Modelling of CO2 Laser Polishing of Glass

The principle underlying laser polishing is relatively straightforward: the laser radiation absorbed by a substrate is used to heat a thin surface film up to the fusion temperature (e.g., in the case of metals) or the vitrous transition temperature (e.g., in the case of silicium glass). At this temperature the viscosity of the film is reduced enough to produce a lateral flow caused by the surface tension of the melted material. In this fashion the surface roughness is much attenuated, leaving a polished surface after cooling.

Research work on the development and implementation of CO2 laser polishing of glass has been published in scientific journals since the 1980s. At that time the scientists were investigating the increase in the damage threshold of the power lasers optical components (e.g., lenses, windows, etc.). Indeed, compared to the usual (mechanical) polishing techniques, CO2 laser polishing has the potential of producing fewer surface scratches or subsurface micro-chinks, which cause damage and reduce the resistance to the optical flow. On the other hand, one of the difficulties of this technique (already known at the time) lies in the unavoidable presence of thermal gradients that induce temperature constraints in the glass substrates and therefore cracks, especially in the case of glasses with high expansion coefficients. This difficulty seems to cancel the potential benefits of the laser polishing of glasses.

In the last 10 or 15 years, several improvements of the technique have been proposed in order to enhance the results of CO2 laser polishing of glass, in particular melted silicium, the most promising of the glasses (because of its chemical purity and low expansion coefficient). This renewed interest is due to the applications requiring the manufacture of very small optical instruments or instruments whose surface is aspherical or free-form. In such cases the usual mechanical polishing techniques are not appropriate or impossible to implement; they are too slow or consume too much manpower. Laser polishing is a contact-free technique that can be easily automated and adapted to most geometries; it is much faster than mechanical polishing (possibly by a factor greater than 10). Among these improvements, the uniformization of the laser beam spatial profile and the rapid sweep of a Gaussian spatial profile laser beam have been implemented by some groups in order to reduce the lateral thermal gradient caused by laser heat. Other groups have introduced the heating of the substrate to be polished (using a hot plate, a convection oven, or microwaves) in order to obtain an initial temperature that is higher than the ambient temperature (typically a few hundreds of degrees on the Celsius scale). This procedure enables one to limit the thermal gradients induced by laser irradiation. Finally some groups have introduced sequences of laser impulsions instead of continuous laser beams in order to limit the thermal load on the substrate.

The approaches described above have improved the results of laser polishing, but the technique still has limitations. For instance the residual thermal constraints cause a distortion of the laser-polished substrate and induce birefringence; thus laser polishing cannot be used in optical imaging. In the case of glasses with high expansion coefficients, these drawbacks lead to the substrate destruction. Also the thermal load due to the optical absorption of the laser beam within the substrate depends upon the dimensions of the substrate. Hence it could be necessary to modify the parameters of the polishing process for a given material whenever the substrate dimensions change; as a result it will be difficult to automate the process. There are relatively few articles on the modelling of laser polishing. Most research groups have adopted an empirical approach, and the modelling usually consists of computing (often in one dimension!) the temperature induced by a continuous laser irradiation of a semi-infinite substrate. One then makes the assumption that the surface temperature determines the glass viscosity. The computation yields the laser parameters (power, beam diameter, interaction time, etc.) guaranteeing a temperature at which the surface viscosity is small enough for the polishing to take place. In practice, however, the relevant physical phenomena are much more complex than what we have just described: the absorption coefficient of a given glass depends upon the wavelength of the laser (denoted by λ).

Almost all the published work on laser polishing of glass has been carried out at λ =10,6 μm and it would be desirable to study the effect of λ on the outcome of the polishing. All the physical properties of a given glass depend upon the temperature. The parameters of the laser-matter interaction, including the absorption coefficient, vary a lot in the course of laser heating, but this important phenomenon is seldom taken into account in the modelling. Also the healing and cooling rates are seldom taken into account. Since the final specific volume of a glass depends upon the cooling rate on either side of the vitrous transition temperature, it would be important to model the influence of this parameter on the residual thermal constraints within the substrate. In a similar fashion, the thermal losses due to convection and irradiation and the dimensions of the glass substrate are never taken into account. The models usually include the assumption of a semi-infinite solid. These factors (absorption coefficient, cooling rate, etc.) greatly influence the thermal load of the substrate induced by the laser heating. The published research work seldom takes into account the coupling between the heat equation and the mechanical deformation of the glass substrate, although such a coupling would enable one to identify the mechanical constraints (of thermal origin) causing the rupture, distortion, or birefringence of the substrate. Models seldom take into account the viscoelastic flow of glass, the main phenomenon underlying laser polishing; in general publications only consider an empirical relationship between the viscosity and the glass temperature (where the viscosity threshold for a glass flow is arbitrarily fixed at 103 Pa s-1 (T is approximately 2450 degrees Celsius). It would be relevant to model this phenomenon, in particular its capacity to reduce the surface roughness (as a function of the asperities spatial period).

The challenge is the following: is it possible to model in 3-D the laser polishing of a glass (with given physical properties) for a substrate whose dimensions are finite, while taking into account the coupling of the thermoviscoelastic equations (including the flow) and heat (including losses due to convection and irradiation), and the variation of physical properties as a function of temperature? The heat source is a laser beam absorbed by the glass substrate. The parameters of this source (which could vary in an arbitratry fashion) are the following: wavelength, average power (in continuous mode) or crest power, the impulsion duration and repetition rate (in impulsional mode), diameter and spatial profile (e.g., Gaussian, uniform-square, rectangular, circular), relative speed between the laser beam and the glass substrate (in two perpendicular directions). Clearly a system of coupled nonlinear equations will have to be solved by numerical methods. A priori we do not have specific requirements for the numerical tools used or the time needed to solve the system of equations. A software such as COMSOL Multiphysics could help solve the problem. A program in Matlab or Python (two languages already in use at INO) would also be acceptable to us.

The objective of the team is to propose a model that will enable one to simulate several laser heating regimes and to determine the parameters optimizing the surface roughness for all spatial periods, while minimizing the residual thermal constraints in the glass substrate under consideration. The results of this model will be used to plan the experimental development of the CO2 laser polishing process.