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Technical Advances in the Continuous Melting of Phosphate Laser Glass

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Continuous melting of phosphate laser glass is now being used for the first time to prepare meter-scale amplifier optics for megajoule lasers. The scale-up to continuous melting from the previous one-at-a-time "discontinuous" batch process has allowed for the production of glass at rates more than 20 times faster, 5 times cheaper, and with 2-3 times better optical quality. Almost 8000 slabs of laser glass will be used in high-energy, high-peak-power laser systems that are being designed and built for fusion energy research. The success of this new continuous melting process, which is a result of a six year joint R&D program between government and industry, stems from numerous technical advances which include 1) dehydroxylating the glass to concentrations less than ~100 ppm OH; 2) minimizing damage-causing Pt-inclusions; 3) preventing glass fracture; 4) minimizing impurities such as Cu and Fe to <20 ppm; 5) improving forming methods to get high optical homogeneity glass; and 6) developing large aperture quality assurance tools to verify properties of the glass.

1. Introduction

Nd-doped metaphosphate glasses are the preferred gain medium for high-peak-power lasers used for fusion energy research mainly because they can store optical energy at greater densities than other glass-types and this energy can be efficiently extracted [1,2]. Two high-energy, high-peak-power laser systems used for fusion energy research (the National Ignition Facility in the US and the Laser MegaJoule in France) are currently under construction, and will require more than 8000 meter sized slabs of high optical quality laser glass. In order to meet the production rate, continuous melting of phosphate laser glass is now being used for the first time to prepare meter-scale amplifier optics. The glasses manufactured by the new continuous melting process are marketed under the product names LG-770 (Schott Glass Technologies) and LHG-8 (Hoya Corporation USA).

The success of this new continuous melting process, which is a result of a six year joint R&D program between government and industry, stem from numerous major technical advances. Unfortunately, space prohibits detailed discussion of each technical aspect of the continuous melting process development. Hence, this paper serves merely as brief overview and provides references where specific subjects are described in more detail. In this paper, we briefly describe the new continuous melting process and compare this technology to the previous one-at-a-time 'discontinuous' process. Then we outline the major technical challenges that had to be overcome in order to ensure the success of the continuous melting process.

2. Continuous Melting

The continuous laser glass melting process, shown schematically in Fig. 1, converts high-purity, powdered raw materials into one continuously moving strip of high optical-quality laser glass.

The laser glass melting process requires seven separate operations carried out in separate vessels; to make the process continuous, the vessels are interconnected [3]. The first process unit is designed to mix and dry the high purity raw materials with minimal contamination. The laser glass specifications require that the raw materials contain only trace amounts ($\leq$10 ppm) of most common transition metal ions and less than 0.1 wt% of either physically or chemically absorbed water. The second unit is the melter system, which dissolves the powdered raw materials into a pool of molten glass and mixes these ingredients using convection currents inside the melter. The melter consists of custom designed high-purity refractory materials and employs a proprietary electrical heating system.

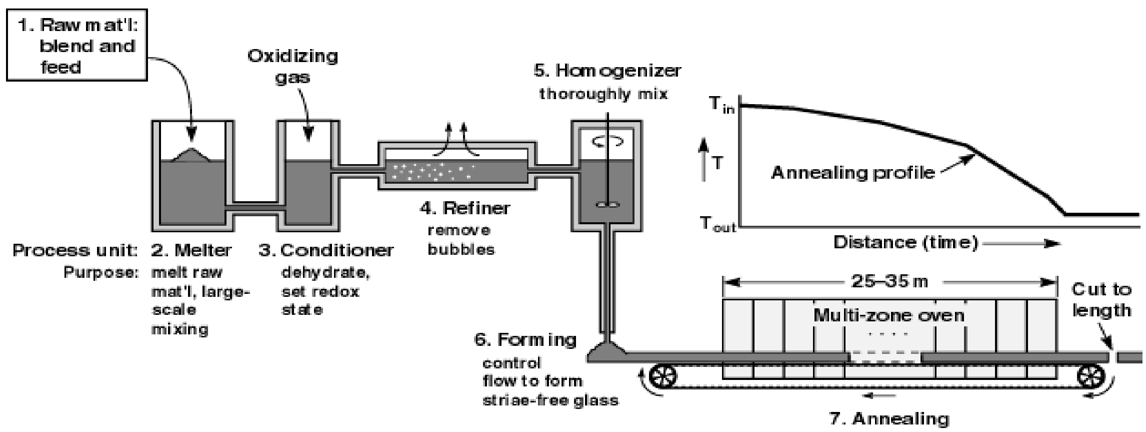

Fig. 1. Schematic representation of the continuous laser glass melting systems being used to manufacture laser glass.

All units beyond the melter are lined with high-purity platinum metal, as are the interconnecting pipes. Platinum is required to achieve the part-per-million optical homogeneity necessary for laser applications. However, the platinum can contaminate the glass with microscopic metallic inclusions. When a high-power laser beam hits an inclusion it causes it to explode, generating small fractures within the glass. To overcome this, we developed a unique conditioner unit (the third unit in the process) that uses oxygen and chlorine to remove platinum inclusions as well as any residual water. This is perhaps the most complex unit in the whole system.

The glass from the conditioner next moves to a refiner section where bubbles are removed using a combination of high temperature and proprietary additives. From here the glass enters the homogenizing unit and is thoroughly mixed to achieve the one-part-per-million chemical uniformity required to meet optical homogeneity specifications. The glass then flows through a platinum tube to a mold where it is formed into one continuously moving strip 5 to 8-cm thick, and about 0.5-m wide. The glass strip then passes through a custom-designed annealing oven where it is gradually cooled from more than 600°C to room temperature. Plates of laser glass (~1 m × 0.5 m for our specific application) are then cut from the end of this strip as it exits the production system.

3. Comparison with Old Technology

Laser glass was previously manufactured by a discontinuous, one-at-a-time melting process. The discontinuous melting process involves first melting raw materials in a refractory vessel, then manually transferring to a second platinum-lined vessel, and then finally manually casting the glass into a mold[3]. The whole process must then be repeated to make the next glass piece. This process has a small throughput of two to three pieces per week. In addition, product quality can vary from one melt to the next simply because of small run-to-run variations in processing conditions. Most importantly, the product cost is high (>$5000/liter). Continuous glass melting, on the other hand, not only has the advantage of a much greater production rate of 70 to 300 pieces per week, but also little, if any, measurable variation in glass properties from one glass plate to the next. Also, the cost is dramatically lower (≤$1000/liter) (see Table I).

Table I: Comparison of continuous melting process with the discontinuous process.

	Discontinuous melting	**Continuous melting**	**Better, worse, or Same**
Glass cost (per liter)	>$5000	≤$1000	>5× Better
Production rate (pieces/week)	2-3	70-300	>20× Better
Optical homogeneity (waves at 633 nm):			
Power	≤0.30 waves	≤0.15 waves	2× Better
Astigmatism	≤0.35 waves	≤0.11 waves	3× Better
Higher order	≤0.15 waves	≤0.07 waves	2× Better
RMS gradient	≤0.01 waves/cm	≤0.0040 waves/cm	2.5× Better
Nd-doping uniformity	±5%	±2.5%	2× Better
Optical transmission (at 1053 nm; 1-cm thick)	≥99.95%	≥99.95%	Same
OH content	<100 ppm	<100 ppm	Same
Impurity concentration	<20 ppm Fe	<20 ppm Fe	Same
	<1 ppm Cu	<1 ppm Cu	Same

4. Technical Advances

The glass compositions of the continuously melted laser glass have been specifically tailored to maximize the laser performance (e.g. gain, extraction efficiency, and damage resistance), while maintaining chemical durability and reasonable mechanical properties. Composition/property relationships in Nd-doped phosphate glasses are reviewed in detail elsewhere[4]. The two commercial, continuously melted laser glasses (LG-770 and LHG-8) are Nd-doped metaphosphate glasses (~O/P=3.0) with the approximate composition: $60P_2O_5$-$10Al_2O_3$-$30M_2O/MO$; K/Ba or K/Mg are typical modifiers.

The technical improvements needed to make continuous melting successful are a result of a six-year, joint R&D effort between LLNL, Schott, and Hoya. The specific technological developments and associated technical references are listed below:

1) ***Pt-inclusion removal***: Microscopic Pt particles (≤10μm) in the laser glass can absorb laser light and cause fracture in the glass (laser induced damage). Research on their formation and dissolution has led to a redox-controlled process for minimizing the number and size of inclusions in the glass [3,5-7].
2) ***OH removal***: Hydroxyl (OH) groups in the glass quench the fluorescence of the Nd and reduce the laser output energy. Our research on the chemical mechanism of OH removal (dehydroxylation) using reactive gas bubbling and the incorporation of this information in numerical process models has led to a 10× reduction of OH content of continuously melted glass [3,8]. Figure 2 illustrates the dramatic improvements in the glass OH content that has been achieved.
3) ***Fracture prevention***: Phosphate laser glasses are prone to fracture due to their low fracture toughness and high thermal expansion. Finite element heat transport and stress

analysis combined with the identification of various stress sources and research in crack growth have led to improvements in the annealing process that eliminate fracturing [9-11].

4) ***Impurity minimization***: Metal ion impurities (such as Fe^{2+} and Cu^{2+}) $\gtrsim$10 parts-per-million level can increase the optical absorption of the glass above acceptable limits. New analytical techniques to quantify impurity levels combined with research on the absorption characteristics of these impurities has led to much improved specifications and QC procedures for both the laser glass and the raw materials [12].
5) ***Homogeneity***: Laser glass requires a refractive index uniformity (i.e. optical homogeneity) of about one-part-per-million requiring advanced forming technologies. The details of this technology are proprietary. Typical optical homogeneity values achieved are described in Table I above.
6) ***Quality assurance***: A number of unique quality-assurance tools have been developed to inspect large optical glass plates at a high rate. These tools include large-aperture (24-inch) phase-measuring interferometers and large-aperture laser damage testers [13].

6. Conclusions

The construction of high-energy, high-peak-power lasers such as NIF is critical to gaining the data needed to define the conditions for nuclear fusion ignition and gain necessary for future fusion energy development. Without the development of continuous glass melting it would be impractical, if not impossible, to build such laser systems. The success of the continuous melting process is a result of numerous technological advances.

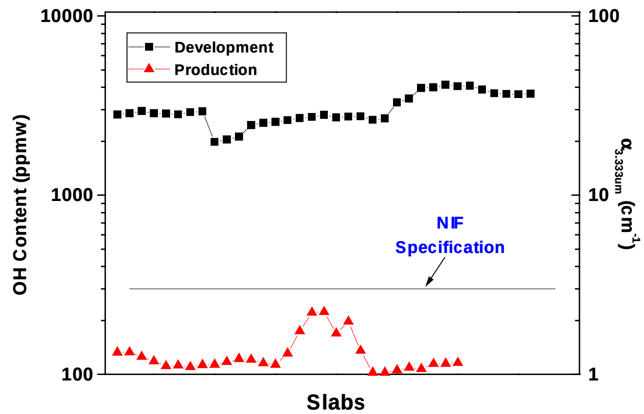

Fig. 2. OH content (in ppmw and OH absorptivity) in randomly selected laser glass slabs showing the nearly 50× reduction in this contaminant from an early development run and a recent production melt campaign.

Acknowledgments

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