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Reconstruction of Fractured Glass by Laser Beam Interferometry

The matching of fractured glass fragments has been extended by von Bremen [*1*] to include the intrinsic heterogeneities referred to in the glass industry as "ream" [*2*]. Von Bremen used a fiber optics source to project a shadowgraph of fractured glass onto a photographic film that was then developed. Although this is a powerful method for comparing ream marking, the technique suffers a disadvantage in that the ream cannot readily be seen with the naked eye in all samples. It is readily apparent in container glass, lamp bulb glass, and drawn window glass. In other types of glass including float glass, the photographic film must be developed before it is known whether an image of the heterogeneities of the glass has been adequately recorded.

Since the argon-ion laser represents an exceptionally powerful source of coherent energy, we initially attempted to apply it to the production of shadowgraphs in the manner of von Bremen. Although the argon-ion laser was found to be applicable to the shadowgraph technique, its principal benefit was in the production of reflected interferograms.

Interferometry is the subject of voluminous literature [*3-6*], and only the briefest of discussions will be included here. When a beam of light is divided into two separate beams that travel different paths and are then recombined, interference may occur and interference fringes may be observed. These fringes have the general appellation of Fizeau fringes, although other names may be applied to them (for example, Newton's Rings) depending upon the manner in which the fringes are propagated. The form of the Fizeau fringes is determined by the difference in optical path traveled by the two beams. But since the optical path is a product not only of the geometrical path but also of the refractive index, the fringes are a manifestation of both.

Consider a piece of glass of thickness D and refractive index N, as depicted in Fig. 1. A ray PQ is partly reflected along QR and at the same time is partly refracted along QS. At the glass-air interface S the ray is again refracted toward Z, but a portion is reflected along ST, where the ray is then refracted along TV. Interference occurs between the rays QR and TV. The optical path difference d between these two rays is given by

$$d = 2\,ND \cos I'$$

where I' is the angle of refraction. A change of phase also occurs at reflection. This change may be anywhere from 0 to 180 deg and will usually be different at the two surfaces.

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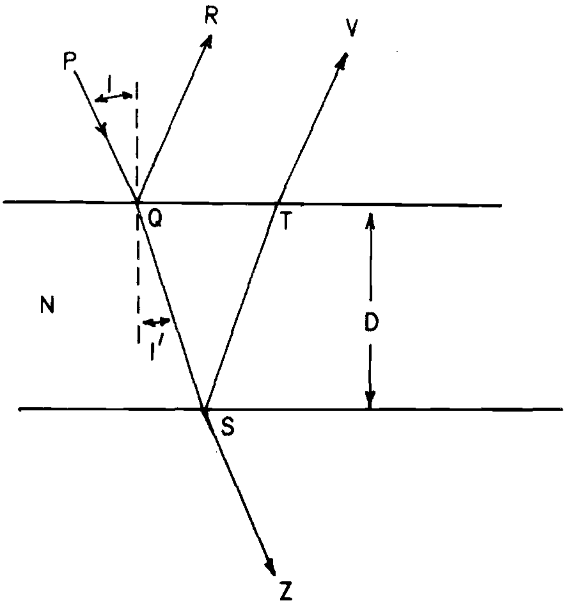

FIG. 1—*Optical path difference between rays reflected at the top and bottom surfaces of a plate of glass, as described in the text.*

It is apparent from this discussion that an optical path difference may be accentuated if D is not constant in the glass plate, or if N is not constant, or if neither is constant. A difference in optical path may be expressed in the form and distribution of the Fizeau fringes. Since differences in thickness and refractive index are likely to be intrinsic characteristics of a sample of glass, the possibility exists of characterizing glass on the basis of the Fizeau fringes.

Experimental Procedure

A Spectra-Physics Model 164 argon-ion laser was used in this study. This is a high power, continuous wave laser capable of lasing at a number of wavelengths, the strongest lines being at 514.5 and 488.0 nm. The laser delivers a beam of 1.5-mm diameter with a divergence of 0.5 milliradians, requiring further divergence of the beam for the production of interferograms from large samples of glass. This divergence was achieved by placing an inexpensive glass negative lens (Edmunds Scientific Corp.) with a focal length of −24 mm in the beam path immediately forward of the laser head. The result was a beam diameter of approximately 8 cm at a distance of 75 cm from the diverging lens. A ×40, 0.65 numerical aperture microscope objective placed in the beam path was found to give a comparable divergence of the beam. The samples of glass to be examined were held in a clamp so that the plane of the glass made an angle of approximately 15 deg with the laser beam. A white paper screen was placed 185 cm from the glass to intercept the transmission shadowgram. A second white paper screen was placed 200 cm behind the diverging lens and offset from the axis of the laser beam to intercept the reflection from the glass. Photography of the interferograms was accomplished with a 35-mm camera with ASA 400 film. Monochromatic energy with a wavelength of 514.5 nm was used in this study, with one exception as described in the Results and Discussion section below. Visual examination was conducted at 2 W of power, and photography was conducted at 5 W of power to decrease the exposure times. Exposure times were found to be on the order of $^1/_{15}$ second at *f*/4.5. Figure 2 represents the equipment configuration.

Results and Discussion

The writers do not contend that a powerful laser of the type described here is necessary to the production of reflection interferograms. In theory, any source of monochromatic energy would be sufficient. From a practical standpoint, however, the laser is of considerable advantage. Only about 4% of the total energy is reflected from glass; unless a powerful source of monochromatic energy is used, the reflection interferogram will be very weak.

A number of samples of glass examined showed pronounced ream in the transmission mode. Figure 3 illustrates such an example. An advantage of using the argon-ion laser for this purpose is that the ream, if present, can be readily perceived with the naked eye. There is no doubt that the continuity of ream in instances of glass fracture can be used to establish that the pieces of glass were the result of the same manufacturing process. Figure 4, a broken microscope slide, illustrates such an example. In addition to the obvious ream in Fig. 4, however, there are some barely perceptible interference fringes superimposed on the more conspicuous ream. The transmission mode is not, however, the best technique for observing interference fringes. In transmission, fringes of similar intensity and distribution are superimposed on an intense background resulting from the

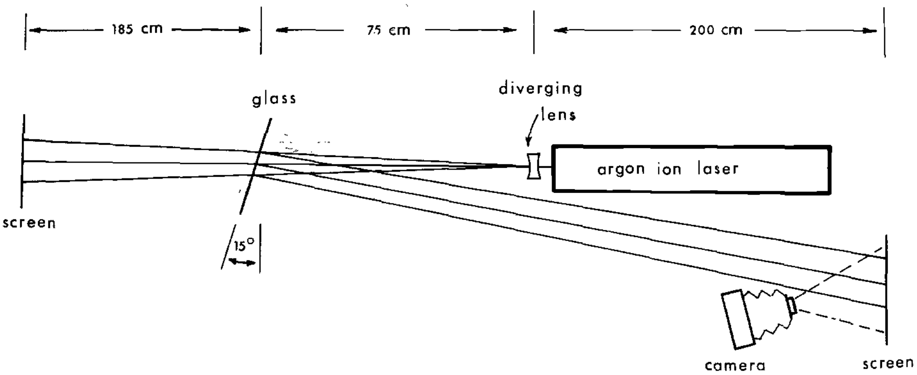

FIG. 2—*Manner of propagation of laser interferograms from a glass plate.*

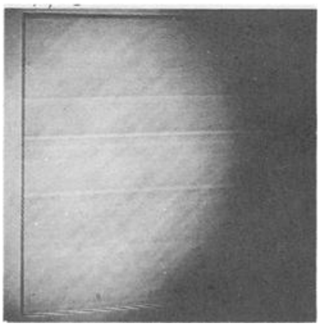

FIG. 3—*Transmission shadowgraph of longitudinal ream in a sample of glass.*

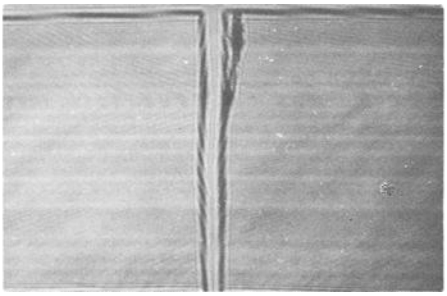

FIG. 4—*Match of ream in a broken microscope slide by the transmission shadowgraph technique.*

primary beam, and consequently are hardly visible. In the reflection mode, on the other hand, the fringes may be seen much more easily because the amplitude of the two interfering beams is about equal and there is a phase shift from the reflected beams.

The Fizeau fringes observed in the reflection image are, in essence, contour maps of the surface microtopography, that is, microtopographical contour maps in the up and down direction. The contour lines each represent a height change of $\lambda/2$, or 257.2 nm for the 514.5-nm line of the argon-ion laser. In our experience, the interference patterns shown by different pieces of glass are unique. Figures 5*a* through 5*f* illustrate the diversity of Fizeau fringe patterns of six different pieces of glass. Since monochromatic light is being used, the fringes may represent considerable optical path differences, and consequently even thick pieces of glass display the fringes.

The application of the Fizeau fringes to the reconstruction of fractured glass is easily achieved. Figures 6*a* through 6*e* illustrate matches in pieces of fractured glass based on the continuity of the Fizeau fringes. Although the fringes bear some apparent similarity to the interference phenomenon observed when strained glass is viewed between crossed polars, the Fizeau fringes are not due to strain. Torsion-induced strain will not materially affect the Fizeau fringes, although a change in the angle of the incident beam certainly will.

In a relatively small number of glass specimens examined, the reflection image showed not the meandering Fizeau fringes but rather a series of striae observed to be correlated with the ream observed in the transmission mode. Figure 7 illustrates the reflection image from the same piece of glass as Fig. 3. In the reflection mode the marks are rather more apparent and, of course, represent a mirror image of the transmission image. It was found that in cases where the ream was noted in reflection, a match of fractured shards could easily be achieved. Figure 8 illustrates such a match. Situations involving ream or longitudinal striae in the reflection image appear to be correlated with extreme heterogeneity, and some samples (for example, Fig. 5*e*) show both ream and Fizeau fringes. The writers have observed some samples of very uniform float glass whose transmission image was totally featureless and without any information content as seen visually but have yet to encounter a sample that does not have a reflection image which provides a "signature" of the glass in question.

Efforts to reconstruct fractured disannealed, or tempered, glass by this technique proved futile. Edge effects and internal reflection cause sufficient distraction to prevent the proper interpretation of the interference pattern (Fig. 9). The glass in this instance is an extensively crazed sample of tempered glass measuring approximately 3 by 6 cm. The reflection at the fragment boundaries confuse the interferogram to such an extent that any continuity of the Fizeau fringes cannot be appreciated.

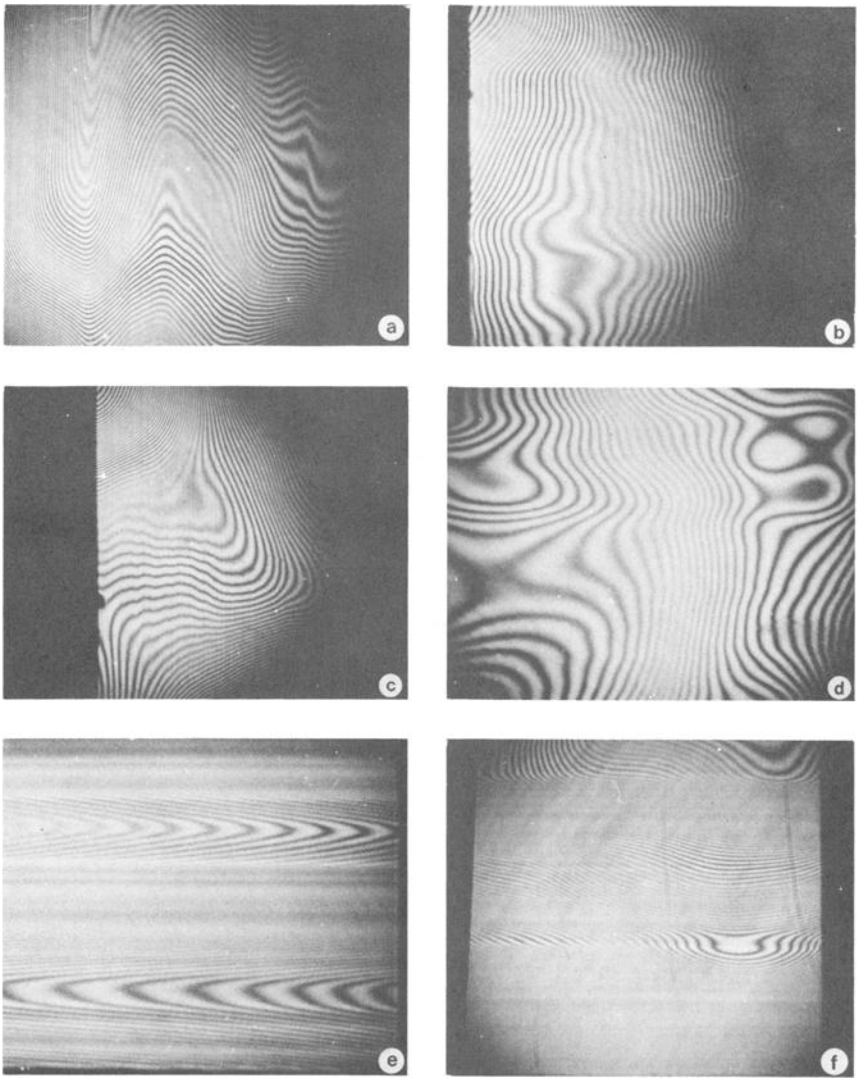

FIG. 5—*Interference figures shown by six different pieces of glass.*

With monochromatic light of 514.5 nm, the interference fringes indicate the surface topography but provide no information as to whether a fringe delineates an elevation or a depression. This information may be obtained, however, if two wavelengths are employed. The argon-ion laser, fortunately, is capable of lasing at a number of wavelengths simultaneously. If the green 514.5-nm and the blue 488.0-nm lines are employed simultaneously, the interference fringes are green on one side and blue on the other. The blue is toward the central fringe or higher area of the glass, while the green side of the fringe is toward the lower area.

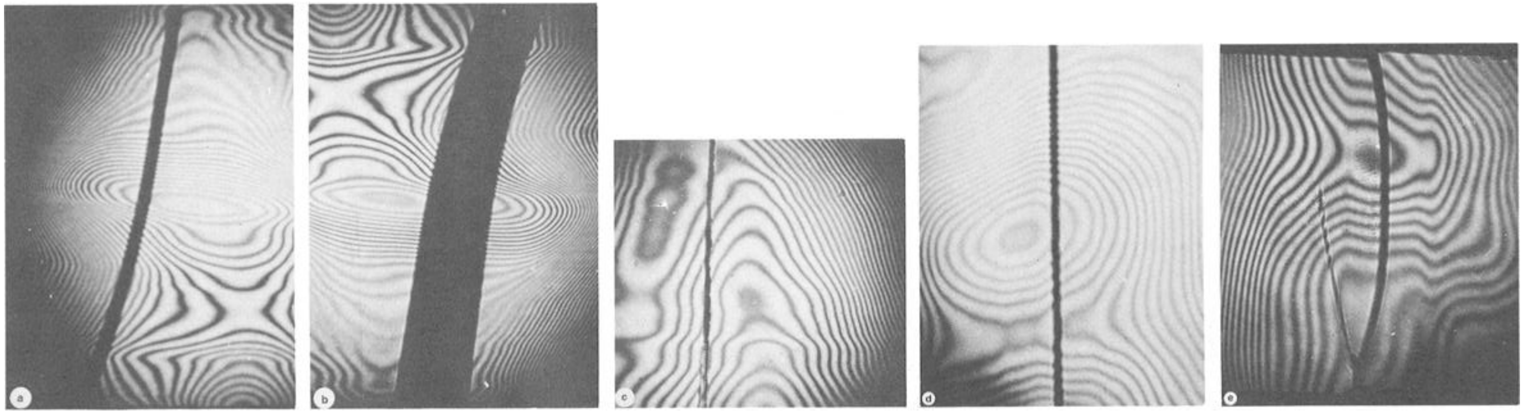

FIG. 6—*Common origin of fractured glass samples demonstrated by the continuity of the Fizeau fringes.*

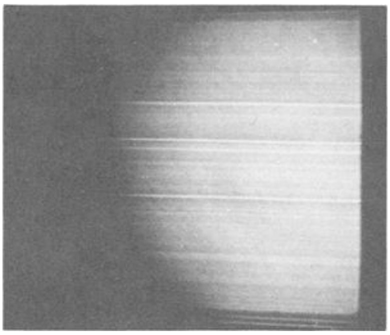

FIG. 7—*Reflection image of the same piece of glass as in Fig. 3. The longitudinal striae are more apparent in the reflection image than in the transmission image.*

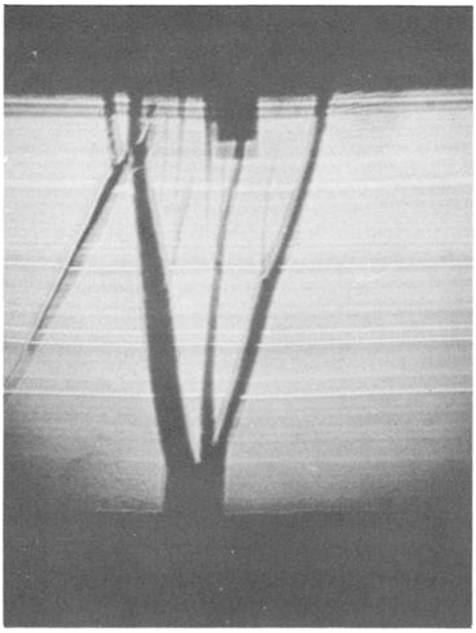

FIG. 8—*Match in longitudinal striae as seen in the reflection image of several shards of fractured glass.*

FIG. 9—*Reflection image of an extensively crazed piece of disannealed glass.*

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