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THE GROWTH OF NECKS IN FUEL SHEATHS DURING HIGH TEMPERATURE TRANSIENTS IN STEAM

Croissance des cols dans les gaines de combustible lors de fortes élévations transitoires de température dans la vapeur

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Résumé

L'oxydation sous contrainte des gaines de combustible, lors de fortes élévations transitoires de température, provoque une tension diamétrale dans les régions où la pellicule d'oxyde se fissure. Il en résulte que la tension totale d'un tube dépend du nombre de fissures formées. L'ouverture d'une fissure et la formation de son col observées sur la surface intérieure peuvent être décrites comme une série de paliers. La largeur initiale du col est égale à deux fois l'épaisseur de la paroi du tube. Si les fissures d'oxyde se forment à un intervalle inférieur à deux fois l'épaisseur leurs cols réagiront l'un sur l'autre. Si les fissures sont proches l'une de l'autre leur col combiné aura un profil assez lisse mais à mesure que l'intervalle entre les fissures augmentera, le profil du col combiné deviendra plus rugueux. Pour une gaine de combustible ayant les dimensions généralement requises dans la centrale nucléaire Pickering (15.24 mm de dia. ext. x 0.43 mm d'épaisseur de paroi) toute fissure simple et son col peuvent donner jusqu'à environ 5% de tension diamétrale avant que la pénétration de la paroi se produise.

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ABSTRACT

In fuel sheaths oxidizing under stress during a high temperature transient, diametral strain is localized in regions where the oxide film cracks. As a result, the total strain in a tube depends on the number of cracks formed. The opening of a crack and the formation of the associated neck observed on the inner surface can be described by a sequence of slip steps. The initial width of the neck is equal to twice the tube wall thickness. If oxide cracks form at a spacing less than twice the wall thickness their associated necks interact. If the cracks are close together the combined neck will have a fairly smooth profile but as the crack spacing increases the combined neck profile will roughen. For a fuel sheath of the dimensions typically used in the Pickering Nuclear Generating Station (15.24 mm OD x 0.43 mm wall) any single crack and its associated neck can contribute up to about 5% diametral strain before penetration of the wall occurs.

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INTRODUCTION

During high-temperature transients the outer surface of Zircaloy-4 nuclear fuel sheaths can oxidize, and under stress the growing zirconium oxide film can crack(1,2,3,4). The diametral strain behaviour of internally pressurized tubes in a steam atmosphere in the temperature range 1000 to 1300°C has been described previously(2). Sheaths can fail with a low overall diametral strain although the localized strain at the point of failure may be very large. This paper examines the relationship between diametral strain, crack growth in the zirconium oxide layer, and the necking strain in the tube underneath, based on a photomicrographic examination of specimens from the earlier work. A mechanism is proposed for the growth of cracks in the ZrO_2 and the associated neck on the inside surface, which will reproduce the uneven inside surface observed when several necks overlap.

EXPERIMENTAL PROCEDURE

One-half metre long specimens of CANDU* nuclear fuel sheathing typical of that used in the Pickering Nuclear Generating Station, 15.2 mm OD x 0.43 mm wall, were internally pressurized with inert gas and maintained at constant pressure while electric resistance heated at a rate of $25°C.s^{-1}$ in an atmosphere of flowing steam. Two specimens, which were stressed at about 8.5 MPa hoop stress and failed at about 1100°C, were selected for microscopic examination. From the photomicrographs of 200X magnification, crack width and tube wall thickness were measured with a millimetre scale and dividers.

RESULTS

Figure 1a shows a cross-section of a ruptured tube. Numerous necks may be observed on the inside surface. Figure 1b shows a detail of one such neck opposite an opened crack in the zirconium oxide. In many cases, one neck on the inside surface is associated with several cracks in the zirconium oxide film on the outer surface, as shown on Figure 2. Earlier work(2) showed that almost all the tube diametral strain could be accounted for by summing the width of all the cracks in the zirconium oxide.

Measurements were made to determine the relationship between the number of cracks in the zirconium oxide on the outer surface of the tube which combined to cause a given neck on the inside surface and the degree

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* CANDU - Canada Deuterium Uranium

of wall thinning which resulted. The wall-thinning strain in the necked region was defined as $e_t = 1 - t/t_0$, where t is the remaining wall thickness from the root of the notch on the outer surface to the inside surface and t_0 is the original wall thickness. This is shown schematically on the inset on Figure 3. Measurements of the strain are estimated to be within ± 0.01, and of the crack width to be within ± 0.01 mm. The results, shown on Figure 3, correlate the number of cracks contributing to each neck. There is much scatter so the data were fitted simply by straight lines. A curved line is shown on Figure 3 to represent an upper bound of the data. The most severe wall thinning was caused by a single crack in the zirconium oxide. As the number of cracks contributing to each neck and the total number of necks increase, the diametral strain in a tube undergoing oxidation in steam increases.

MODEL OF NECK FORMATION

A simplified model for the growth of the neck on the inside surface as a single crack opens on the outside surface is shown on Figure 4. The idea is adapted from a model proposed by Orowan(5) and Rogers(6). The neck will form by a series of slip steps as the crack opens; the width of the neck is defined by the 45° slip lines required by the von Mises theory(7) for the plane of maximum shear. There are simple geometric relationships between the major dimensions of this model. The width of the neck at any instant (w_n, defined by the intersection of the first pair of slip lines with the inside surface) may be calculated by

$$w_n = 2\,t_0 + w_c \qquad (1)$$

and the remaining wall thickness by

$$t = t_0 - w_c \qquad (2)$$

where t_0 is the original wall thickness less the thickness of the initial oxide film, t is the current wall thickness and w_c is the width of the opened crack in the zirconium oxide.

This simple model may be extended to investigate the effects of adjacent cracks in the zirconium oxide whose necks, defined by the 45° slip lines, overlap. Two cases will be considered;

i) two cracks very close together, and

ii) two separated by a distance almost equal to the wall thickness.

The behaviour of two cracks close together is described on Figure 5. Figure 6 shows an example of the analysis applied to a typical photomicrograph. Two cracks cause a much wider neck than that shown for one crack in Figure 4 but the neck is still symmetric, with the centre located mid-way between the two cracks. Only when the wall has thinned almost to failure do the slip lines from the two cracks cease to overlap.

Figure 7 shows the model for two ZrO_2 cracks separated by a distance nearly equal to the wall thickness. The slip lines only overlap for a short while, producing a broad common neck. From Figure 7d to the end of the sequence, two separate necks form leaving an island of material between them. Figure 8 shows an example from the photomicrographs. From Figures 5 and 7 one can easily imagine how several cracks, randomly spaced and starting to open at different times, can result in a very uneven interior surface.

DISCUSSION

Figure 9 is a photomicrograph of a section of a tube cross section where there is a single crack on the outer surface. The width of the neck on the inside surface is poorly defined but the crack width and remaining wall thickness can be measured. Therefore, equation 2 can be checked. Since the diametral strain, e_d, is related to the wall thickness and to the crack opening, we can predict the diametral strain from the crack width and wall thickness:

$$e_d = \frac{w_c}{D_o} = \frac{t_o - t}{D_o} \tag{3}$$

where D_o is the initial tube diameter. The maximum predicted strain can then be compared with the measured value. For tubes of the nominal dimensions used in this work (15.24 mm OD x 0.43 mm wall) the predicted maximum diametral strain resulting from one crack opening to the point of tube penetration is 2.82%.

Figure 10 compares the diametral strain predicted from measurement of the remaining wall thickness with that calculated from the width of the oxide crack for single oxide cracks. The measured diametral strain is consistently greater than would be predicted using the 45° slip lines of the model and the original tube dimensions. In fact the diametral strain at failure is about 2 times the predicted value. From this, one may obtain the remaining wall thickness as a function of the width of a crack on the oxidized surface at any time by an empirical relation:

$$t = t_o - \frac{w_c}{2} \tag{4}$$

The reason this empirical correction is required can be seen from Figure 11.

The model requires that the surfaces of the opening crack remain at 45° to the tube surface. The photomicrographs show that this geometric requirement is not maintained. Since the von Mises planes of maximum shear lie at 45° to the tensile axis, one must conclude that the crack tip, as required in the model described above, is not the only site of slip steps. Figure 11 shows that as a crack opens the average angle between the crack surface and the tube surface decreases from 45° to about half of this value, and possibly less. This result can be achieved if we allow slip steps to originate anywhere along the crack surface instead of just at the tip. The probable mechanism to trigger extra slip sites along the crack surface is the mis-match between the growing zirconium oxide film and the underlying material. The volume increase in converting zirconium to ZrO_2 is approximately 50%. Since ZrO_2 is very strong in compression, the component of the volume increase in the tangental direction is sufficient to cause yielding in the substrate after a buildup of only a few μm in thickness. A rapidly opening crack would therefore be expected to show a curved surface continuously varying from a 45° angle at the root to much less at the edge, as the ZrO_2 layer becomes thicker. This behaviour is demonstrated in Figure 12.

Figure 10 shows 6 points obtained from preoxidized tubes ruptured in vacuum which failed with a single crack. In these tests there is no oxide forming on the crack surfaces to initiate new slip sites. The results should, therefore, agree with the model of equation 3. Three of the points lie close to the 45° line as expected, the other three do not. The reason for the disagreement of the latter three is not certain, however there is some evidence from the photomicrographs that some oxidation of the crack surfaces did occur. This may have been because of a poor vacuum or there may have been some redistribution of the pre-existing oxide during the test.

Previous work(2) has shown that cracks in the oxide film will form at pre-existing flaws in the tube surface, such as scratches. When there is only one such scratch it is possible that it will initiate the only macroscopic oxide crack to form and the tube will rupture with an overall diametral strain of about twice the theoretical value from equation 3, or about 5% for the sheath dimensions used in these tests. Around most of the perimeter of the tube the strain will be almost zero but within the crack the strain will be very high. Thus, although the tube diametral expansion is low, the mode of failure is by ductile shear. When there are no pre-existing surface flaws many macroscopic cracks form around the perimeter of the tube and each one contributes to the overall diametral strain. Thus, by the time one crack has opened to contribute about 5% and the tube ruptures, the others have also contributed measurable amounts of strain. In fact one of the tubes used in this study had an overall diametral strain at rupture of 15%, and the other had 30%. In the experimental program reported in reference 2 there were no single crack failures where there was not a pre-existing surface scratch on the tube at the start of the test.

In the absence of pre-existing flaws like scratches, the factors governing the nucleation of oxide cracks are not well understood. Cox(8), Ploc(9) and Biederman et al.(10) have shown that the oxide/metal interface is very irregular, with a cell-like structure. The latter workers also show there is preferential growth along the α-phase grain boundaries. When a film with such an uneven surface is stressed in tension there will be many points where the stress concentration might reach the ultimate strength of the ZrO_2. Inhomogeneities of structure within the growing oxide film may produce a similar effect.

In "unstressed" specimens of iodide zirconium oxidized in dry air at 573 K for up to four years, Ploc(11) found cracks forming in the oxide both at grain boundaries and across the grains. For engineering purposes we can probably consider crack nuclei to be numerous and randomly distributed. Therefore, it should be possible to treat the crack distribution on a straining and oxidizing tube statistically as a function of stress, temperature, time, etc. If one can predict the probable crack distribution one should be able to predict the cumulative tube strain up to the point when one of the cracks has contributed 5% to the overall strain and the tube ruptures. Crack distribution studies have not yet been completed. It is hoped that further study will reach a point where such predictions can be made.

CONCLUSIONS

1. For a strained, oxidized Zircaloy tube, much of the strain is concentrated in regions below cracks in the ZrO_2 layer.

2. The maximum diametral strain which can be attributed to a single crack in the oxide surface is about 5%.

3. The strain concentration can be modelled by considering the propagation of slip lines from the crack tip. Some modification is required when the Zircaloy is oxidizing during straining.

4. The deformation pattern observed when two or more close oxide cracks interact to form the same neck is reproduced by the proposed model.

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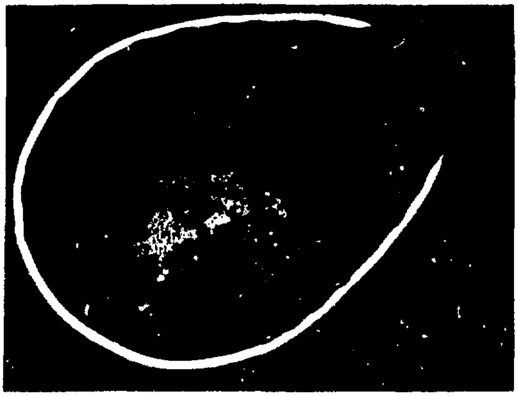


FIGURE 1a

Cross section of a ruptured tube.

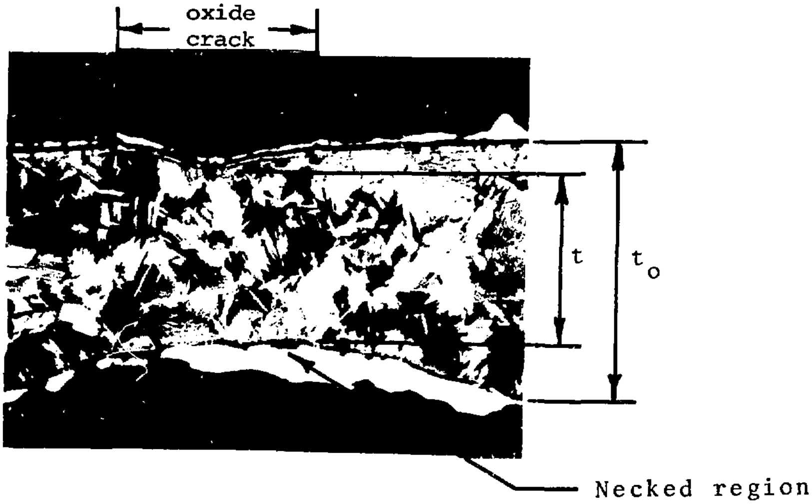


FIGURE 1b

Typical oxide crack and associated neck.

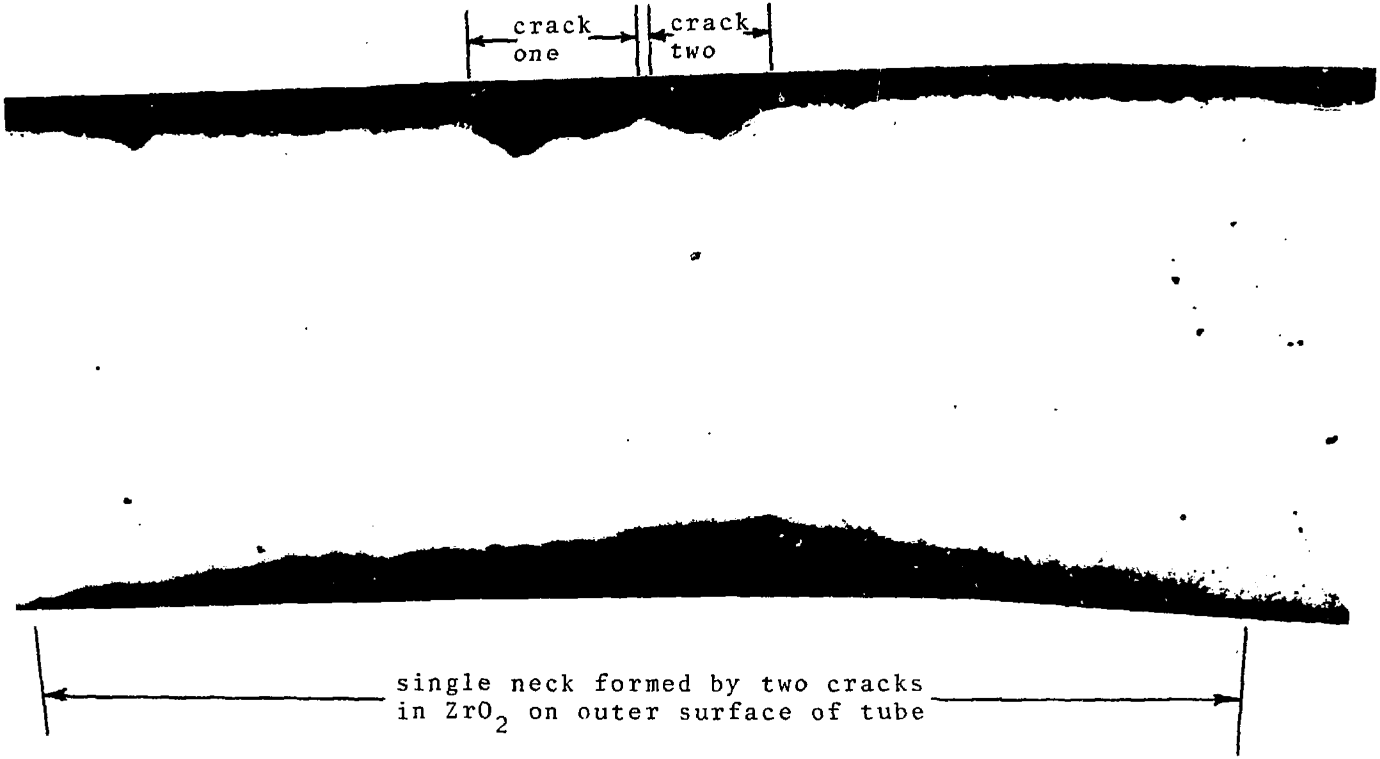
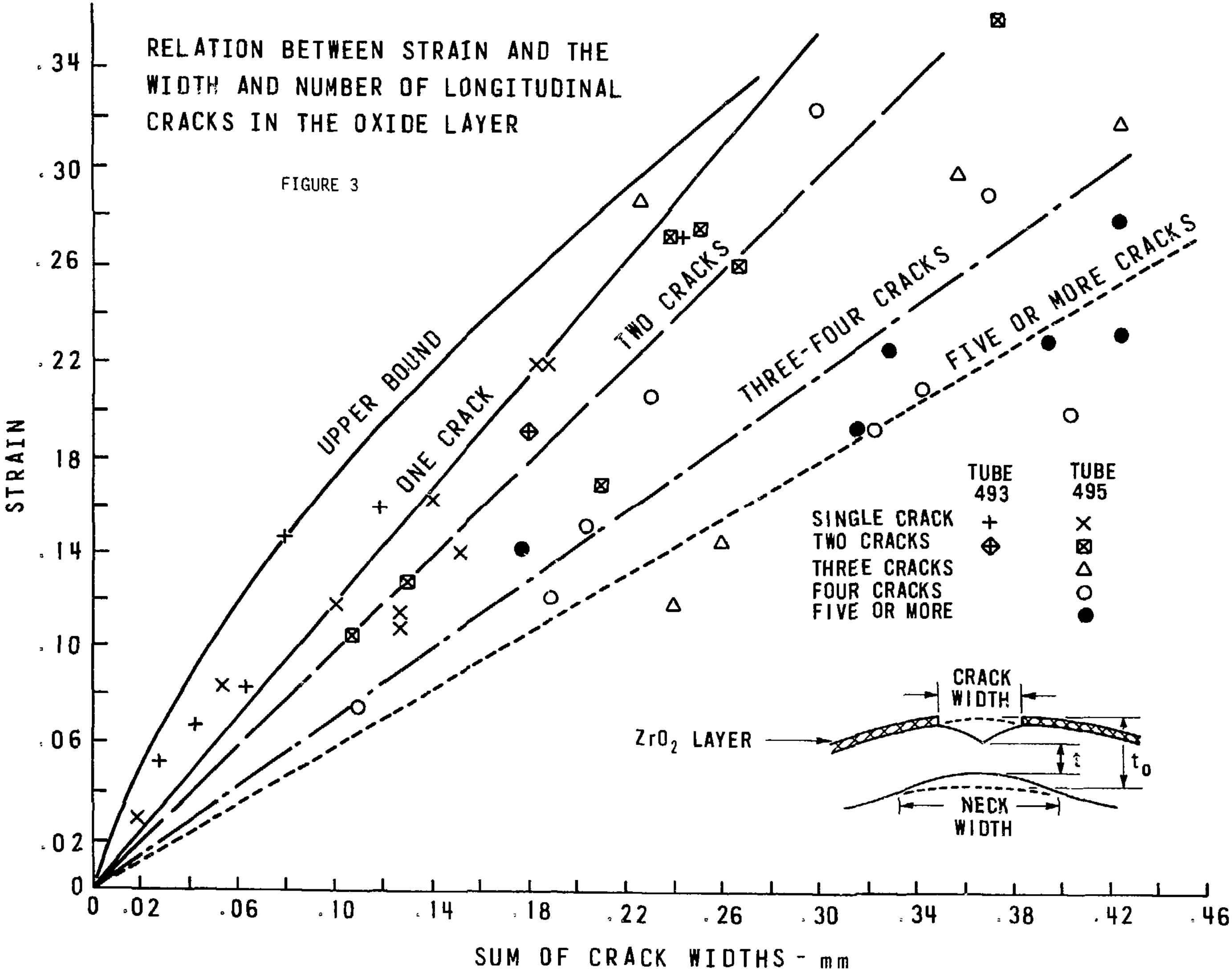


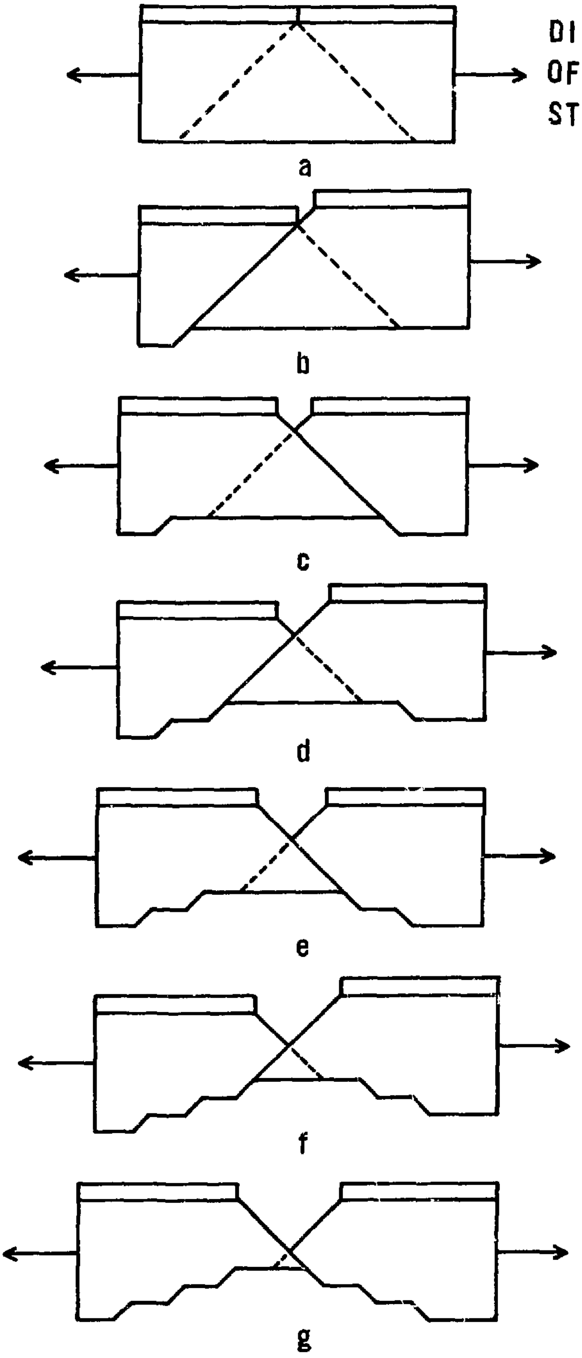
FIGURE 2

Neck formed by opening of closely spaced cracks in the ZrO_2 layer. Magnification 200X



RELATION BETWEEN STRAIN AND THE WIDTH AND NUMBER OF LONGITUDINAL CRACKS IN THE OXIDE LAYER

FIGURE 3



UPPER LAYER REPRESENTS OXIDE WITH A SINGLE CRACK

DOTTED LINES INDICATE POTENTIAL SLIP PLANES

ONE SLIP STEP COMPLETED

TWO SLIP STEPS COMPLETED

NOTE THAT DIFFERENT SLIP PLANES ARE ACTIVATED IN SUCCESSION, ALWAYS ORIGINATING FROM THE CRACK TIP

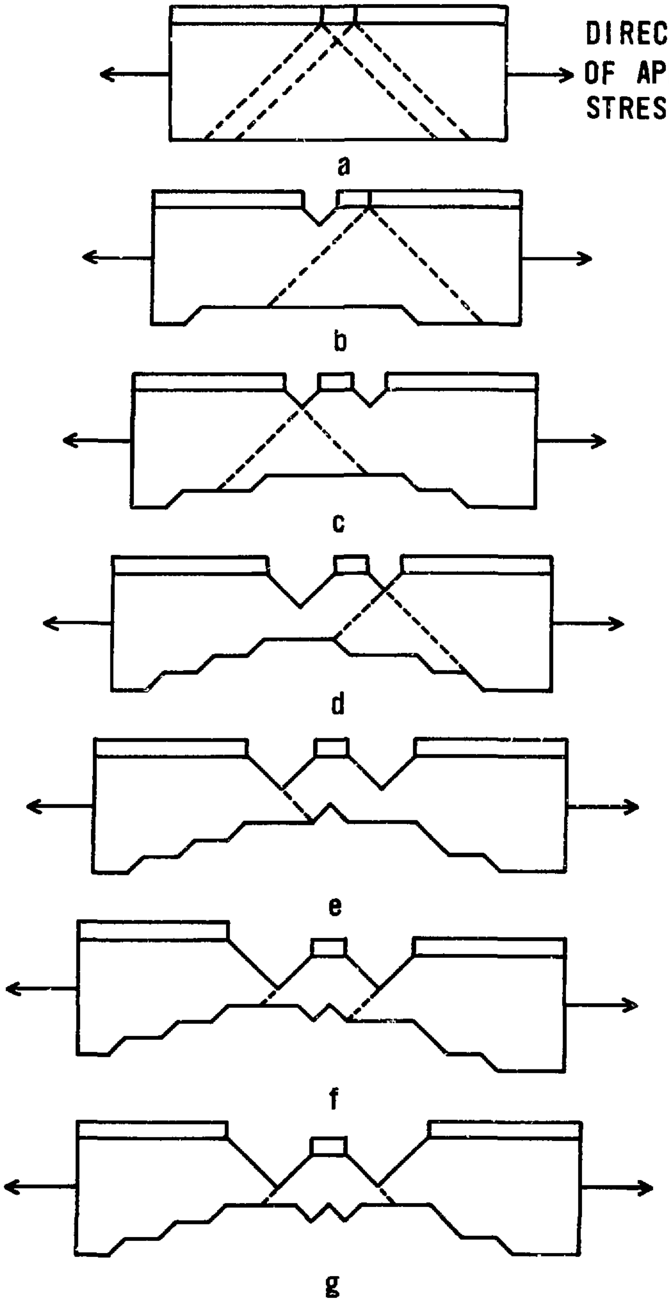
FOUR SLIP STEPS COMPLETED

NECK IS CONSIDERABLY WIDER THAN CRACK. IDEALLY THE NECK WIDTH SHOULD BE $2t_0 + W_c$ WHERE t_0 IS THE WALL THICKNESS FROM THE TIP OF THE STARTER CRACK AND W_c IS THE CURRENT WIDTH OF THE OPENED CRACK

SIX SLIP STEPS COMPLETED, NEXT SLIP STEP WILL RESULT IN PENETRATION OF THE WALL

SEQUENCE OF SLIP STEPS OPENING UP AN INITIAL CRACK AND LEADING TO RUPTURE

FIGURE 4



DIRECTION OF APPLIED STRESS

ONE CRACK OPENED.

SINGLE BROAD NECK FORMED SINCE SLIP PLANES OVERLAP

MAXIMUM PENETRATION OF NECK FROM INSIDE SURFACE IS BETWEEN THE TWO CRACKS

UPPER LAYER REPRESENTS OXIDE WITH TWO CRACKS CLOSE TOGETHER

DOTTED LINES INDICATE POTENTIAL SLIP PLANES

SEQUENCE OF SLIP STEPS SIMULTANEOUSLY OPENING TWO CRACKS SPACED CLOSE TOGETHER SO THAT THEY MUTUALLY CONTRIBUTE TO THE SAME NECK ON THE INSIDE SURFACE.

FIGURE 5

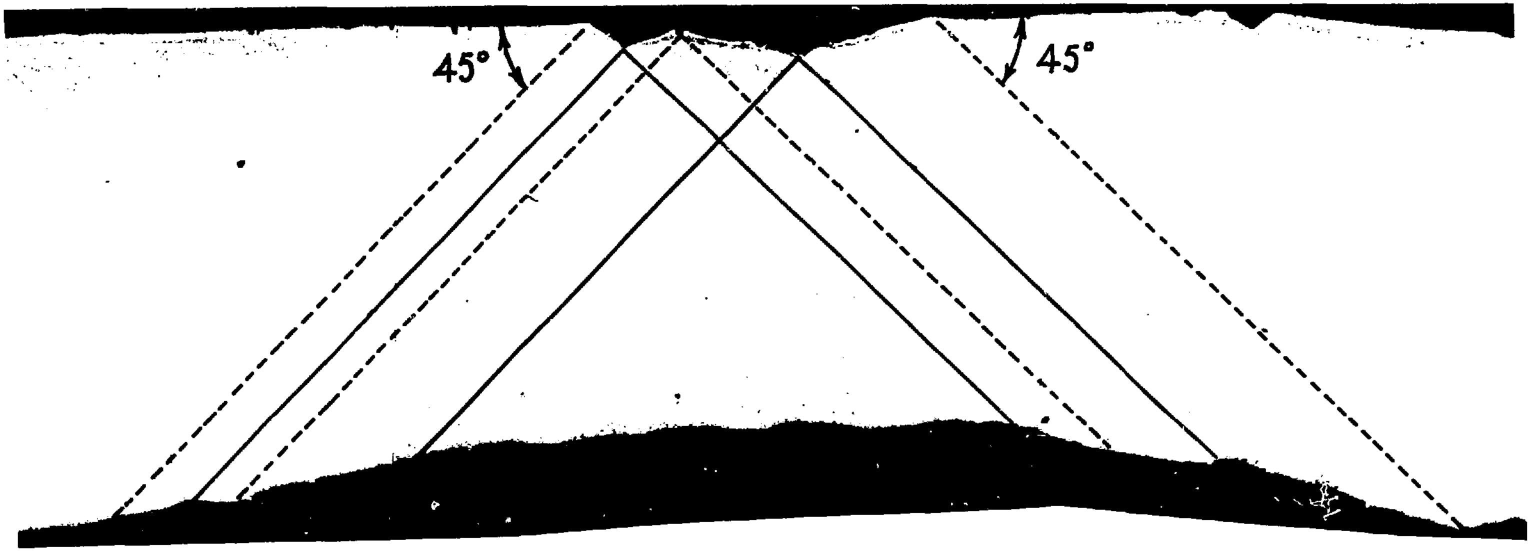
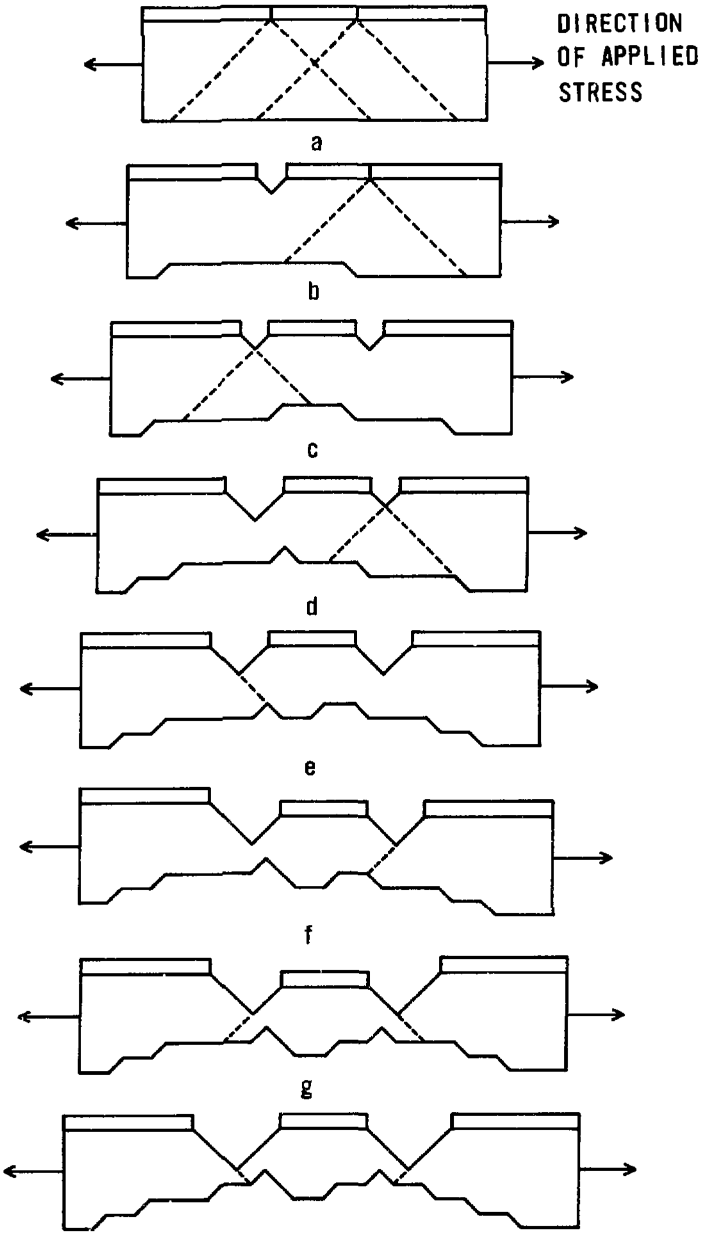


FIGURE 6

Analysis of two closely spaced cracks. Magnification 200X.



UPPER LAYER REPRESENTS OXIDE WITH TWO CRACKS ~ 3/4 WALL THICKNESS APART

DOTTED LINES INDICATE POTENTIAL SLIP PLANES

DOTTED LINES INDICATE NEXT SLIP PLANES TO BE ACTIVATED

FOR FIRST PERIOD OF STRAINING A SINGLE BROAD NECK IS FORMED ON THE INNER SURFACE

DOUBLE NECK STARTS TO FORM WHEN SLIP PLANES FROM TIPS OF THE TWO CRACKS NO LONGER OVERLAP

REGIONS UNDER EACH CRACK CONTINUE TO NECK INDEPENDENTLY UNTIL ONE FAILS

SEQUENCE OF SLIP STEPS FOR TWO CRACKS SPACED 3/4 WALL THICKNESS APART. MUTUAL CONTRIBUTION TO THE NECK ON THE INSIDE SURFACE UNTIL THE SLIP PLANES NO LONGER INTERSECT. THEN TWO SECONDARY NECKS FORM INDEPENDENTLY.

FIGURE 7

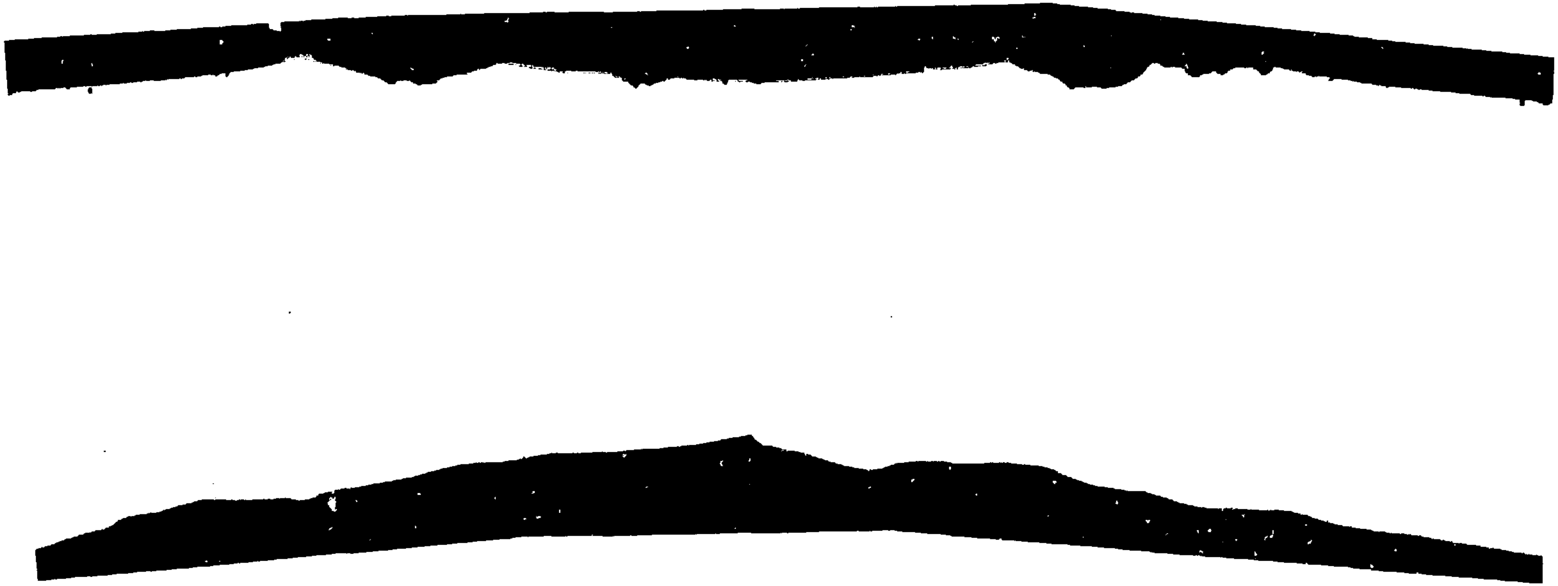


FIGURE 8

Neck resulting from two widely spaced cracks. Magnification 200X.

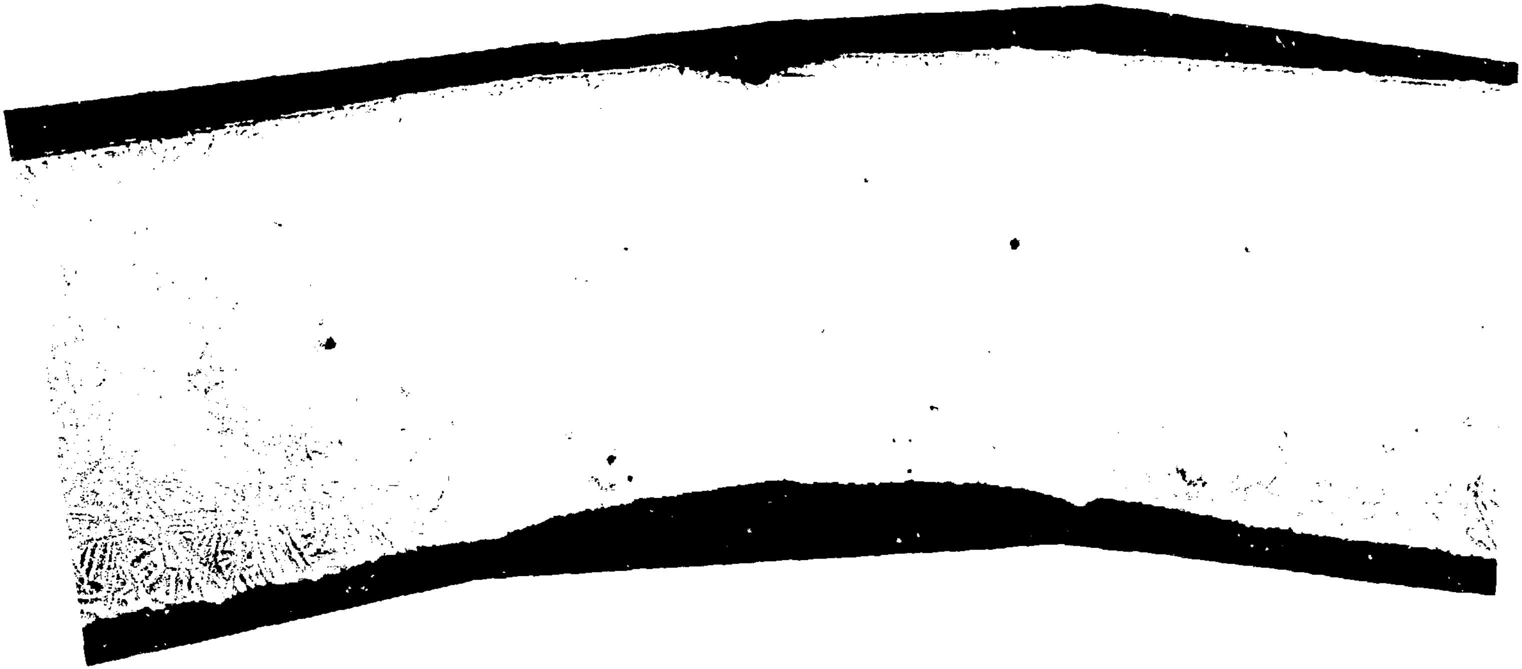


FIGURE 9

Tube cross section with single oxide crack. Magnification 200X.

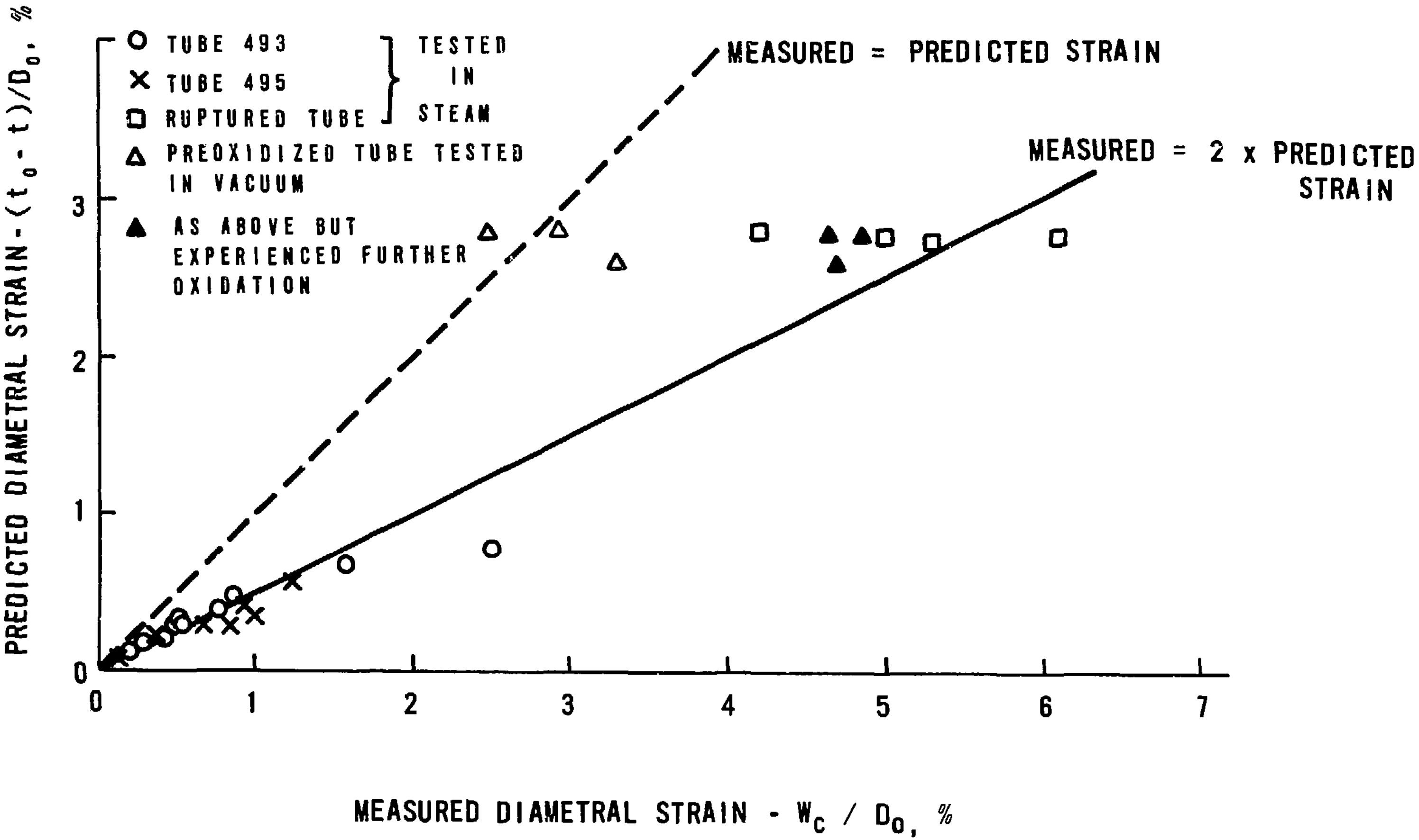


FIGURE 10

Predicted vs measured diametral strain.

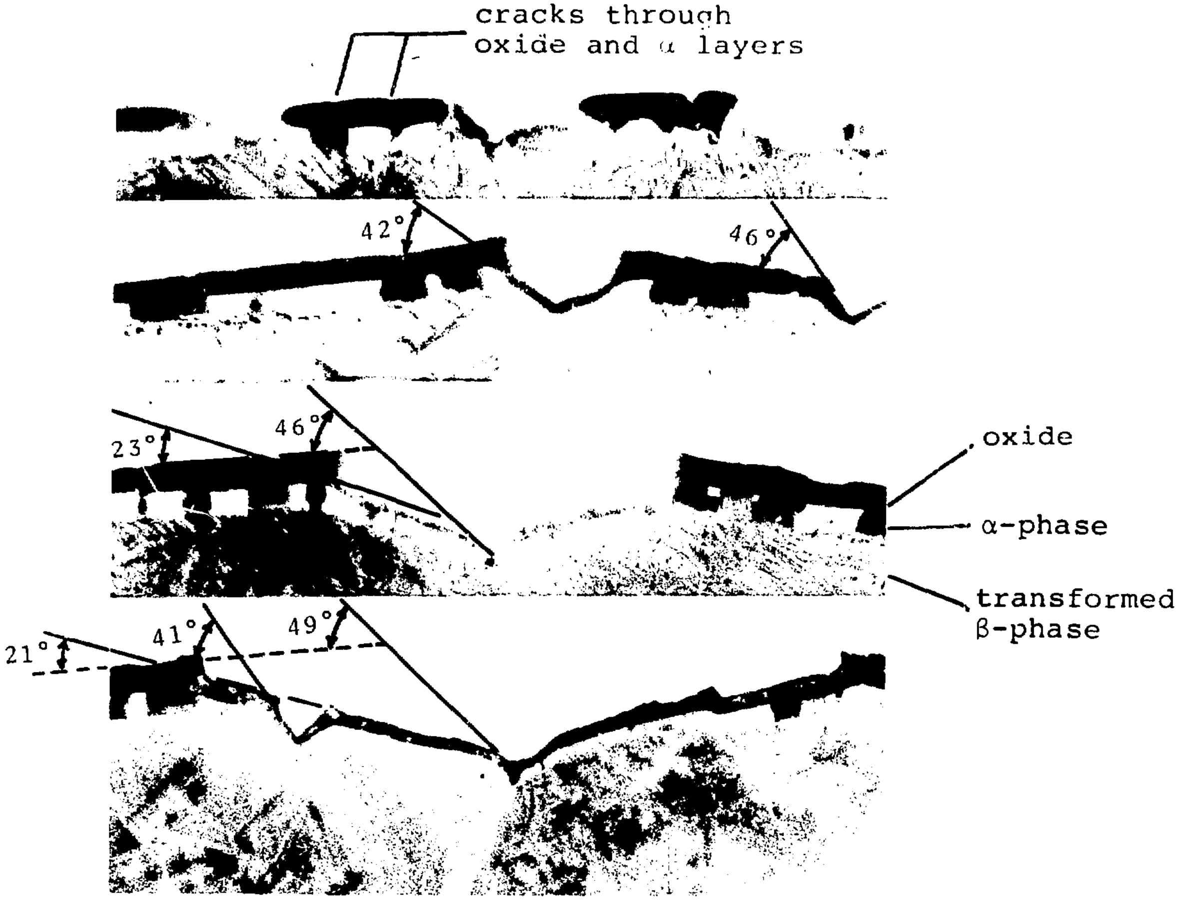


FIGURE 11

Progressive growth of cracks on a tensile surface exposed to steam. Polarized light, magnification 500X.

FIGURE 12

Continuous curvature from crack tip to crack edge. Magnification 200X.

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