Water jet: a promising method for cutting optical glass

Javier Salinas-Luna, Roberto Machorro, Javier Camacho, Esteban Luna, and Juan Nunez

We present an alternative method for cutting optical glass. It works with a high-pressure fluid, carring abrasive powder. This technique offers some advantages over conventional methods that use diamond abrasive covered wires or disks. We make a critical comparison between those two techniques, characterizing cuts with interferometric, polarimetric, and Ronchi testing. The main feature of the water-jet technique is that it allows surface of any shape, already polished, to be cut safely.

OCIS codes: 220.4610, 220.4840.

1. Introduction

Cutting glass is a well-established technique used in every optical shop.[1] It is used to extract small pieces from a bigger piece of glass by using a disk or a wire covered with diamond powder. It has some advantages: It is simple, inexpensive, and reliable. Nevertheless it also has disadvantages: Heat is generated during the process, introducing plastic deformations and stress inside the slab. This technique must be used before polishing, otherwise any trace of grains of diamond or glass left might introduce scratches. A limitation of the disk cutter is that basically only straight cuts are allowed. Unless a special fixture is used the size of the slabs is limited. Last, but not least, the edges left by the cutter are rough, requiring finish work to smooth them.

There are reports in the literature regarding the defects created by cutting glass before and after polishing an optical surface. Cordero-Dávila *et al.*[2] discussed the polishing process when wear is greater at the edge and the tool extends beyond the border of the workpiece (Fig. 1). Lynn *et al.*[3] showed what happens when a surface is cut after polishing; the ion figuring process was successfully used in that case to correct the residual surface figure error on the 1.8 m Zerodur off-axis segment of the Keck telescope's primary mirror.

In this paper we introduce a novel technique, at least for an optical shop, for making very smooth cuts of any shape even after the surface has been polished. This technique is currently used at the industrial level to cut metal, wood, and plastic with a water jet at high pressure. Sometimes abrasive powder is mixed with water to accelerate the cutting. Here we compare both techniques, disk and water-jet cutting, side by side and apply them to two parabolic off-axis mirrors.

This paper is organized as follows: In Section 2 we deal with the characteristics of each technique and how they work. In Section 3 we present cuts made with the disk and water jet. In Section 3 we include testing, geometrical and interometric, for evaluating the quality of the edges, surface, and stress inside the glass slab. In Section 4 we present conclusions.

2. Characteristics of Glass-Cutting Technique

A. Disk with Diamond Powder

This technique is the standard in any optical shop. It is essentially the same procedure dating from centuries ago, limitations included. A metal or SiC disk, covered with diamond powder, is mounted on a spindle driven by a motor. The piece to be cut is fixed on a table. Some devices are capable of moving the cutting disk; others move the piece of glass on a table to bring it to the saw. The disk and glass are in a liquid

J. Salinas-Luna (e-mail, jsl@ccmc.unam.mx) and R. Machorro are with Centro de Ciencias de la Materia Condensada de la Universidad Nacional Autonoma de México (UNAM), Km 107 carr. Tijuana-Ensenada, Ensenada, B. C., México, Apdo. Postal 2681, 22800. J. Camacho is with Centro de Invesigación Científica y de Educación Superior de Ensenada (CICESE), Km 107 carr Tijuana-Ensenada, Ensenada, B. C., México, Apdo Postal 2732, 22860. E. Luna and J. Nunez are with Instituto de Astronomía, Observatorio Astronómico Nacional, Universidad Nacional Autonoma de Mexico, Km 107 carr. Tijuana-Ensenada, Ensenada, B. C., México, Apdo. Postal 877, 22830.

Received 18 August 2005; revised 12 December 2005; accepted 13 December 2005; posted 14 December 2005 (Doc. ID 64260).
0003-6935/06/153477-05$15.00/0

Fig. 1. Evident edge effects in the Ronchi fringes for a hexagonal spheric surface.

bath (water, oil, or alcohol) to reduce temperature effects.[4] Depending on the disk diameter, the disk may cut the glass slab thickness. In our experiment we used a homemade machine with a disk 22 in. (55.88 cm) in diameter, capable in principle of use on a 10 in. (25.4 cm) thick slab. As mentioned above, this system makes straight cuts only at reduced speed. The feeding speed depends on the size of the glass slab, the thickness and hardness of the material, and the abrasive used. In our experience, for a 2 in. (5.08 cm) thick Pyrex, the appropriate speed is 0.4 in. (1.016 cm)/min.

The piece being cut must be secure and firmly fixed; otherwise unexpected fractures are introduced. Even then, small vibrations of the disk spindle create a slightly wider cut than that due to the disk thickness alone, usually 2–3 mm. When a diamond disk is used, it is necessary to perform all the cuttings first and then grind and polish the surfaces to avoid any remaining scratches from glass or diamond powder. The edges are rough after the cut, requiring a finished or bevel edge.

B. Water Jet

The water-jet cutter has been used in industry to cut wood, plastic, and metal blocks of any given shape. Our experience is with a 40k Bengal 48 × 48 machine,[5] used to cut guitar frames and fixtures for musical instruments with high precision and speed. Except for wood cutting it usually works with the cutting piece immersed in a liquid, typically water, to keep it cool and recirculate the abrasive powder. In this form the procedure can be considered a cold technique. Another advantage is that the cutting nozzle is mounted on an x–y computer-controlled table, which allows one to cut any prescribed shape. The computer program controlling the machine accepts *.dxf formats, widely used in the computer-aided design. The cutting speed is high; when a 1/16 in. nozzle is used, cutting a 2 in. (5.08 cm) thick Pyrex slab, it rates 5 in./min. This is ~12 times the disk-cutting speed. The computer-controlled table is precise; it has an uncertainty of 0.0005 of an inch (0.0127 mm). The exactness of the cut depends on the accuracy of the zero position.

Among its disadvantages are its high initial cost and its price range from $20,000 to $500,000, depending on bed size and special features. If used in extreme conditions, continuous maintenance of the nozzle may be required. But for standard application the machine consumes ~2 tons of abrasive without noticeable erosion. The high noise level is a disadvantage. With a proper catcher the abrasive water jet is as loud as 90 dB according to the manufacturer.

A mixture of fluid, abrasive powder, and air is forced through a small hard metal nozzle with a small exit diameter, 1/16 in. (0.15875 cm) to 1/8 in. (0.3175 cm), depending on the requirements. The pressure is ~50,000 psi, which gives a high-velocity throughput. For our purposes it is convenient to introduce the glass slab completely into water to keep it at room temperature. The abrasion is done by the liquid coming from the nozzle, at the same time the heat transfer is restricted to a small area, similar to the wire cutter, reducing friction and maintaining a low temperature. The 40k Bengal 48 × 48 machine has a 1.2 m × 1.2 m table, and the nozzle covers this area. Thus the size of the slab is restricted by the dimensions of the table. Smaller and larger machines are on the market.[6] With this kind of machine it is possible to make practically any cut, including artistic ones, on most materials.

3. Characterization of Glass Cuts

A. Preliminary Cuttings

1. Stress, Polarization

To compare the characteristics of the cutting on glass made with different techniques, we made them on the same piece of glass, a Pyrex 5 cm thick slab. Two cuts were made, one with a disk and the other with a water jet. We checked stress in the glass before the cuts were made, using a polarimeter, noticing that the volume is uniform, with no apparent birefringence. During the disk cut, which takes several minutes, there is friction between the disk and the glass during this time, and the heat associated with it creates stresses as shown in Fig. 2. The same piece of glass is also cut with the water jet; in this case there is stress at the point in front of the nozzle where the high-pressure water starts the attack. Once the jet penetrates the piece, the stress vanishes until the cut stops. This suggests that, making cuts continuously, we have only two hot spots, one at the entrance and one at the exit of the jet, which is an improvement over the disk method, where stress is always present while the cutting is done. When a disk is used, the internal stress is higher than when a water jet is used and is present all along the cut.

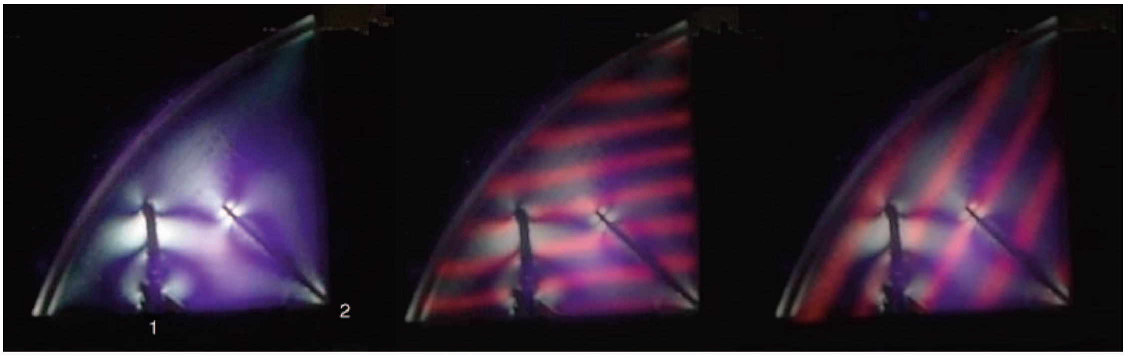

Fig. 2. Superimposed images of perpendicular Ronchigrams in each case and polarization fringes: left, (color online) glass slab observed between two linear polarizers: 1, disk cut; 2, water-jet cut; center, (color online) vertical disk cut analyzed only with a Ronchi test; right, (color online) 45 deg water-jet cut analyzed only.

2. Ronchi Testing

The first test of the piece of glass with a cutting as described in Subsection 3.A.1 is by Ronchi testing. One aligns the Ronchi fringes perpendicular to each cut to appreciate any frequency changes in the fringe pattern due to the piston effect[7] or fringe shift due to tilt between segments.[8] Figure 2, right, corresponds to the fringes perpendicular to the water-jet cut (45 deg) and Fig. 2, left, to the diamond disk cut (vertical). As can be seen, the fringes are slightly wider near the cut, but they coincide from one side to the other. This implies that Ronchi is not sensitive enough to detect differences due to the cut. A Ronchi ruling with 150 lines/mm was used.

Note that when Ronchi fringes are superimposed on stress fringes (Fig. 2), they have similarities. Ronchi fringes are produced by a mirror surface, and they are strongly influenced by the volume stress. This is clear for the disk cut where the stress is higher than for the water-jet cut.

3. Fizeau

The Ronchi test gives qualitative information on the surface. To quantitatively describe the surface deformation during cutting, we perform some interferometric testing. The first is by the Fizeau interferometer.[9] This technique does not require close contact between a reference surface and the surface being tested. We repeat the cutting on a flat piece of glass. The fringe pattern is shown in Fig. 3. A very small deflection of the fringes can be seen at the edges of the glass when the water jet is used. The main objective in this case is to analyze whether the cut with the water jet shows the same behavior on a flat surface and a spherical surface, considering that the water-jet technique works well on a flat surface.

4. Shack

The Shack interferometer[10] uses a noncontact testing method that requires high spatial coherence, and it is used to test surfaces with large curvature radii. In our case such an interferometer produces concentric quasi-circular fringes, because the surfaces being compared are parabolic (test) and spheric (reference). Measuring the water-jet cutting by introducing as many fringes as possible in the area being studied (Fig. 4) is recommended. Linear fringes are necessary to introduce tip/tilt on the test surface, in our case, the water-jet section. If the fringes are linear, the interpretation becomes easier. A line is drawn from one fringe minimum at one side of the cut and extrapolated to the other side of the cut. In general the cuts do not necessarily coincide with a minimum at the other side because of a possible tilt between both sides. The optical path difference between the consecutive fringes is $\lambda/2$ (when a He–Ne laser is used, $\lambda = 632.8$ nm). When the average is taken on 20 fringes along the cut, the average deviation is of the order of $\Delta\lambda = 36.88$ nm, approximately $\lambda/20$, with a rms of 5.99 nm (Fig. 4).

In Fig. 4 the fringes are slightly defocused on the left side of the water-jet cutting, which is due to the surface curvature, because the interferometer is focused over a small area of approximately half an inch

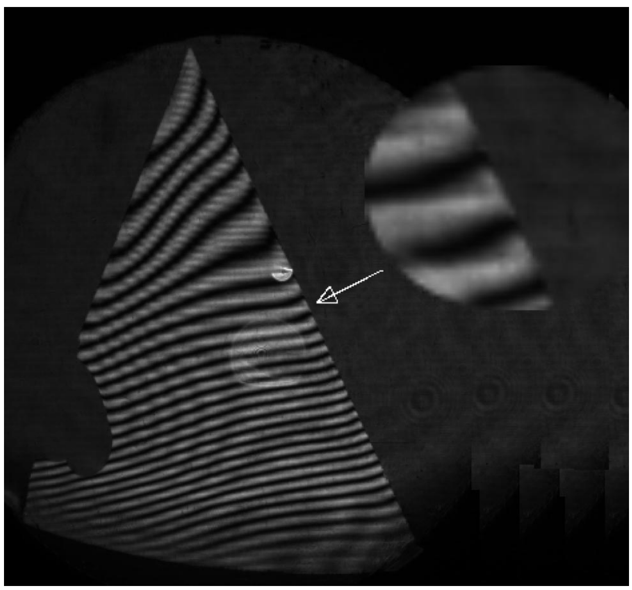

Fig. 3. Fizeau interferogram fringes from a flat glass slab with a water jet.

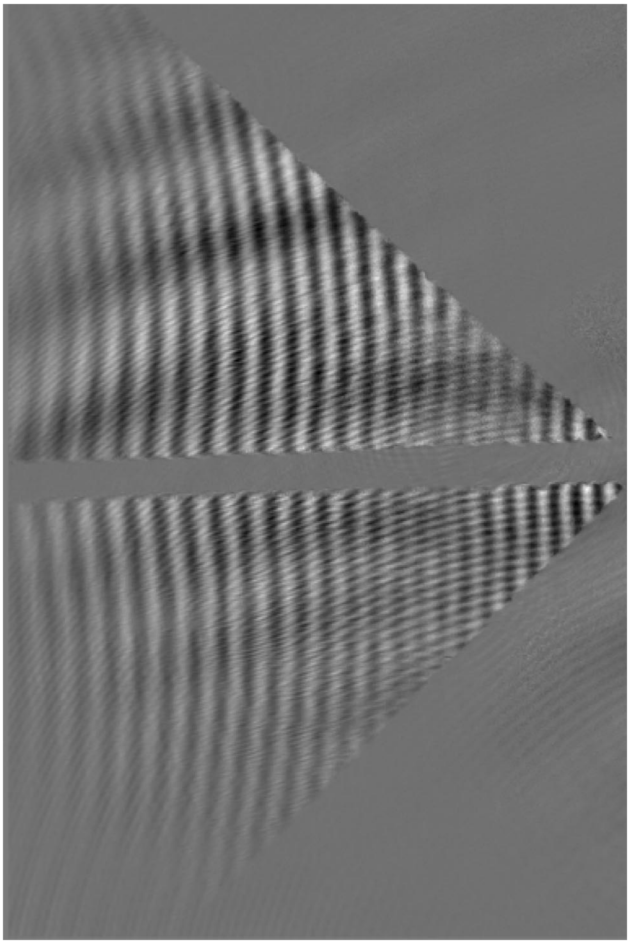

Fig. 4. Shack interferogram fringes from a parabolic mirror segment. The region being studied has a water-jet cut.

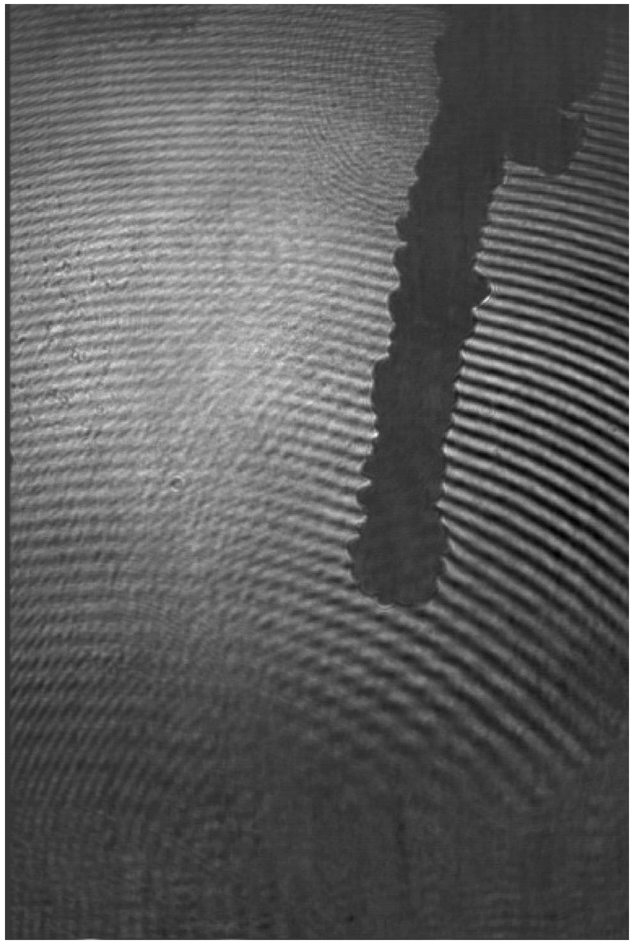

Fig. 5. Shack interferogram fringes from a parabolic mirror segment. The region being studied has a disk cut.

(1.27 cm). We can also see in the amplification of the cutting a slight roughness on the edges.

In Fig. 5 we can see multiple fractures on the edges when a cut with a diamond disk is developed; edges can be corrected with a bevel edge, which increments the time the manufacture taken.

In Figs. 1 and 7 it is evident that the water jet produces the best results when cutting an optical surface.

B. Cutting the Parabola Off Axis

The main objective of our experiment is to obtain four off-axis parabolas from a polished one-piece parabola. This is to reduce the size and weight of the wide-field spectrometer being built. We started with the Ebert–Fastie version, to be transformed into a Czerny–Turner-type spectrograph.

We tested the original surface, before cutting, with a Ronchi test to have a reference before any cut was made. We compared the fringes with those from a numerical simulation. We used ray tracing for the maximum of the ideal central Ronchi fringes (Fig. 6). We assume that the illumination source is close to the optical axis; thus the influence on the fringe deformation is negligible.

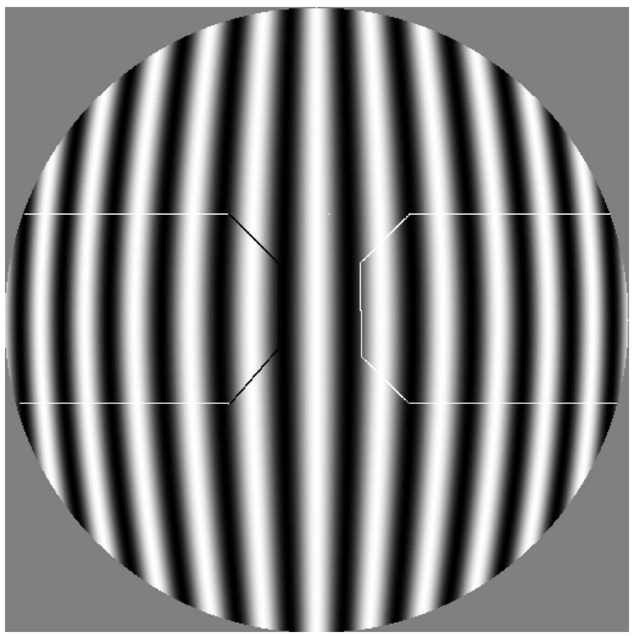

Fig. 6. Simulated Ronchi fringes used to estimate the fringe shape of the real surface before the cuts.

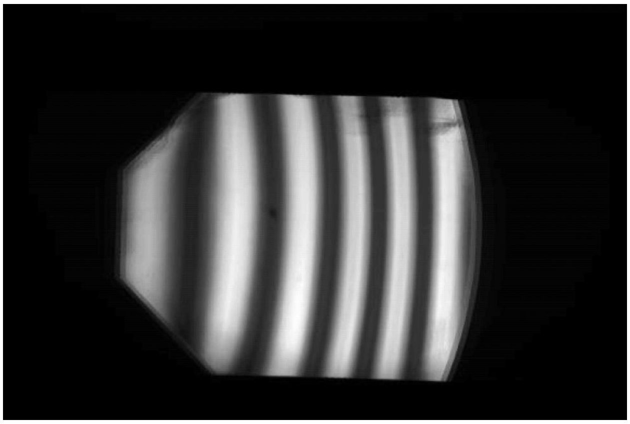

Fig. 7. Off-axis parabolic mirror obtained from a 12 in. (30.48 cm) parabolic mirror with a water-jet cutter.

The segments required for our spectrometer have a trapezoidal shape (Fig. 7). The surface is protected with a special spray paint to avoid scratches. We noticed later that these precautions were unnecessary since the water jet left no damage at all on the surface. A proper fixture is necessary to keep the piece being cut in place, because the high pressure of the jet might displace the glass.

4. Conclusions

The water-jet cutter for optical glass has several advantages over the traditional method of rotating a disk. It is a cold procedure and does not introduce appreciable stress on the glass volume. The cutting is 12 times faster than the disk technique. In a computer-automated water-jet table, almost any cut shape is possible. The cuts are sharp and without distortion, reducing manufacturing time.

The authors thank the Fender Company and its engineers, Jesús Benitez and Moisés Lucero, for support. Also important was the participation of Eng. Jorge Valdez, Universidad Nacional Autonoma de Mexico, Distrito Federal, Mexico (IA-UNAM), Alejandro Tiznado and Enrique Medina, Centro de Ciencias de la Materia Condensada (CCMC) UNAM, and Javier Dávalos, Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE). This work was partially supported by Consejo Nacional de Ciencia y Tecnologiá (CONACYT), project 400380-5-G36531E.

References

1. F. Z. Fang, X. D. Liu, and L. C. Lee, "Micromachining of optical glasses—a review of diamond-cutting glasses," Sādhanā **28,** Part 5, 945–955 (2003).
2. A. Cordero-Dávila, J. González-García, M. H. Pedrayes-López, L. A. Aguliar-Chiu, J. Cuatle-Cortés, and C. Robledo-Sánchez, "Edge effects with the Preston equation for a circular tool and workpiece," Appl. Opt. **43,** 1250–1254 (2004).
3. N. A. Lynn, R. E. Keim, and T. S. Lewis, "Surface error correction of a Keck 10 m telescope primary mirror segmented by ion figuring," in *Glasses for Optoelectronics II,* G. C. Righini, ed., Proc. SPIE **1531,** 195–204 (1991).
4. M. G. Shinker and W. Doll, "Turning of optical glasses at room temperature," in *Process Optical Metrology for Precision Maching*, P. Langenbeck, ed., Proc. SPIE **802,** 70–80 (1987).
5. http://www.fender.com/ensenada/.
6. http://www.trimade.com/waterjet.html, http://www.waterjet-cutting.com/.
7. J. Salinas-Luna, E. Luna, L. Salas, I. Cruz-González, and A. Cornejo-Rodríguez, "Ronchi test can detect piston by means of the defocusing term," Opt. Express **12,** 3719–3736 (2004); http://www.opticsinfobase.org/abstract.cfm?URI=oe-12-16-3719.
8. A. Nava-Vega, L. Salas, E. Luna, and A. Cornejo-Rodríguez, "Correlation algorithm to recover the phase of a test surface using phase-shifting interferometry," Opt. Express **12,** 5296–5306 (2004); http://www.opticsinfobase.org/abstract.cfm?URI=oe-12-22-5296.
9. M. Nuñez, E. Luna, L. Salas, E. López, F. Quiros, and J. Salinas, "Interferómetro de Fizeau para prueba de superficies ópticas," Tech. Rep. RT-2004-18 (Instituto de Astronomía, Universidad Autónoma de México, Apdo Postal 70-264, C. P. 45020, México City, México, 2004).
10. M. V. Mantravadi, "Shack interferometer," *Optical Shop Testing,* D. Malacara, ed. (Wiley, 1992), pp. 34–35.