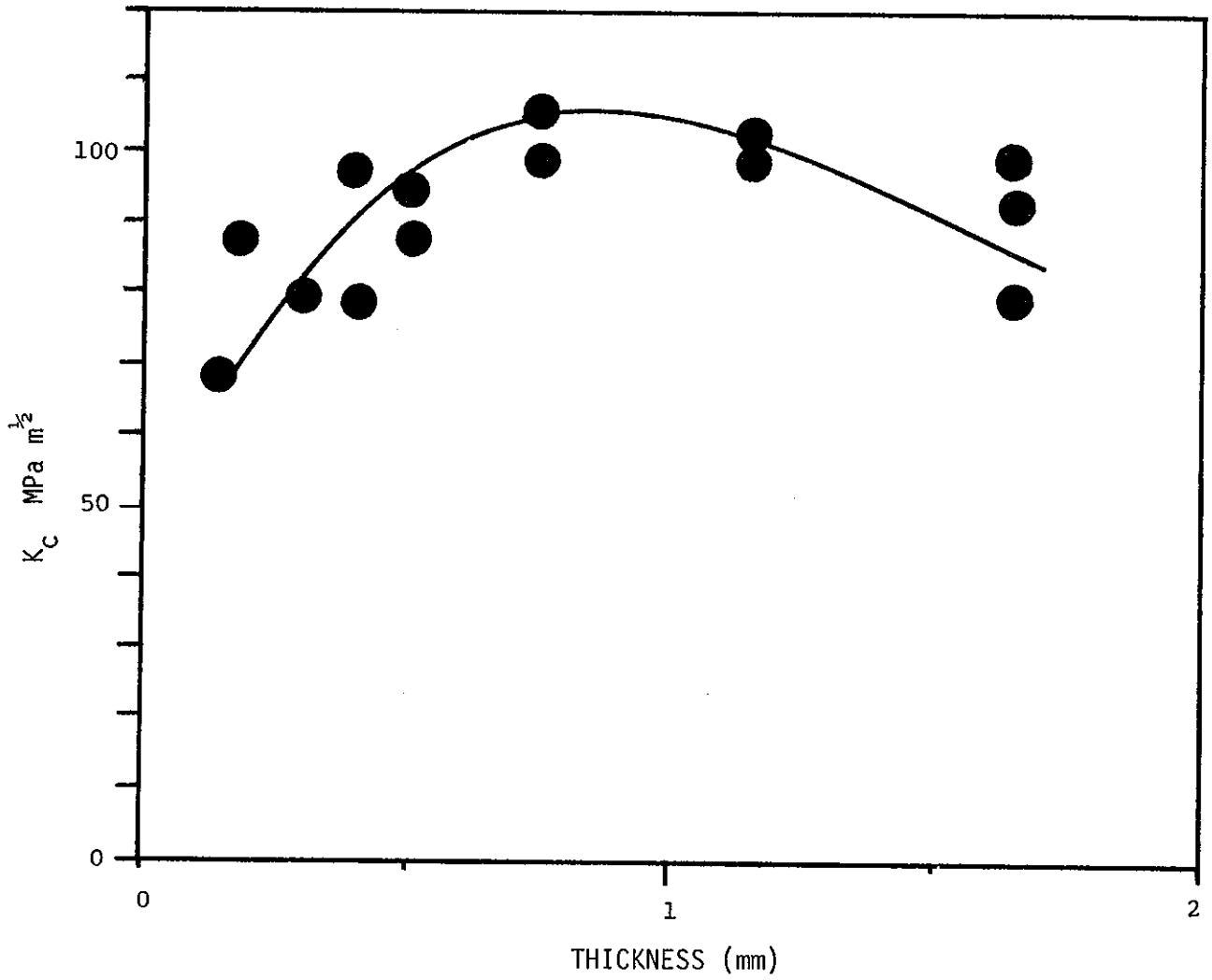


FIGURE 2(a) PLOT OF FRACTURE TOUGHNESS AGAINST SHEET THICKNESS FOR MARAGING STEEL SHEET

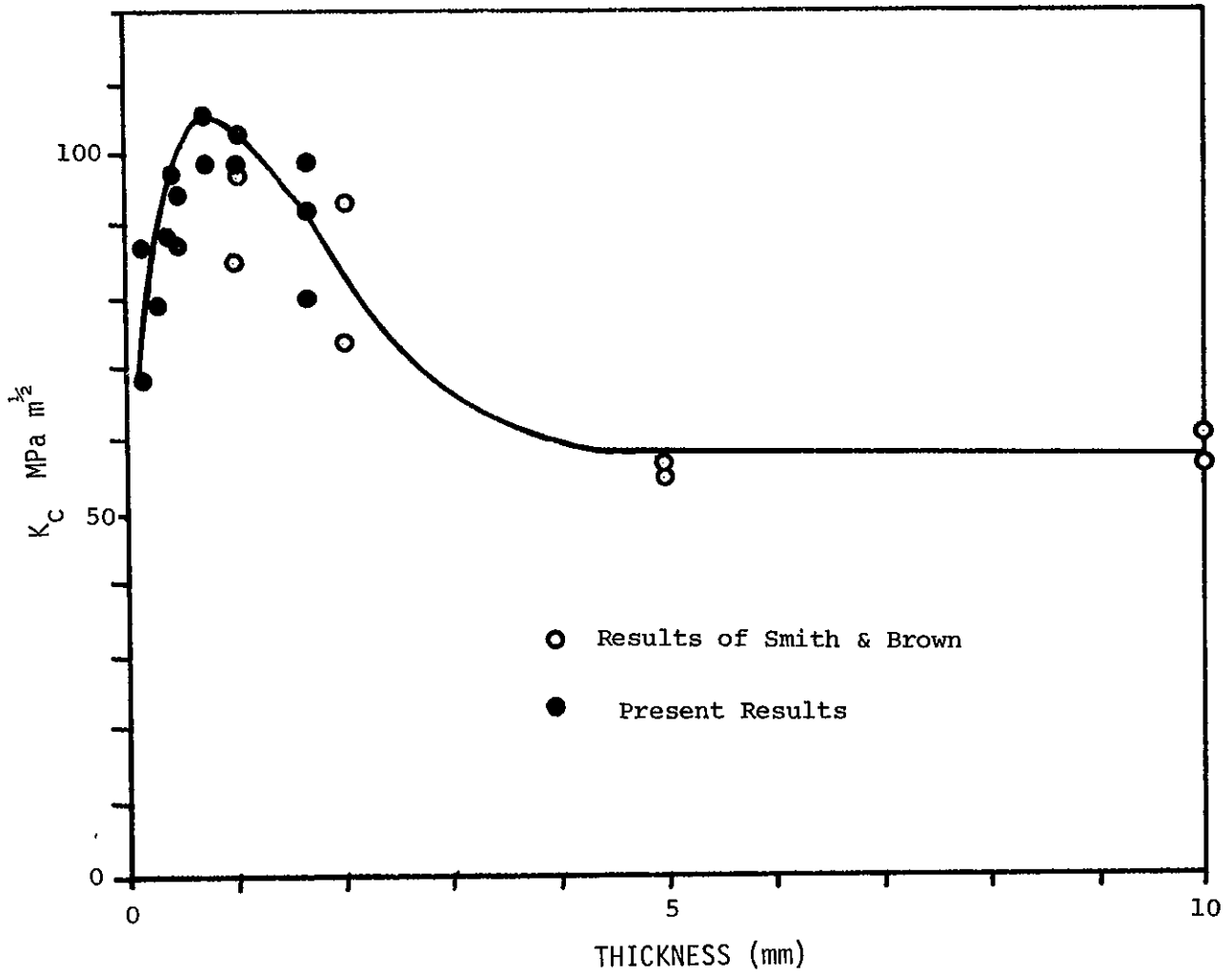


FIGURE 2(b) PLOT SHOWING COMPARISON OF THE PRESENT RESULTS WITH THOSE DETERMINED BY SMITH & BROWN USING BEND TEST SPECIMENS

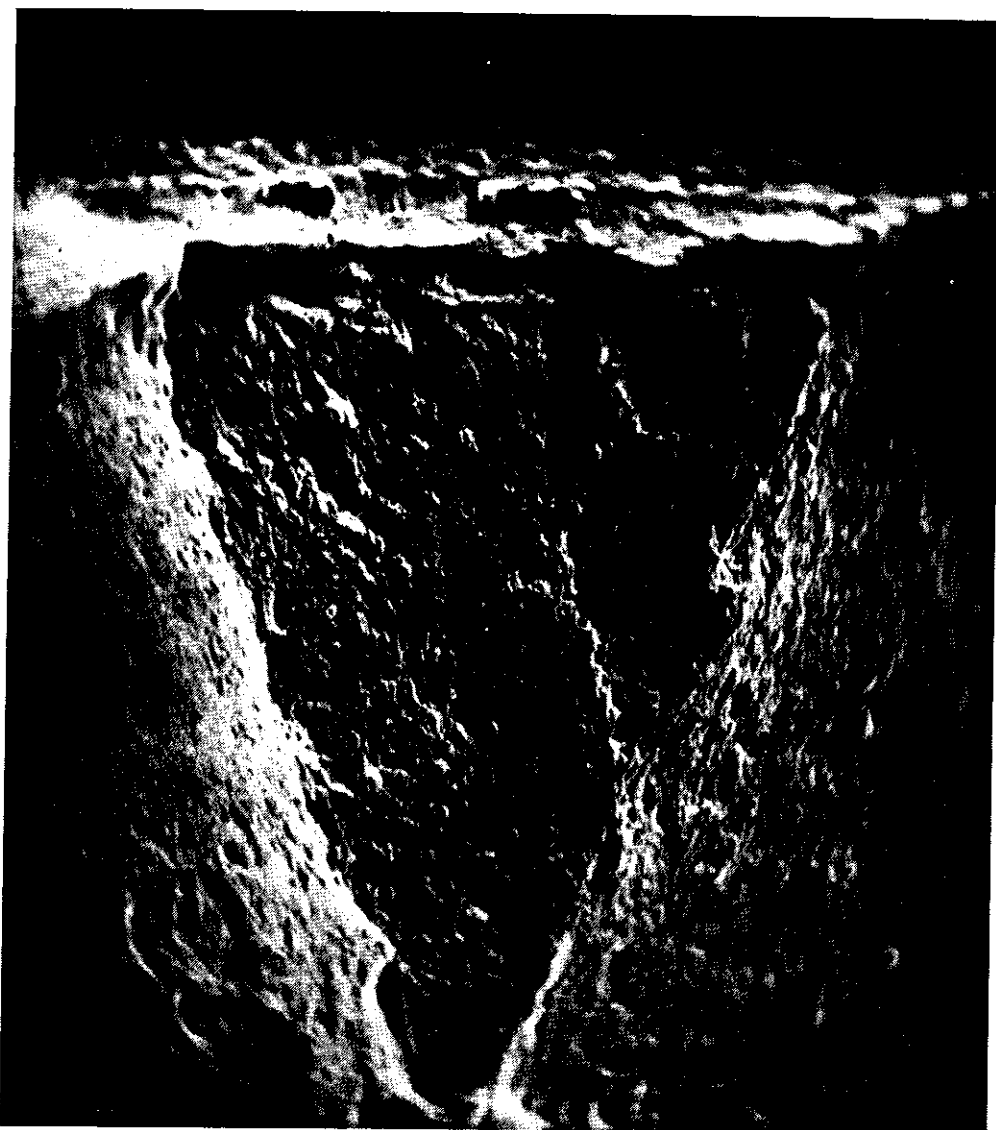


FIGURE 3 TRIANGULAR SHAPE PLANE STRAIN REGION ON 1.65 mm THICK SPECIMEN. NOTE THE DIMPLE DUCTILE FRACTURE OF THIS REGION. THE SPARK MACHINED FLAW IS AT THE TOP AND THE CRACK PROPAGATED TOP TO BOTTOM OF THIS PICTURE SCANNING DETECTION MICROGRAPHY, MAGNIFICATION X 130

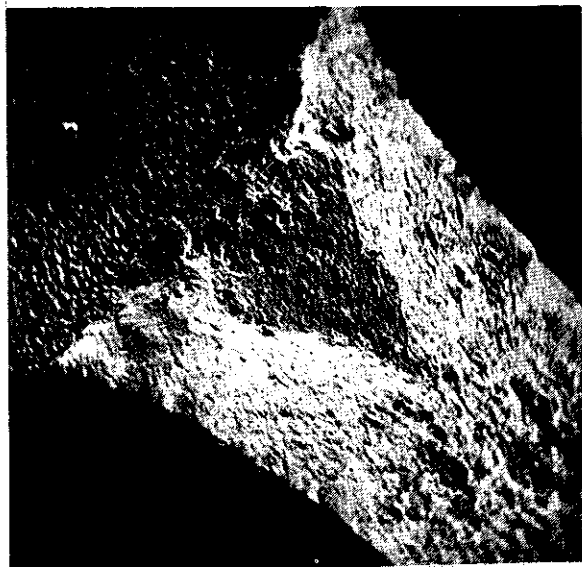


FIGURE 4 PLANE STRAIN REGION
AND SHEAR LIPS ON 1.65 mm
THICK SPECIMEN. 50 X.

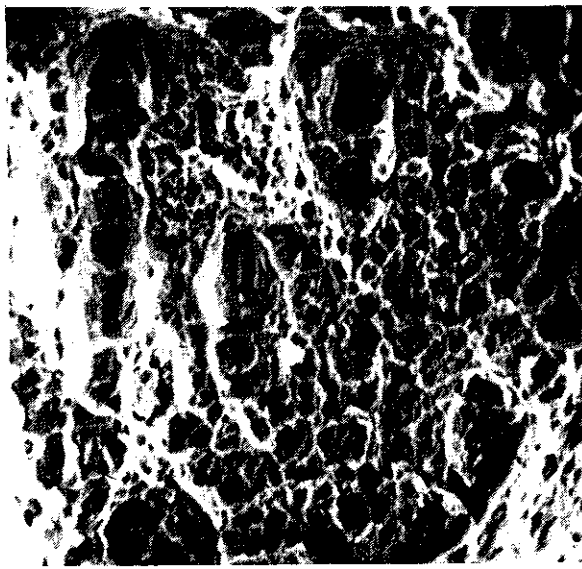


FIGURE 5 PLANE STRAIN REGION
SHOWING DIMPLE FRACTURE
AND PRESENCE OF INCLUSIONS.
800 X.

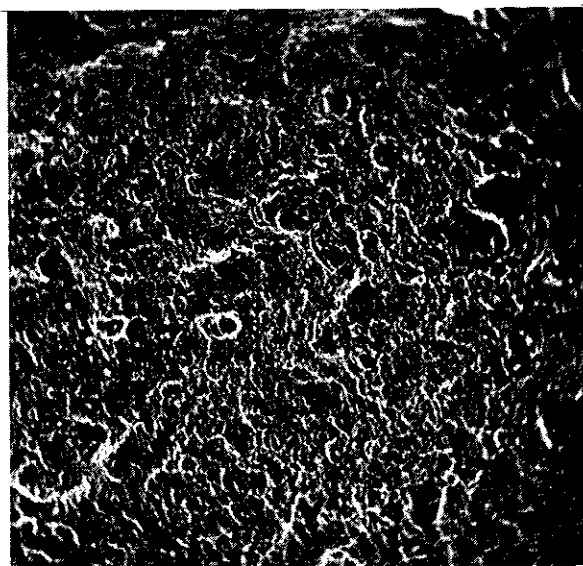


FIGURE 6 SHEAR REGION OF 0.5 mm
THICK SPECIMEN. 400 X.



FIGURE 7 SHEAR FRACTURE AT 45° TO
TENSILE AXIS ON 0.175 mm
THICK SPECIMEN. 160 X.

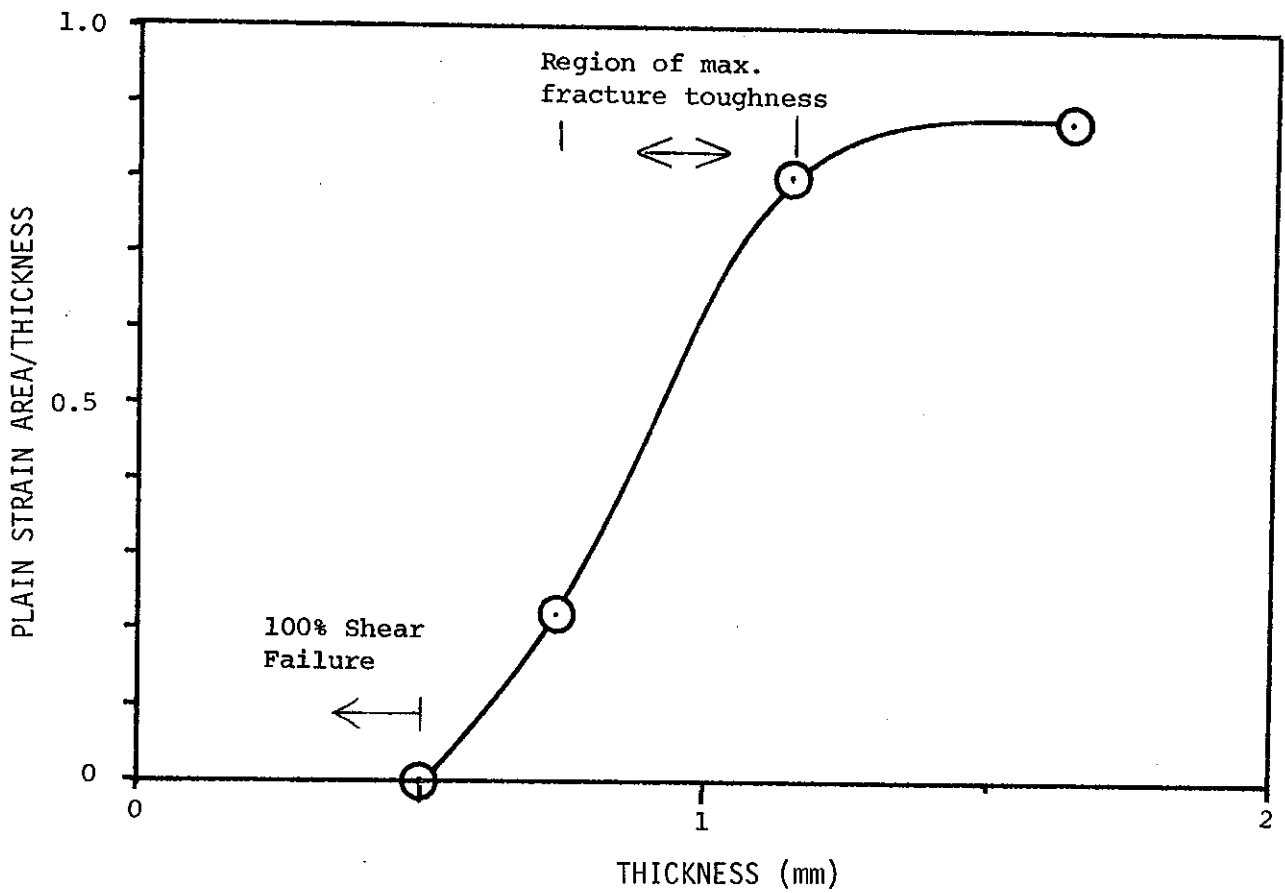


FIGURE 8 PLOT OF THE AREA OF PLANE STRAIN FRACTURE RELATIVE TO SHEET THICKNESS AGAINST SHEET THICKNESS