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C. T. Hoard

STATIC FATIGUE OF GLASS

Background

Recently, two spherical glass mirrors intended for use in the E-97 Cerenkov counter cracked. It has been suggested that an outline of this event and a review of the current theory of glass failure would be informative to others concerned with the handling of glass structures.

The Mirrors

The mirrors were originally planned for acrylic and were changed to glass to obtain more accurate curvature. Four blanks, 27 × 36 inches, were cut from 1/4-inch soda-lime plate. Slumping into a graphite mold was done at LBL. According to Dane Anderberg of LBL, mirrors are cooled 18 hours from 675°C to 200°C in contact with the mold, and are therefore annealed. No stresses have appeared on polarimeter checks made on other similar mirrors at LBL.

To avoid support fingers in the central gap, the mirrors were mounted on three acrylic blocks, 2-inches square, epoxied to the back as in Fig. 1. The three locations were roughened with emery paper before the epoxy was applied and numerous scratches remained outside the epoxy area.

The first aluminum coating was unsatisfactory and the mirrors went to Jim Pope for stripping and cleaning. The first mirror was immersed in 60°C alkaline cleaner (to the depth shown by the waterline in Fig. 1) for 3 or 4 minutes. It was removed, turned end for end, and while being lowered into the cleaner, cracked in two as shown in Fig. 1. Minute initiating cracks and the sharp curves indicate that cracking started under the center block.

One of the halves of this mirror was re-immersed in the cleaner on the following day, rinsed in 27°C water, and then half-immersed in 96°C water for several minutes with the corner block submerged. No cracks were observed and it was left overnight, wrapped in paper. The next day, two short cracks were found, normal to the plate, and one smooth crack nearly parallel to the plate, making a reflective area shaped like a clam shell, as in Fig. 2. There were no loose pieces, however.

The blocks were then sawed from the remaining mirrors at the epoxy level but no attempt was made to remove the last wafer of acrylic or the epoxy. The same alkaline cleaner was used but at room temperature. The second mirror was recoated; in lifting it from the coating chamber one corner cracked off. Again the crack appeared to originate under the epoxy.

The Theory

The current theory of glass failure by "static fatigue" has been summarized by Shoemaker.[1] The theory applies to annealed glass (as distinguished from strengthened) and states that failure occurs from growth of microcracks under the influence of water vapor and a continuing load.[2] Failure is delayed and occurs at low stresses, often much lower than the glass had already sustained.

All glass surfaces contain microcracks. Even cracks sufficiently less than one wavelength of light to be invisible, are large enough to permit diffusion of water molecules. In addition, scratches of varying depths from handling are usually present. Shoemaker correlates "flaw severity" with reduction in strength and gives a relation between flaw severity and the mesh size of the grinding compound used to produce the flaws.

Static fatigue does not occur with dry glass and increases with increasing humidity. Two practical occurrences of dry glass are after vacuum bakeout and in liquid nitrogen. Baker and Preston[3] show that glass exposed to moisture can lose more than half its strength in 10 seconds and be reduced to 1/3 strength in 24 hours. Wiederhorn[4] divides crack propagation into three successive stages: (I) corrosive attack of water vapor on the fresh glass at the tip of a crack, wherein crack velocity is low but depends on humidity and increases exponentially with the load, (II) corrosion limited by water vapor transport to the tip, wherein crack velocity depends on humidity and is independent of load, and (III) crack propagation independent of water concentration, exponential with the load and at a high rate. Figure 3, from Wiederhorn,[4] shows this effect.

Recovery of glass from overstressing tends to complicate the theory. Pranatis[5] and Shand[6] note increases in strength when glass is stressed at less than the fatigue limit. Wiederhorn and Johnson[7] and Shoemaker[1] consider blunting of the crack tip by water vapor to be the mechanism of this recovery.

Covering scratches and abrasions with a coating to block access of water vapor to cracks is an obvious possibility. Ritter[8] tested epoxy, silicone, and acrylic coatings on abraded soda-lime glass. All significantly increased the short-term strength but had little effect on the long-term stress corrosion susceptibility. He concludes that the coatings do not alter the basic reaction between water and the glass.

Conclusions

Three factors contributed to failure of the mirrors:

1) Attachment blocks covered too large an area; stresses set up by epoxy shrinkage were probably high.

2) The glass should not have been abraded.

3) In the presence of factors 1 and 2, the glass should not have been immersed.

For future design, when glass must be supported by adhesive supports, the glass should be cleaned but not abraded and the supports should be designed with multiple small attachment feet to minimize shrinkage stress.

References

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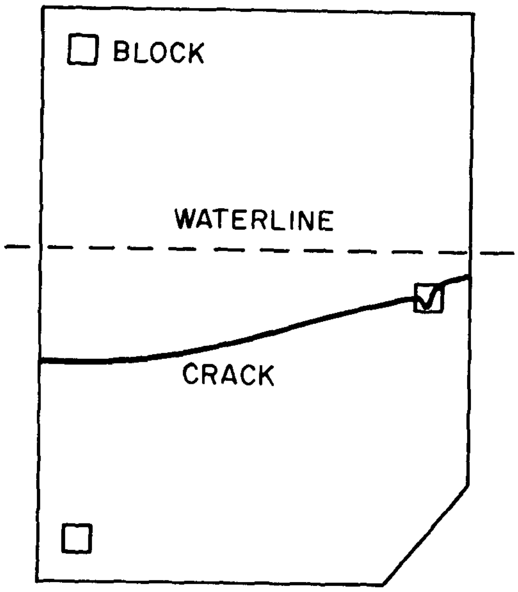

Fig. 1--Mirror

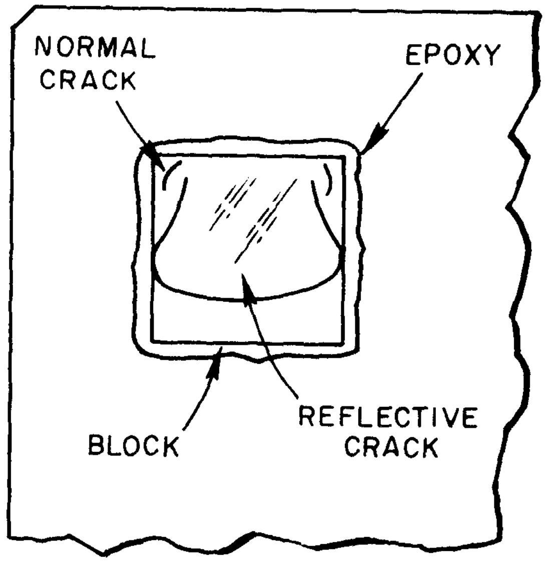

Fig. 2--Mirror Corner

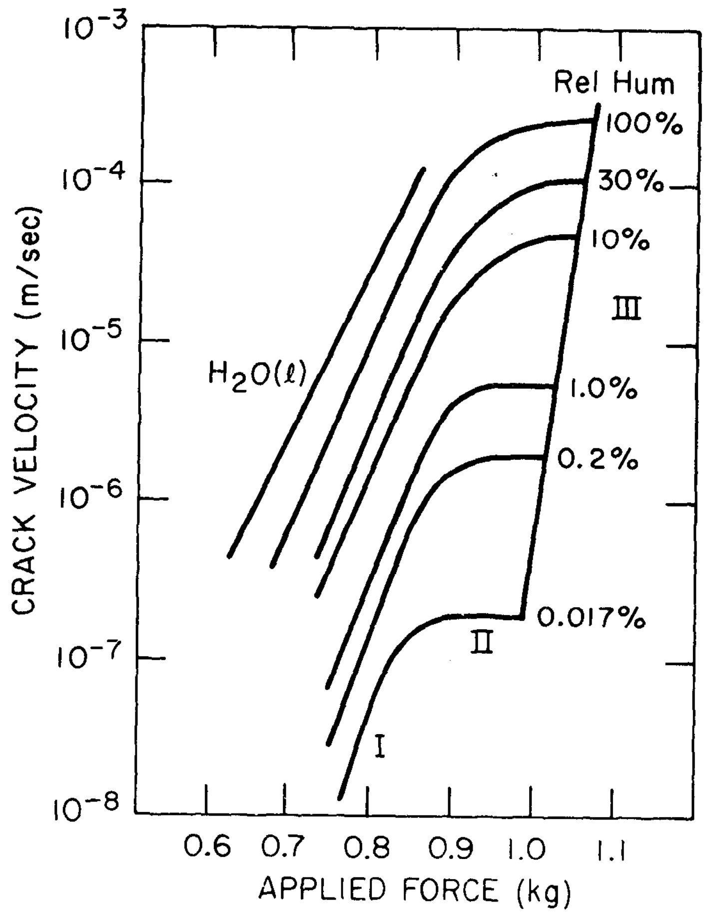

Fig. 3

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