a reprint from Applied Optics

Optical glass polishing by controlled laser surface-heat treatment

F. Laguarta, N. Lupon, and J. Armengol

It is shown that optical surfaces traditionally ground in conventional glasses with high coefficients of thermal expansion may be polished by irradiation with a space- and time-controlled uniform CO_2 laser beam. Comparisons of a theoretical simulation model of the laser-driven heating process with the experimental results allow us to determine the conditions for successful and reliable use of this technique. The technique can be applied indiscriminately to preheated samples made of different glasses, with any topography, and, of any size in a limited range that depends only on the available laser power.

Key words: Laser-materials processing, CO_2 laser application, optical glass polishing, laser beam shaping, laser-driven surface flow.

1. Introduction

Directed energy beams have been used in recent years to enhance the resistance of crystal and glass surfaces to laser damage. For instance, annealing with a ruby laser gives higher laser-induced damage threshold values in germanium or silicon, and treatment of fused silicon and $LiNbO_3$ with CO_2 laser beams has been shown to reduce surface features and scatter.[1–3] Low-intensity CO_2 laser beams have also been applied to laser-fire polishing of optical glasses.[4] This process is successful for materials with small coefficients of thermal expansion ($10^{-6}/°C$) such as Pyrex or fused quartz. However, most conventional glasses used in the optical industry, such as K and BK crowns, exhibit higher expansion coefficients ($10^{-5}/°C$) and always seem to crack dramatically during laser-fire polishing because of thermal-stress limitations.[4]

In this paper we propose and demonstrate a new CO_2 laser application for obtaining polished optical surfaces in conventional glasses that are used by the optical industry. The method lies in a laser surface-heat treatment and it is based on the traditional fire-polishing techniques.[5] A space- and time-controlled CO_2 laser beam is applied statically to the surface of the glass sample to be polished. The extremely strong absorption of the 10.6-μm radiation by conventional glasses promotes the softening of a very thin layer of material that flows under the action of the surface tension. As a result, the surface roughness decreases without any outstanding change in the surface figure. To avoid the generation of irresistible thermal stresses, we recommend heating the samples to bulk temperatures above their transformation points before starting the laser-driven surface-heating process.

This method, for which international patents are pending, can be applied indiscriminately to surfaces of any topography and any size. It is the available laser power that limits the glass surface area that can be polished. Starting from preheated samples with maximum roughnesses in the 1–10-μm range (as provided by traditional grinding), we obtain polished optical surfaces without macroscopic low-frequency deformations and with rms roughnesses of approximately 1 nm. Thus, controlled laser surface-heat treatment proves to be a real and valuable alternative to the traditional polishing of optical glasses. It can improve the production efficiency of standard components because it requires no mechanical abrasives or surface-adapted polishing tools. The proposed technique may also be considered novel in the sense that it can be used to polish shapes that currently are very difficult or even impossible to obtain.

2. Theory

The laser-heating process of a conventional glass sample has been simulated on a computer by the numerical solution of the one-dimensional heat-

---

The authors are with the Department d'Òptica i Optomeria Universitat Politècnica de Catalunya, Calle Violinista Vellsolà 37, 08222 Terrassa, Spain.

Received 21 December 1992; revised manuscript received 4 October 1993.
0003-6935/94/276508-06$06.00/0.

conduction transfer equation:

$$\frac{\delta}{\delta x}\left[k(T)\,\frac{\delta T(x,t)}{\delta x}\right] + g(x,t) = \rho c\,\frac{\delta T(x,t)}{\delta t}, \qquad (1)$$

where $T(x, t)$ accounts for the depth-dependent temperature distribution in a semi-finite medium. This is a standard assumption[6] that is valid provided that the width of the irradiated zone is much larger than the softened depth. The heat input to the material delivered by the laser beam is given by

$$g(x,t) = (1 - R)I_0(t)a\exp(-ax), \qquad (2)$$

where $I_0(t)$ is the uniform CO_2 laser intensity on the entire glass surface that is being treated. We have measured the 10.6-μm absorptivity a and the reflection coefficient R of conventional glasses. The ranges of the obtained results are $a \sim 10^5\ m^{-1}$ and $R \sim$ (5–20%), where R depends on the surface roughness of the sample. Representative values of the glass density $\rho = 2.5 \times 10^3\ \mathrm{kg\ m^{-3}}$ and the specific heat $c = 1\ \mathrm{kJ\ kg^{-1}\ K^{-1}}$ have been adopted, and we assume that they remain constant in the whole range of temperatures achieved throughout the process. We have also considered a temperature-dependent value of the thermal conductivity $k(T) = 1.047 + 0.001489\ T\ \mathrm{W\ m^{-1}\ K^{-1}}$ below 900 °C and a constant value of $k = 2.387\ \mathrm{W\ m^{-1}\ K^{-1}}$ for higher temperatures.[7] Convection and radiation heat-transfer mechanisms are neglected in the simulation. Thus, cooling is carried out only by conduction.

In Figs. 1 and 2 we have represented the calculated thermal evolutions of several glass layers at different depths of two samples that were preheated to homogeneous initial temperatures of 350 °C and 550 °C and irradiated by uniform CO_2 laser beams of constant intensities $I_0 = 235\ \mathrm{W/cm^2}$ and $I_0 = 50\ \mathrm{W/cm^2}$, respectively. The results of a nonconstant irradiation intensity are plotted in Fig. 3. These results are discussed in Section 5.

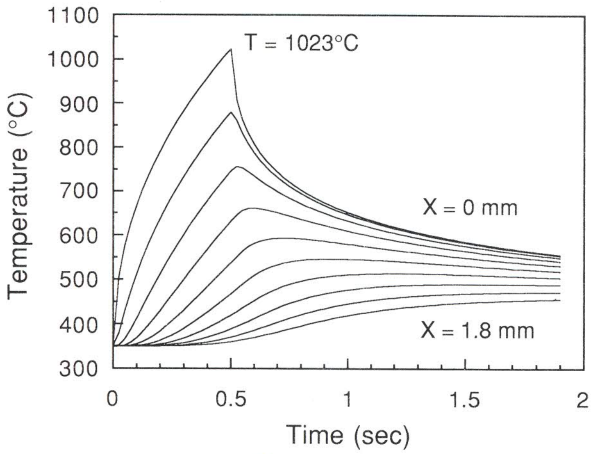


Fig. 1. Temperature as a function of time at different glass layers at depth increases of 200 μm, corresponding to a 0.5-s CO_2 laser irradiation with uniform and constant intensity at the surface ($x = 0$ mm) of $I_0 = 235\ \mathrm{W/cm^2}$.

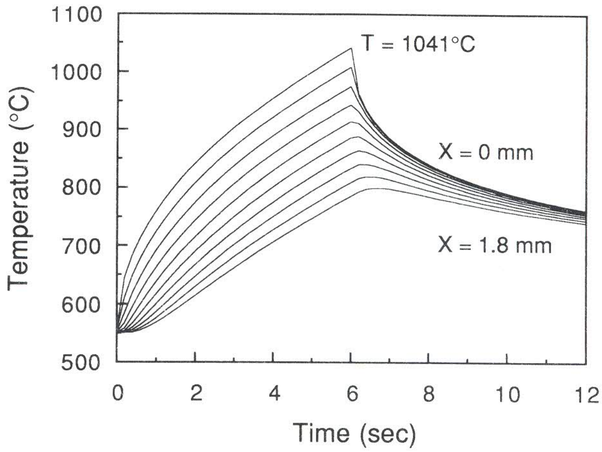


Fig. 2. Same as in Fig. 1 but corresponding to a 6-s constant irradiation intensity of $I_0 = 50\ \mathrm{W/cm^2}$.

3. Experiment

The experimental setup used to perform the laser surface-heat treatment is illustrated in Fig. 4. We used a Crilaser A-100/0 CO_2 laser, which can deliver a maximum power of 100 W. The laser beam had a transverse energy distribution corresponding roughly to the TEM_{00} mode and was expanded and reshaped by means of a vibrating reflective integrator to obtain a spot of uniform intensity with an area of 80 mm² in the sample.

The selected samples were opthalmic lenses made of conventional crown glasses, such as B-270 or BK-7, with traditionally ground surfaces. The samples to be treated were carefully cleaned and dried to remove any remaining abrasive or embedded glass fragments. Before the laser heat treatment, the samples could be heated homogeneously in a conventional clean oven, up to selected temperatures lower than 700 °C.

To control and supervise the laser irradiation process, we developed the following systems[8]:

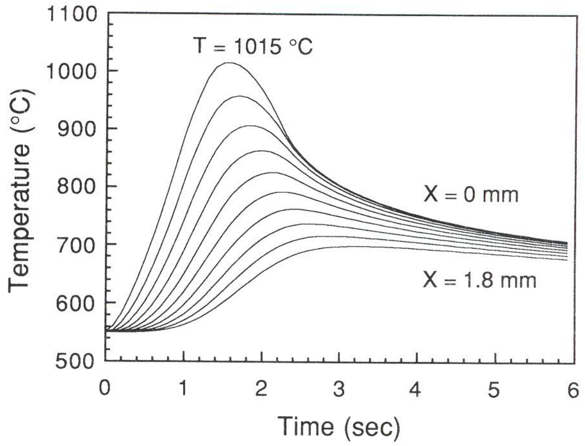


Fig. 3. Same as in Figs. 1 and 2 but corresponding to a heating cycle of 1-s linear rising ramp from $I_0 = 0\ \mathrm{W/cm^2}$ to $I_0 = 125\ \mathrm{W/cm^2}$, followed by a 0.3-s constant irradiation of intensity $I_0 = 125\ \mathrm{W/cm^2}$ and a final 1-s linear descending ramp from $I_0 = 125\ \mathrm{W/cm^2}$ to $I_0 = 0\ \mathrm{W/cm^2}$.

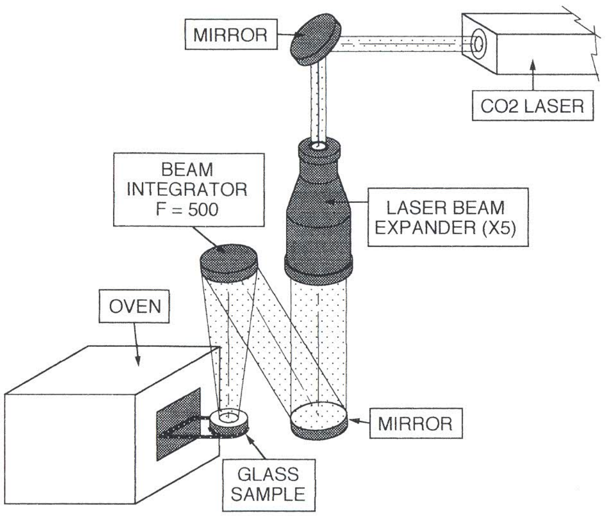


Fig. 4. Schematic drawing of the laser-irradiation experiment.

- A CO_2 laser whose power can be controlled externally with a computer program to obtain the desired heating and cooling cycles: A proportional fraction of the power delivered by the laser was measured with both a Coherent model 201 thermopile and a Laser Precision Rk-5700 calibrated pyroelectric fast-detection system with RkP-575 probes.
- A highly sensitive, self-made pyrometric detection system based on a PbSe sensor, IRGN-6 optics and a lock-in technique: This system allows us to determine the real-time temperature depth distribution on the sample by comparison with the simulation model.
- An optical monitoring system based on the diffuse reflection of a linearly polarized He–Ne laser: This system gives us continual information on the roughness of the glass surface.

A sketch of the second and third detection systems is shown in Fig. 5. Further details on their technical and operating performances are given in Ref. 9.

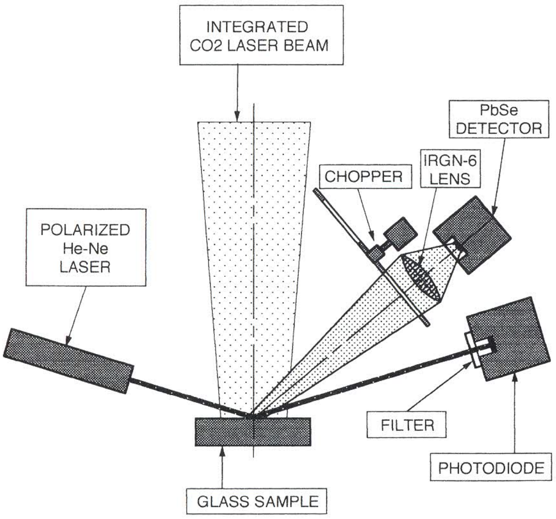


Fig. 5. Schematic drawing of the detection systems used in the experiment.

Laser irradiation of many samples at different laser intensities and heating times has been performed and shows that the numerical simulation model properly describes the thermal evolution of the process. When heating cycles such as those shown in Figs. 1, 2, and 3 are programmed, the dynamics of the generated temperature distributions allow the surface layer to flow and the result is a progressively polished appearance of the treated sample. The measured flowing times between ground and polished surface conditions were of the order of several tenths of a second.

The heating and surface-flow process ended with a cooling stage. In the first place, the temperature distributions induced by laser irradiation were homogenized. This process, even though not essential, may be driven and slowed down by the laser itself, if a final cooling cycle with gradually decreasing laser intensities are carried out. Finally the samples were cooled to room temperature in a temperature-controlled oven, as occurs in the well-known annealing process. Cooling rates of approximately 5 °C min^{-1} were shown to be sufficient to avoid excessive thermally induced tensile stress, which could cause cracking and fracturing of the material during this stage.[4]

4. Results

Figure 6 shows the nondiffusing appearance of an 80-mm^2 laser-polished area on the surface of a ground opthalmic lens made of conventional B-270 glass. Inspection of both treated and untreated areas of this lens was carried out through optical microscopy. Figure 7 shows a micrograph of the transition region between irradiated and nonirradiated areas. The highly rough section corresponds to an unaltered ground surface, and it shows a large contrast with the laser-treated section, in which the smooth texture is evidence of the laser-driven surface flow. Even in the frontier area, where the temperatures reached are lower than those of the irradiated area because of transverse heat flow, a few hollows can be seen. Their rounded shapes confirm the action of the surface tension on the softened glass layer.

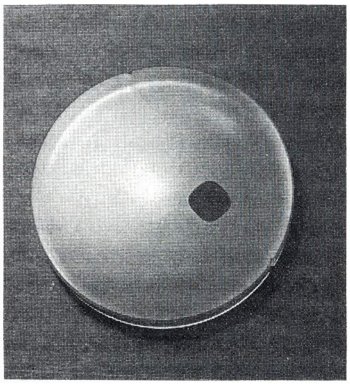


Fig. 6. Ground surface of a conventional B-270 optical glass after successful laser fire polishing of an 80-mm^2 area.

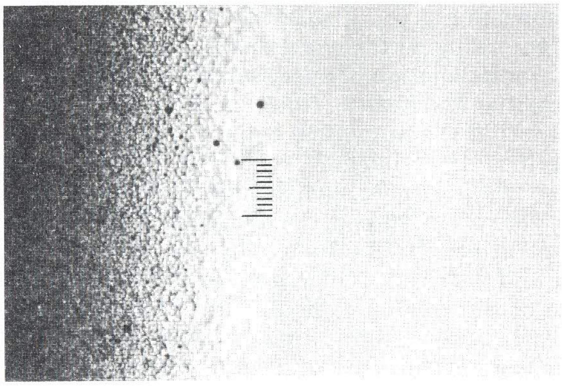
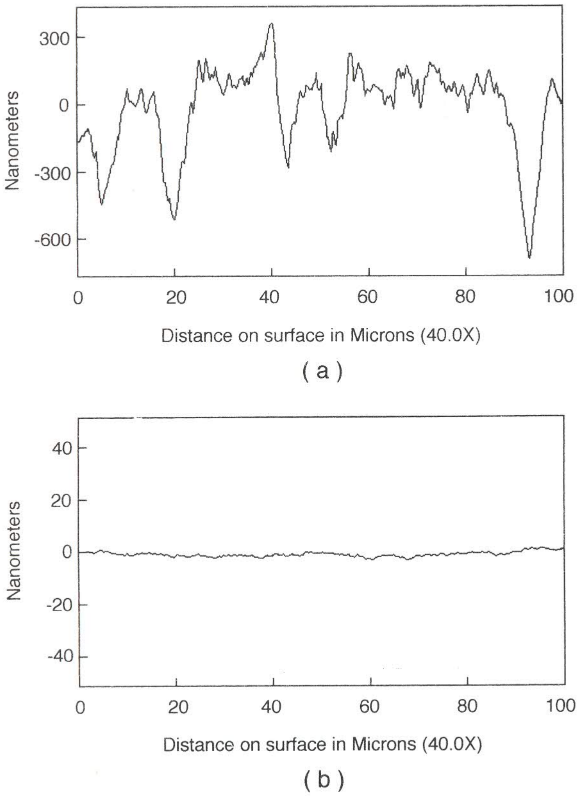


Fig. 7. Micrograph of the B-270 glass surface represented in Fig. 6 showing the transition region between irradiated and nonirradiated areas. Full scale is equivalent to 200 μm.

Measurements of surface roughness were accomplished by means of an interferometric optical profiler[10] with a 40× objective with a Mirau interferometer. This magnification head allows the measurement of profile lengths of 0.33 mm with spatial sampling intervals of 0.33 μm and an optical resolution of 0.65 μm.

Figure 8 shows the measured profiles of both ground and laser-polished surfaces. The obtained rms roughness of the ground sample, as it appears in Fig. 8(a), is 259 nm, with an average roughness of 219 nm and a maximum peak-to-valley difference of 1081 nm. These figures are in complete agreement with the values of roughness parameters obtained in traditionally ground surfaces by means of mechanical stylus profilometers. The obtained rms roughness of the laser-polished sample, as it appears in Fig. 8(b), is 0.89 nm, with an average roughness of 0.73 nm and a maximum peak-to-valley difference of 4.49 nm. Clearly these figures are competitive with those obtained through conventional mechanical polishing of optical glass surfaces, and they should provide an idea of the potential of the proposed laser fire-polishing technique. More experiments designed to improve the quality of the polished surface, mainly through the optimization of laser heating cycles, are planned.



(a)

(b)

Fig. 8. Measured profiles of (a) ground and (b) laser-polished surfaces of the B-270 glass sample represented in Figs. 6 and 7.

5. Discussion

As is well known, glass is an amorphous material and accordingly it does not exhibit a well-defined fusion-phase transition. By gradually increasing the temperature of a glass sample, a progressive decrease in its viscosity coefficient is observed, and we refer to this process as glass softening. What is done when a laser beam is applied to the surface of a glass sample is the induction of a time-varying depth-decreasing temperature distribution in the material. Therefore, we have given the glass the ability to flow under the action of the surface tension. The closer to the surface the material is, the greater is its ability to flow.

Traditional grinding of optical glass causes scratches with depths that range between 1 and 10 μm. Moreover, it has been proved that the high pressure of the abrasive against the glass surface being ground generates microfractures that can reach points situated 25 μm under the surface. Therefore, the efficiency of the proposed laser-polishing technique will be guaranteed only if the temperatures reached in the 25-μm surface layer are high enough and endure long enough to permit the discontinuities of this layer to be homogenized and the surface to be smoothed by the viscous glass flow.

There are two opposite approaches to performing the laser-heating cycle. One of them lies in the application of a medium- to high-intensity laser beam (above 200 W/cm^2) to the sample. This process is represented in Fig. 1; we started with a sample that was preheated to a homogeneous initial temperature of 350 °C. In this case, the heating time needed for the sample to reach temperatures of approximately 1000 °C at the surface layer is approximately 0.5 s. The extreme thermal gradients that are generated are larger than 700 °C/mm, and the temperature rising rates are approximately 700 °C/s. As can also be seen in Fig. 1, just after the interruption of laser irradiation, the cooling of the surface layer is as fast as 3600 °C/s. In this situation the 25-μm surface layer remains at temperatures corresponding to a viscosity coefficient lower than 10^3 Pa s, during times of the order of 0.1 s. This means that the permitted flow is just within the limit of its ability to smooth the glass surface to optical polished quality. This approach also proves to be very sensitive to both the thermal parameters of the glass sample and the variations in the effective laser intensity at different points of the surface. Such variations can arise, for instance, from the effect of the curvature of the surface being treated and from the nonuniformities of the transverse energy distribution of the applied laser beam. Moreover, the high values of the generated thermal gradients are responsible for the appearance of induced stresses, which depend on the coefficients of thermal expansion and may exceed the practical strength of the glass.[4] As a result, the growth of cracks is initiated and causes the material to fracture. The effects of such thermally induced stresses are expected to be extremely pernicious in positions where the glass has a temperature T_R corresponding to the transformation point, because the coefficient of thermal expansion undergoes a sudden rise in the interval around such a point.[7] As a result, the stresses induced by thermal gradients are amplified in glass layers at temperatures contained in this interval, which in most conventional glasses is centered around T_R values of 500 °C.

In the experiment simulated in Fig. 1, any point located in the glass layer 1 mm under the surface passes through the transformation point in the heating cycle. It can also be observed that the closer to the surface the T_R point is situated, the higher is the thermal gradient generated around it. The predicted stress also is higher. However, these points cross the transformation interval quickly (at approximately 700 °C/s) and immediately reach temperatures well above T_R, which causes a partial relaxation of the previously induced stresses. The most critical position is that situated roughly 1 mm under the surface, because it just reaches the T_R temperature with a still-high value of thermal gradient, approximately 300 °C/mm, and it holds that temperature for a long time, approximately 0.5 s, which favors the growth of cracks in the sample. This situation explains why in fire-polishing experiments that are driven by medium- to high-intensity laser beams, most conventional glasses fracture in the first stages of the cooling cycle, after laser irradiation.

The opposite approach to performing the laser-heating cycle lies in the application of a low-intensity laser beam, below 50 W/cm^2, to the sample. This experiment is represented in Fig. 2; we started with a sample that was preheated to a homogeneous initial temperature of 550 °C. In this case, the heating time required to reach temperatures of approximately 1000 °C at the surface layer are much longer, approximately 6 s, than those described for the high-intensity experiments. The extreme thermal gradients that are generated, the temperature rising rate, and the surface-layer cooling are much lower, approximately 150 °C/mm, 40 °C/s, and 400 °C/s, respectively. Under these conditions the 25-μm surface layer remains at temperatures corresponding to a viscosity coefficient lower than 10^3 Pa s for approximately 4 s. This proved to be longer than was needed for the surface-polishing glass flow. Therefore, small variations in thermal parameters of the glass and nonuniformities of the effective laser-intensity transverse distribution are shown to be less critical than before. Induced thermal stresses are also much lower than those resulting from the higher-intensity approach, the main reason being the uniform preheating of the sample at a temperature well over the transformation point. However, laser-polished surfaces treated according to this apparently better low-intensity approach usually exhibit low-frequency macroscopic deformations that become more visible in the thinner glass samples. In fact, even if we start with a sample at a higher temperature, the total amount of energy absorbed by the sample in the second approach is more than 2.5 times that corresponding to the medium- to high-intensity irradiation. As a result, the bulk of the glass is softened and deep glass layers undergo slow gravity-driven flows, which cause small areas of the surface to sink, as we have observed.

Between these two extreme approaches there is a wide operative interval of laser-driven heating cycles that yield controlled thermal gradients low enough to avoid excessive thermal stress, and at the same time high enough to achieve surface temperatures well above the deformation point of the glass. In this region the viscosity coefficient is lower than 10^3 Pa s, and the surface tension is higher than 0.2 N m^{-1}, which provides the measured fast-flow polishing dynamics with no visible macroscopic surface deformations. These controlled gradients represent the main difference between the polishing method proposed in this paper and the traditional fire-polishing techniques, in which the maximum temperatures reached by the samples must be kept strictly under the deformation point everywhere to avoid widespread softening of the glass.

5. Conclusions

A new CO_2 laser application to obtain polished optical surfaces in conventional glasses used by the optical industry has been proposed and demonstrated. The reported experiment may be scaled up easily to obtain laser-polished surfaces in standard components for optics and opthalmic glass with commercially available 2–5 kW CO_2 lasers. Moreover, the suggested technique may be especially suitable for obtaining nonspherical as well as nonrevolution optical polished surfaces. This technique may also provide the possibility of real automation of the polishing process, which could bring the possibility of operating in a computer-integrated manufacturing environment to the optical factory.

The authors acknowledge valuable conversations with W. M. Steen, S. Mayoral, R. Soliva, and A. Savall, as well as the contribution to this work of INDO, S.A.

References

1. P. A. Temple and M. J. Soileau, "1.06-μm laser-induced breakdown of CO_2-laser polished fused SiO_2," Natl. Bur. Stand. (U.S.) Spec. Publ. **620,** 180–189 (1980).

2. P. A. Temple, W. H. Lowdermilk, and D. Milam, "Carbon dioxide laser polishing of fused silica surfaces for increaed laser-damage resistance at 1064 nm," Appl. Opt. **21,** 3249–3255 (1982).
3. R. M. Wood, *Laser Damage in Optical Materials* (Hilger, Bristol, UK, 1986), Chap. 3, pp. 79, 80.
4. Y. M. Xiao and M. Bass, "Thermal-stress limitations to laser fire polishing of glasses," Appl. Opt. **22,** 2933–2936 (1983).
5. E. Plumat, "Technologie du poli au feu," in *Table Ronde sur le Polissage du Verre,* Union Scientifique Continentale du Verre (Union Scientifique Continentale du Verre, Charleroi, Bruxelles, 1960), pp. 221–230; M. I. Peyches, "Conclusions table ronde," ibid., pp. 253–258.
6. E. M. Breinan and B. H. Kear, "Rapid solidification laser processing at high power density," in *Laser Materials Processing,* M. Bass, ed., Vol. 3 of Materials Processing—Theory and Practices (North-Holland, Amsterdam, 1983), pp. 235–295.
7. D. A. McGraw, "The transfer of heat in glass during forming," J. Am. Ceram. Soc. **44,** 353–363 (1961); J. M. Fernández Navarro, *El Vidrio* (Consejo Superior de Investigaciones Científicas, Madrid, 1985), Chap. 13, p. 405.
8. J. Arasa, J. Caum, J. Armengol, N. Lupon, F. Pi, and F. Laguarta, "Optical glass polishing by laser surface heat treatment," in *Abstracts of the First Conference on Lasers and Electro-Optics* (Madrid Trade Fair Organization, Madrid, 1990), p. 94.
9. N. Lupon, "Contributions to the study of optical glass polishing by CO_2 laser surface heat treatment," degree dissertation (Departament d'Òptica i Optometria, Universitat Politècnica de Catalunya, 08222 Terrassa, Spain, 1993).
10. K. Creath, "Phase-measurement interferometry techniques," Prog. Opt. **26,** 349–393 (1988).