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HOLOGRAPHIC DETERMINATION OF THE YIELD STRENGTH OF A WELDED STAINLESS STEEL PRESSURE VESSEL

by

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July 14, 1976

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MASTER

DISCLAIMER

Introduction

A part of the Metallurgy Division's Advanced Steel Technology Program involves evaluation of stainless steels used in pressure vessels. In particular, the strength and toughness of a high energy rate formed (HERF'ed) stainless steel, as influenced by the heat input from a variety of welds, are being measured. Using holographic interferometry, we have examined a welded spherical pressure vessel constructed from HERF'ed stainless steel with a composition of 21% Cr, 6% Ni, 9% Mn, 0.23% N, balance Fe.

Stainless steels which have been high-energy-rate forged exhibit strengths higher than normally attainable, while keeping most of their stainless properties. In the HERF'ed condition the material we examined has a yield strength of 880 MPa, and ultimate strength of 970 MPa and an elongation of about 20%. Annealing the material significantly decreases these yield and ultimate strengths to about 410 MPa and 690 MPa respectively. In welded structures some annealing takes place in the material adjacent to the weld, the so-called heat affected zone. In this study we measured the plastic deformation in the heat affected zones near an equatorial electron beam weld in a pressure vessel. From several of these measurements we constructed a stress-strain curve of the material in the heat affected zones.

The pressure vessel was constructed from parts which, after being HERF'ed into somewhat oversized shapes, were machined into hemispheres of 113 mm o.d. and 88 mm i.d. These were welded with an LLL electron beam welder using standard weld parameter settings. There was a step joint at the weld junction of 2.54 mm depth, so that the wall thickness was reduced from 12.5 mm to 9.9 mm at the weld. After welding, any raised material was machined off to form a smooth spherical shape.

Method of Strain Measurement

We used light, collimated by a 6 inch lens, from an argon-ion laser to illuminate the object, and viewed the object in the same direction. In this configuration, the fringe pattern obtained from a double exposured hologram represents a contour map of the motion of the surface in the direction of viewing.[1] The shape of the fringe pattern is independent of rigid body translation and depends on the surface strain and any rotation that occurs between exposures.

We can calculate the strain along a line on the object in the following manner: for a diametrical line on a spherical object, the relationship between the tensile strain, ε, and the slope of the fringe pattern, ρ, on the line, is given by

$$\varepsilon \tan \theta + \beta = \frac{\lambda}{2} \rho \qquad (1)$$

Here θ is the angle between the surface normal and the viewing direction, λ is the wavelength of the laser light, and β is the rotation of the object surface about an axis perpendicular to the diameter. The parameter ρ has dimensions of reciprocal length and is the number of fringes per unit length crossing the diametrical line at the point of interest.

We use a mirror to obtain a similar equation from another direction. If the mirror deflects the collimated beam through an angle of θm, then for a diametrical line which lies in the plane of both the undeflected and deflected light, we can write

$$\varepsilon \tan (\theta - \theta m) + \beta = \frac{\lambda}{2} \rho_m \qquad (2)$$

Equations (1) and (2) suffice to determine the tensile strain ε and the rotation β for points along the diameter which are visible both in the direct and the mirror views.

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Experimental Procedure

After we had attached several strain gages to the sphere, 6 mm in length and oriented across the weld, we positioned the vessel on the holographic table so that the weld plane was vertical and made an angle of about 45° with the viewing direction. A mirror was placed beside it to deflect the collimated light through an angle of 75° (Fig. 1). We coated the sphere with Magnaflux developer for visibility, and placed a chromel-alumel thermocouple on the sphere to monitor its temperature. The signal from a 100,000 psi pressure transducer was fed to a strip-chart recorder which was used to measure the maximum pressure during each pressure cycle. Below 180 MPa the pressurization fluid was argon gas, above this pressure we used a mixture of kerosene and hercoflex.

To obtain fringe patterns showing the plastic deformation, we took the first exposure of the hologram at zero pressure, raised the pressure to a predetermined value, then released the pressure and exposed the hologram for the second time at zero pressure. The fringe pattern from the hologram then represented the permanent strain due to the increase in pressure between exposures. We developed each hologram and examined it before the next pressure cycle in order to estimate the appropriate increase in pressure to give a useful fringe pattern to the next hologram. We then obtained another hologram with exposures separated by a higher pressure cycle. (Fig. 2) Each hologram then contained information about the permanent deformation which occurred due to the increase in pressure over that of the previous pressure cycle.

Results

We obtained 8 holograms covering various pressure intervals between zero and 282 MPa (41,000 psi). A photograph of a typical hologram is shown in Fig. 3a. The strain measured from this fringe pattern using equations (1) and (2) is shown in Fig. 3b. The latter curves show that the plastic strain goes through a maximum at about 5° on either side of the weld, corresponding to a distance of 5 mm distance along the diameter. The strain at the weld itself is nearly zero, as is the strain beyond about 24° on either side of the weld. In some cases there was an increase in temperature between exposures in which case there was some thermal strain beyond 24°. This we subtracted from the strain measured in the heat-affected zones. The one operating strain gage across the weld indicated a strain of about 60% of the maximum value obtained holographically.

We have considered the question of how much of the strain we measured consisted of residual strain. Of course, if we measured residual strain as well as plastic strain, the calculated value of the yield strain would be in error in proportion to the ratio of the residual strain to the plastic strain. We believe that the amount of residual strain we measured is small compared to the plastic strain for several reasons. First, the curve corresponding to Figure 4, if consisting mainly of residual strain, would have opposite curvature. This is because the amount of residual strain a material can hold is limited to the value of the yield strength divided by its elastic modulus. Thus as more and more pressure in the vessel is applied, the increase in residual stress would become less, giving an upward curvature to Figure 4.

The second reason for believing the residual strain included in Figure 4 is small is that as the regions on either side of the weld become plastic, residual strain is reduced. When these regions become plastic through the complete wall thickness, the residual strain becomes zero. Based on Figure 4, we believe that the heat affected zones on each side of the weld become plastic through the wall, so that any residual strain measured at low pressure is subtracted from the strain measured at high pressure, with the net effect of there being no net residual strain in the total strain measured.

From the series of holograms we constructed the pressure-plastic strain curve shown in Figure 4 corresponding to the maximum strain in the heat affected zones on either side of the weld. In one pressure range, 175 to 207 MPa, we did not have data due to inadvertently failing to take the first exposure of the hologram. For this region we extrapolated the data on either side to form a smooth curve. At a pressure of 282 MPa the total strain was .165% for the heat affected zone to the right of the weld and .117% for the heat affected zone to the left. The difference in strain between the left and right side is probably due to the shape of the lip below the weld.†

We had intended to obtain several more holograms and extend the strain curves to .2%, but during the last pressure cycle the vessel began to expand continuously at a pressure slightly over 282 MPa, exceeding the strain that could be recorded holographically. This occurred because the pressurization system we have, even using a liquid as the pressure medium, is effectively a very compliant strain apparatus. This makes control in the flat portions of the pressure-strain curve very difficult.

The vessel was subsequently pressurized to burst in a different facility. The maximum pressure reached during this test was 365 MPa. The vessel failed in a very ductile manner, with the fracture evidently starting at a small flaw on the right side of the weld near the line on which strain was holographically measured. A photograph of the failed vessel is shown in Figure 5a and a close-up of the fracture surface showing a flaw is shown in Figure 5b.

We calculated the stress in the wall based on the equation for thin walled spherical vessels of radius R and wall thickness t. This relation is valid if the strain is uniform throughout the walls, and is

$$\sigma = \frac{PR}{2t} \qquad (3)$$

We obtained values of 287 MPa and 297 MPa for the internal pressure at yield of the right and left heat affected zones by extrapolating the curves of Figure 12 to .2% strain. Substituting these values in equation (3), and using the wall thickness of 9.9 mm at the weld, the calculated yield strengths

† Phil Landon, private communication

for the right and left heat affected zones are 750 MPa and 770 MPa respectively. We calculated the ultimate strength using the same expression and obtained a value of 960 MPa.

Discussion

Holographic examination of the weld vicinity shows that plastic deformations in the heat affected zones reach a maximum at a distance of 5 mm on either side of the weld, and tails off for another 20 mm to zero strain. The yield and ultimate strengths of the heat affected zones, based on the thin wall relation (equation 3) and using the wall thickness just above the weld, is nearly that of the parent material. However the mode of deformation indicates that if the heat affected zones were either of higher strength or narrower, the pressure vessel would be stronger. Several more vessels are being electron beam welded using different weld parameters, and we will examine these to determine how the strength of the vessel is affected.

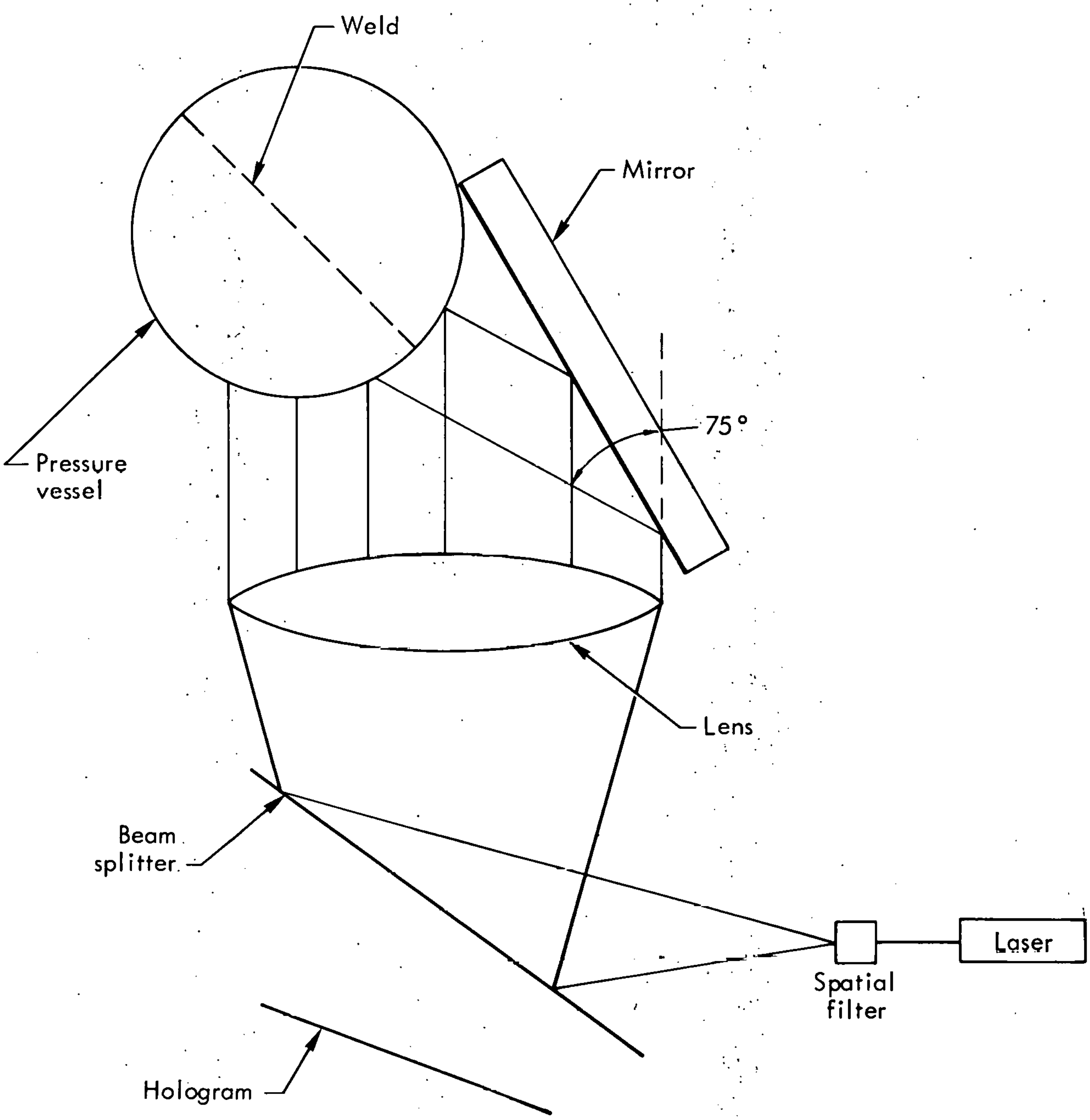
Weld
Mirror
Pressure vessel
75°
Lens
Beam splitter
Laser
Spatial filter
Hologram

Figure 1

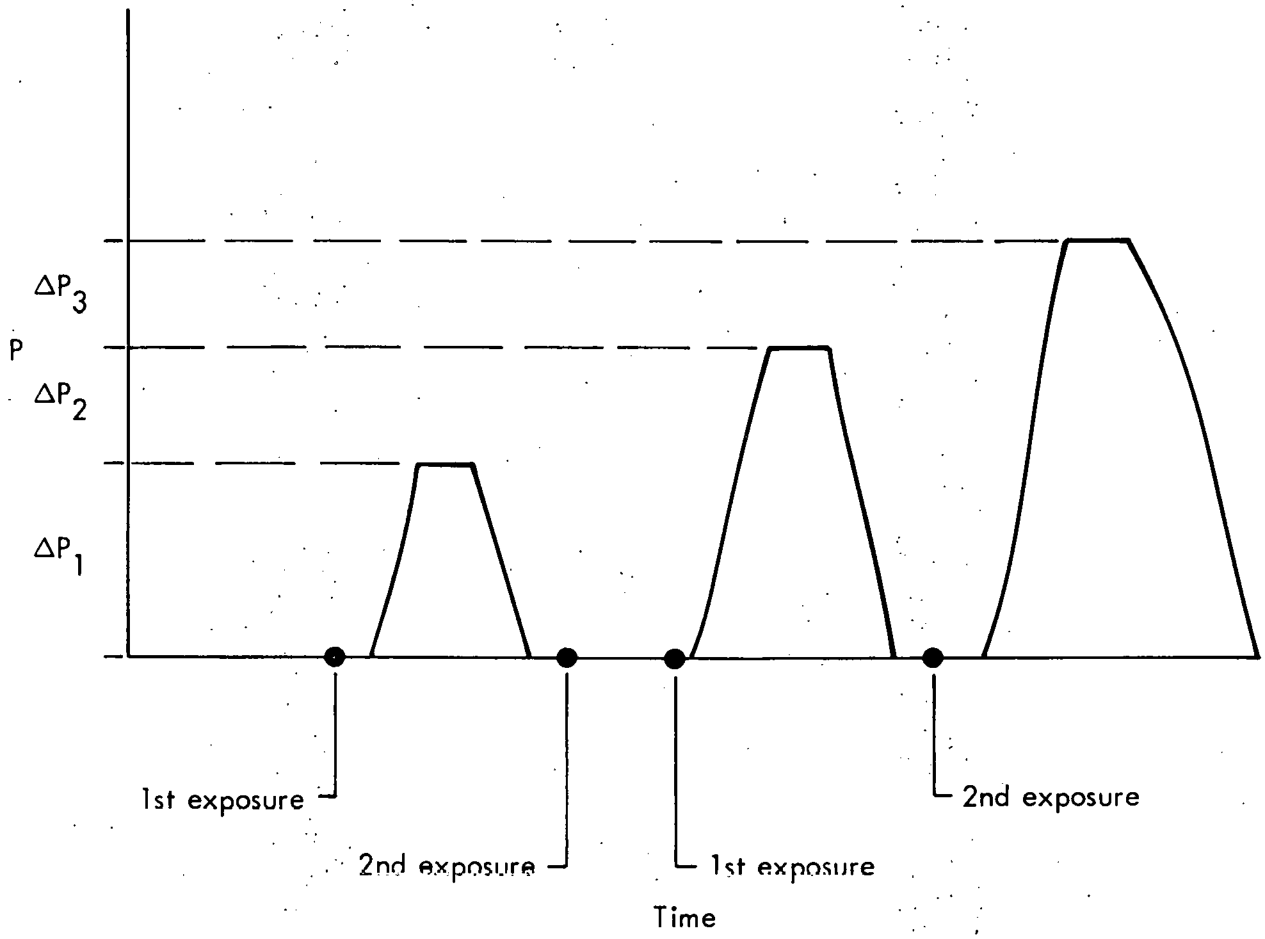
ΔP3
P
ΔP2
ΔP1
1st exposure
2nd exposure
1st exposure
2nd exposure
Time

Figure 2

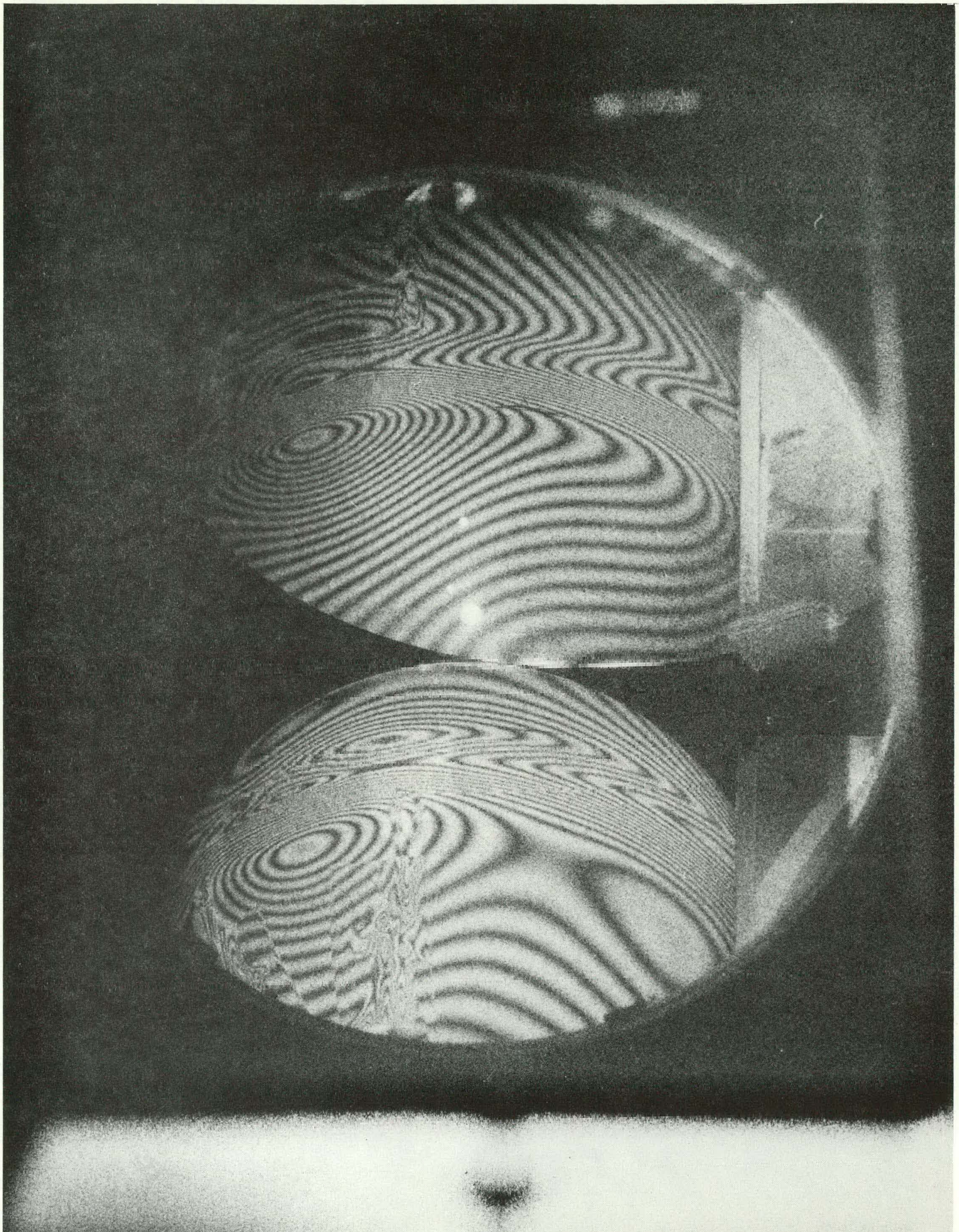

Figure 3A

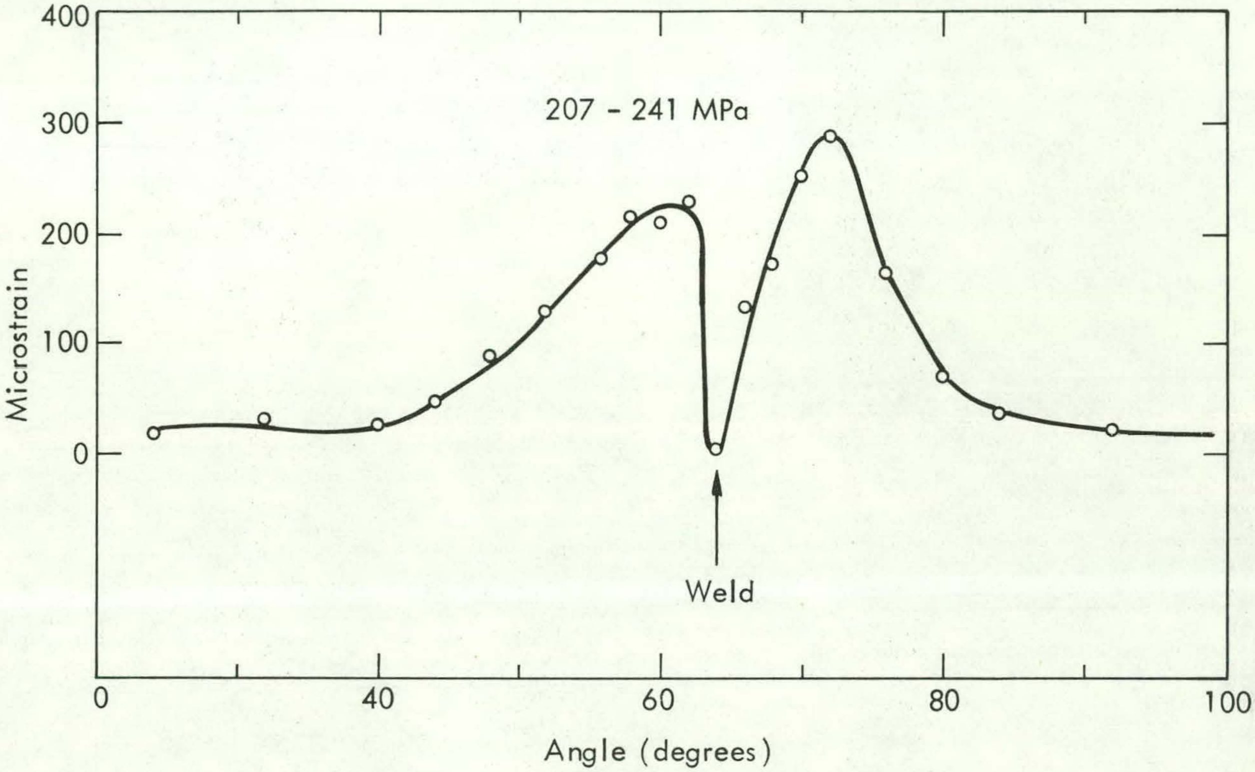
400
300
200
100
0
Microstrain
207 - 241 MPa
Weld
0
40
60
80
100
Angle (degrees)

Figure 3B

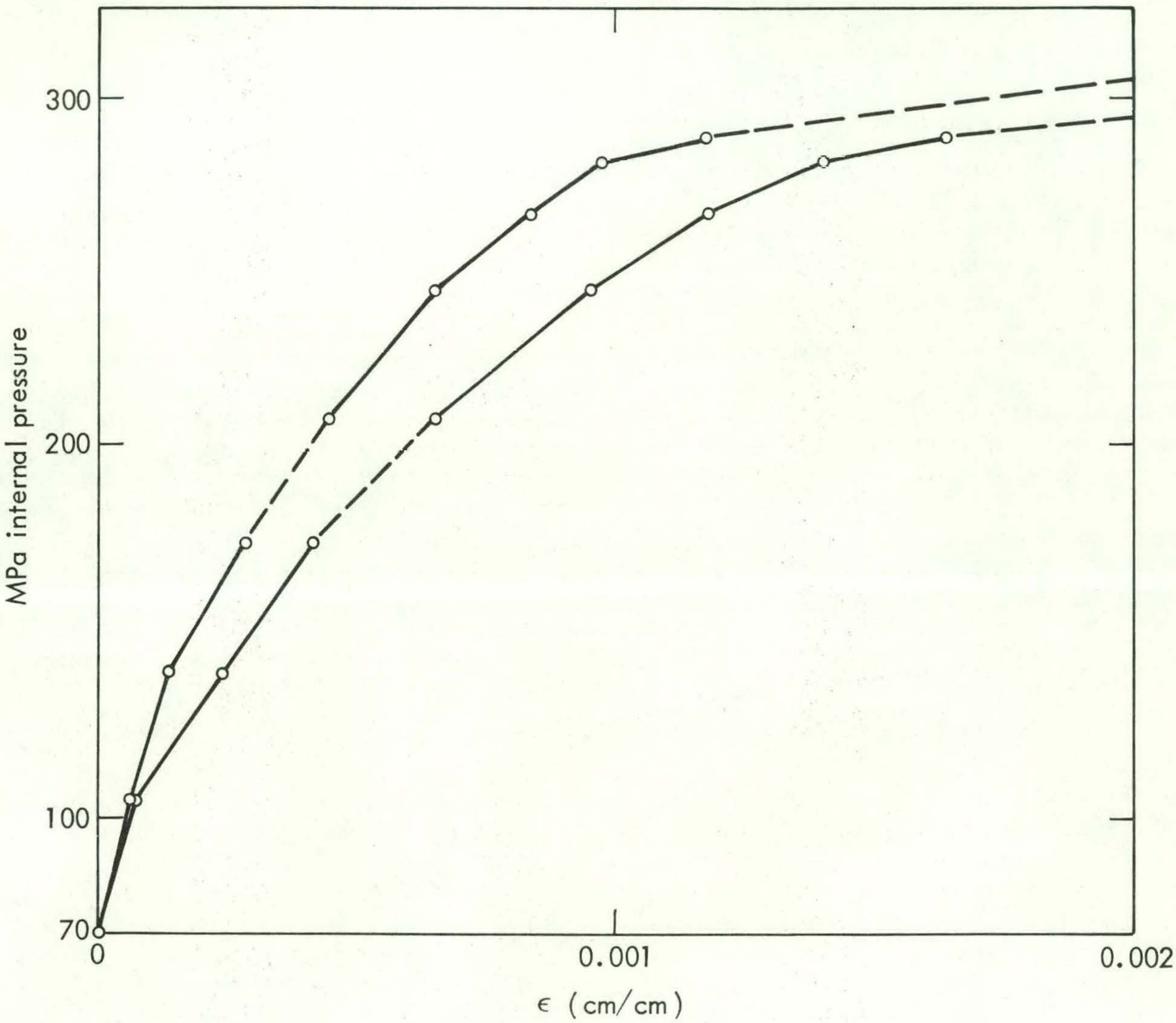

Figure 4

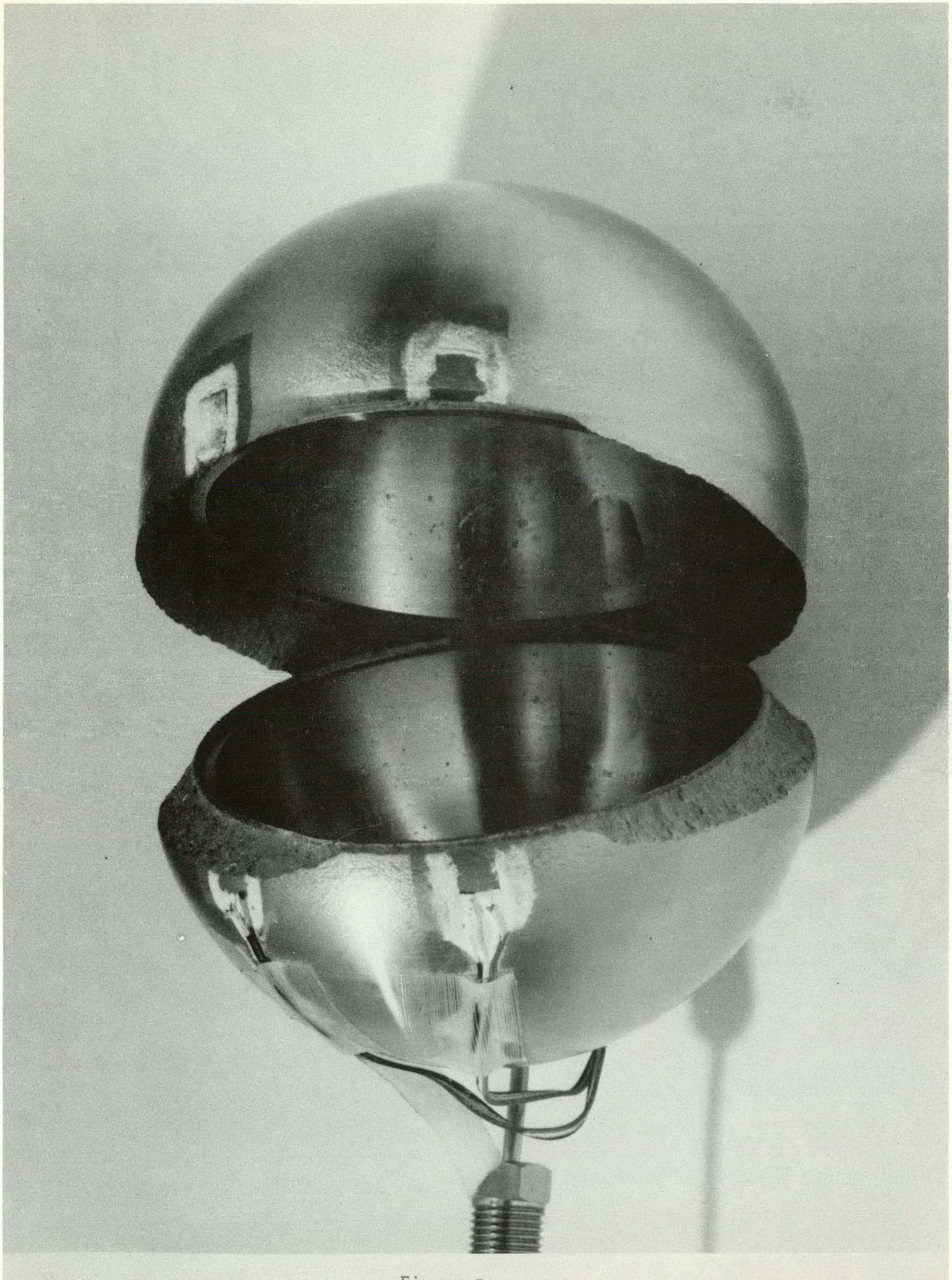

Figure 5A

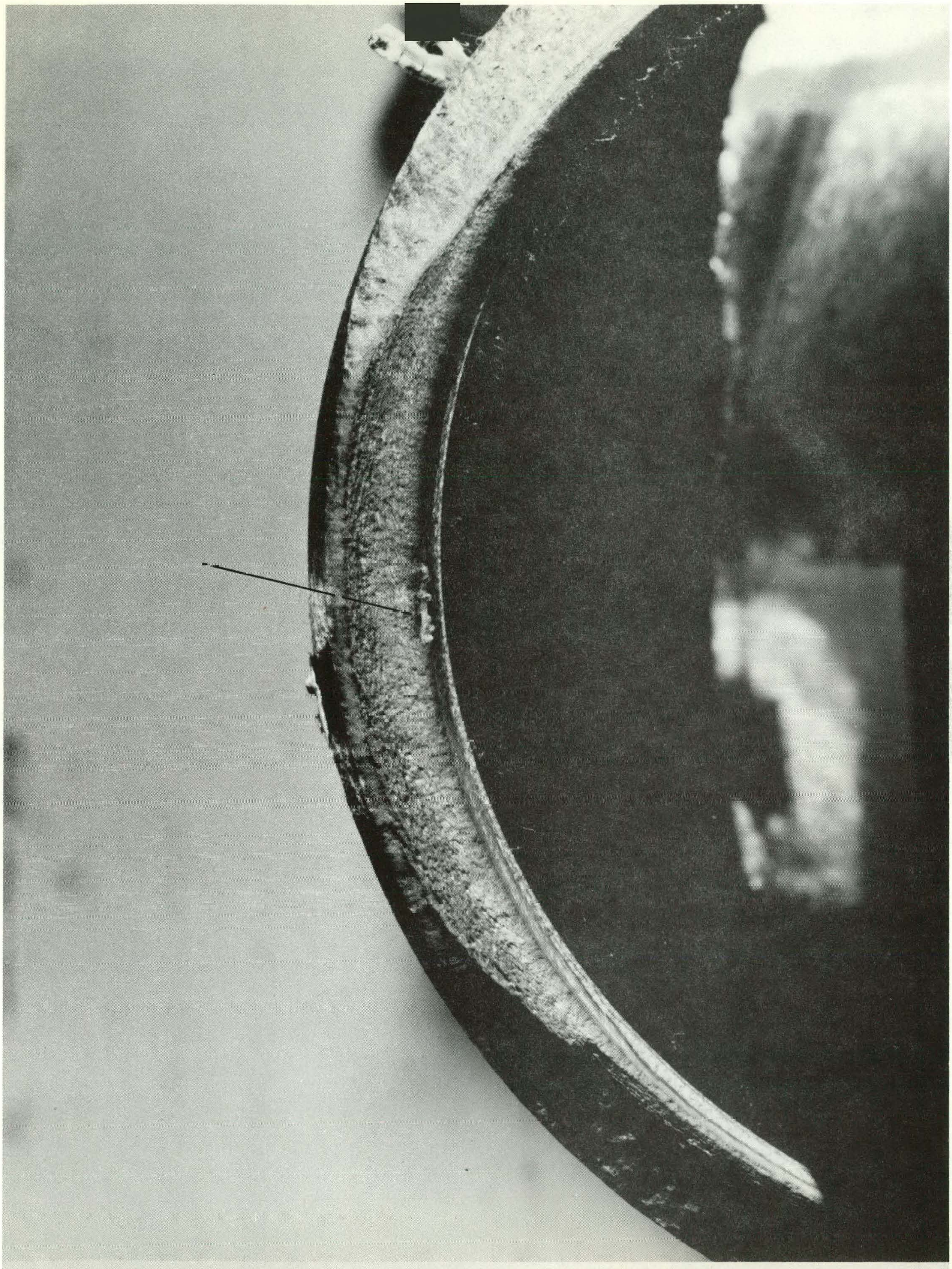

Figure 5B

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