Hydrodynamic processes in fused quartz under the action of laser radiation

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Abstract. The paper analyzes numerically the hydrodynamic processes developing inside the fused quartz under the action of intense laser impulses. Depending on laser intensity two basic regimes are obtained and described in details. At low intensities, the slow regime driven by the heat transfer is observed. Herewith, the fracture took place in the heated region before the phase transition. At higher intensities, the high-speed propagation regime is established characterized by the fracture events exactly at the interfacial boundary between the hot plasma and condensed phase. The propagation of absorption wave coupled with the fracture wave is limited by the value of sound speed in the hot plasma, which determines the expansion of plasma into the spallation region ahead of the absorption front. The proposed model of the process agrees well with the recent experimental data, in particular with the characteristic velocity scales.

1. Introduction
An important issue related to the effective data transfer by optical fibers is the increase of optical breakdown probability with the power of laser radiation. Nowadays, one uses optical silica-based fibers as a carrier for data transfer with laser energy. Herewith, the alloyed fused quartz is a common material of the fiber core since the difference in refractive index is necessary for the effective energy transfer through the waveguide. The presence of impurities and micro defects in the bulk of fiberglass determines a possibility of localized optical breakdowns of the medium under the action of intense laser impulses. As a result, the plasma discharge arises together with the region of high concentration of free electrons. The laser radiation begins to be absorbed intensively by this region, and a stable absorption front starts propagating towards the laser beam. The temperature inside the absorption zone increases sharply while the corresponding expansion of the hot plasma causes compression in the cold medium. Eventually, the fracture of the material takes place and the fracture wave propagates together with the absorption front towards the energy source.

The experimental study [1] considers two basic regimes of the medium fracture under the action of intense laser impulses: (1) localized slow melting under the less intense laser action and (2) high-speed fracture wave formed under more intensive laser action. It should be noted that in most experimentally considered cases [1] the value of absorbed energy is relatively low and does not exceed the amount of 0.25–0.6 mJ. However, the focusing of the energy inside the optical fiber core of ~ 7.0–9.5 μm diameter causes rather high intensities reaching the values of ~ 4.0 GW/cm² [1]. Such an energy concentration on the micro scales determines specific physical mechanisms of absorption wave propagation.

The slow regime of melting front propagation associated with the absorption front is defined mainly by the mechanisms of heat transfer from the hot plasma region to the adjacent layers of condensed phase
Herewith, heat losses, radiant losses and multi-dimensional rarefaction should be taken into account. In this case the absorption wave propagates with a speed of $\sim$ several meters per second [1, 2] similarly to the gas combustion under the action of laser impulse [3].

At laser radiation with higher intensity (of the order of GW/cm$^2$) one observes a regime of high-speed fracture wave propagation together with accompanying absorption front. In this case, the speed of absorption wave propagation is of the order of 2.6–3.2 km/s that is much higher than in the slow regime but almost two times lower than sound speed in the cold fused quartz (longitudinal sound speed in the fused quartz equals to 5.5 km/s). It is evident that such a high-speed regime is associated with high energy densities and the corresponding evolution of violent hydrodynamic processes. However, the detailed mechanisms and the sequence of processes evolution are still not clearly understood.

The paper considers numerically the hydrodynamic processes developed in the fused quartz under the action of intense laser impulse. The obtained sequence of hydrodynamic processes allows detailed description of the medium response to the energy impulse that is important for a clear understanding of the phenomenon of fused quartz destruction.

2. Problem setup and numerical method

Let us consider the following one-dimensional problem setup. The laser radiation propagates from right to the left through the planar layer of fused quartz. At a certain point, the medium starts to absorb the radiation according to the Beer–Lambert–Bouguer law. At the initial stage the absorption takes place in the cold solid quartz. As soon as the hot medium begins to expand heating the adjacent layers of solid quartz the absorption is assumed to proceed at the point with the temperature of 1000.0 K. It is assumed that the radiation is absorbed by heated plasma on the spatial scale of the order of wavelength presumed to be equal to 1.0 $\mu$m. Due to the lack of information on the absorption coefficient $\alpha$ the following form of density dependence is assumed $\alpha = (1/D)(\rho_0/\rho)^{1.5}$, where $\rho$ is the local density of medium and $\rho_0 = 2.2$ g/cm$^3$ is the initial density of the cold fused quartz.

The hydrodynamics of the medium is described by the conventional system of partial differential equations [4] with account of heat conductivity and energy absorption at the interface between solid medium and hot plasma. The equation of state is built on the basis of Hugoniot experimental data for fused quartz, experimental data on heat capacity at conditions near normal ones and heat capacities of silica in disordered phase calculated using so-called chemical model of matter [5] and data from IVTANTHERMO database. The detailed description of the utilized semi-empiric equation of state is presented in [4]. The model for thermal conductivity is presented in [4] as well.

The formulated problem setup reflects all the peculiarities of the studied process. The absorbed laser energy is treated by the medium as the source of inner energy localized on the spatial scale of the order of radiation wavelength. This energy is re-distributed in space via heat conduction and hydrodynamic expansion of the heated region. As a result, the deformations arise in the bulk of medium. This leads to the formation of compression and rarefaction waves, medium spallation, fracture and related phenomena considered in details below.

A series of calculations was carried out with various energy intensities. As a result different regimes of absorption wave propagation and related mechanisms of medium fracture were analyzed. For detailed analysis two types of signal were used: sinusoidal ($I(x,t) \sim I_0 \sin(\omega t)$, $I$ is intensity of laser radiation) as a model of experimental laser pulse and step-wise one ($I(x,t) \sim I_0$). In case of sinusoidal impulse the first half of 250 $\mu$s impulse was used.

3. Results and discussion

Let us first consider the sequence of processes developed in the region of energy absorption. The heating of the medium first causes its expansion relative to the initial state. As a result the heated region pushes the cold medium causing its compression. It should be noted that cold solid medium is almost incompressible and the discussed compression effect is negligible. Herewith, the expansion of the heated layer can be rather strong that causes localized spallation of the medium on the spatial scales of the order of heat layer
Figure 1. (a) Temperature field evolution in the region of expanding hot medium heated by the energy flux. (b) Characteristic flow pattern in the vicinity of the energy absorption zone \((x = x_f)\), temperature and pressure profiles are presented. Sinusoidal signal, \(I_0 = 10\ \text{W}/\mu\text{m}^2\). The early stage of the process, before transition from the slow regime to the fast one, is shown. The laser radiation is transferred from right to left.

thickness. At the same time at sufficient energy release the heated medium undergoes phase transition to the hot gaseous plasma state. Hot plasma expands into the cold region much more intensively that causes more violent deformations of the solid medium at the interface. As a result one can observe spallation of the solid medium exactly at the interface. The hot plasma flows into the spallation region that results in the propagation of the interface towards the energy source. As well, the heat flux from the hot plasma transfers the energy to the cold layers that in turn can cause medium melting. In such a way two basic mechanisms determines the absorption wave propagation. The first one is related to heat transfer and subsequent melting. The second one is defined by hydrodynamic expansion and subsequent spallation. In turn, these two mechanisms define two basic regimes of absorption wave propagation. In the first case the slow regime is established while in the second case the high-speed regime arises. The characteristic velocity scales are respectively: speed of the heat wave in the solid medium \((\sim 20\ \text{m/s})\) and the sound speed in the hot plasma \((\sim 3\ \text{km/s})\).

Let us now consider in details each of the regimes of absorption wave propagation through the fused quartz. Figure 1(a) shows the \(x–t\) diagram of the process of slow wave formation and subsequent propagation at laser energy flux of 1.0 GW/cm\(^2\) (or 10.0 W/\(\mu\text{m}^2\) in units used in [1]). At the early stage, one can observe the expansion of the heated region with local kernels of spallation at the background of the expansion. At the subsequent stages the heat is transferred to the adjacent layers of solid medium and according to the assumed problem setup the absorption front propagates together with the heat wave. As a result, the additional heating of this new layer takes place that leads to its expansion and spallation. After this, the process repeats itself for next layer etc. In such a way the slow regime of absorption wave propagation establishes. Herewith, this absorption wave is followed by the fracture wave representing the series of subsequent spallations. Figure 1(b) shows characteristic flow pattern in the vicinity of absorption front at the fixed time instant \((t = 50\ \mu\text{s})\). At the background of temperature rise, one can observe pressure oscillations associated with the discrete manner of fracture.

Figure 2(a) shows the \(x–t\) diagram of the process of high-speed absorption wave propagation under the action of laser pulse providing the energy flux of 4.0 GW/cm\(^2\) (or 40.0 W/\(\mu\text{m}^2\) in units used in [1]). The early stage of medium heating and expansion proceeds in the same manner as in the case of slow regime. Afterwards, as soon as the absorption wave is formed, the permanent spallation of the solid medium proceeds directly at the interface between expanding hot plasma and cold solid quartz. Corresponding flow pattern is shown in figure 2(b). The spallation region is characterized by the steep pressure drop up to the negative values. In such a regime the fracture wave propagates together with the absorption wave which speed is defined by the intensity of hot plasma expansion into the region of fractured solid quartz.

Figure 3 presents the diagram of speed regimes of absorption wave propagation through the fused
Figure 2. (a) Temperature field evolution in the region of expanding hot medium heated with the energy flux. (b) Characteristic flow pattern in the vicinity of the energy absorption zone \((x = x_f)\), temperature and pressure profiles are presented. Sinusoidal signal, \(I_0 = 10\) W/\(\mu\)m\(^2\). The laser radiation is transferred from right to left.

quartz under the action of laser pulses of different intensity. Here it is important to note that the silica fibers are able to transpose without losses the radiation flux not higher than 10.0 GW/cm\(^2\), even in pulse regime of laser operation. In view of this the data for higher values of radiation flux presented in figure 3 should be treated as qualitative for clearer understanding of the limiting scales determining different regimes. At energy flux in the range between \(\sim 0.6–1.5\) GW/cm\(^2\) (or 6.0–15.0 W/\(\mu\)m\(^2\) in units used in [1]) one can observe the transition from the slow regime to the high-speed one (zone II). Here it is interesting to note that in case of sinusoidal signal the transition from the slow regime to the fast one can be observed in this range of intensities. Thus, in case of 1.0 GW/cm\(^2\) presented in figure 1 there is such a transition at time instant of 80 \(\mu\)s. In case of step-wise signal it is more convenient to define the margin between the slow and fast regime that is found to be equal to 0.6 GW/cm\(^2\). Herewith, it is useful to note that experimental data obtained earlier correlates well with the obtained critical value [1]. In particular, in [1] the slow regime was observed at radiation fluxes up to 0.3 GW/cm\(^2\) while the fast regime was observed in the range of radiation flux from 3.4 to 4.0 GW/cm\(^2\). In [6] faster regimes were observed at radiation fluxes higher than 2.0 GW/cm\(^2\). Moreover, as one can see from fig. 3 the maximum speed of the fast absorption wave obtained numerically is of the order of experimental value and equals to the calculated sound speed in the hot plasma. This experimental fact substantiates the formulated mechanism of absorption wave propagation in the high-speed regime. The velocity of hot plasma expansion is limited with the sound speed. Plasma cannot expand into the spallation region with velocity exceeding the sound speed value.

The main differences between the speed regimes observed experimentally and numerically are the following. The first distinction is that numerically reproduced slow regimes occur to be almost twice faster compared with the experimentally observed regimes which is most probably related to the one-dimensional approximation of the problem setup. The second distinction concerns the fast regimes speed values. The calculated values occur to be lower than the experimentally observed ones at the same intensities of laser radiation. On the one hand this can be also related to the multi-dimensional nature of the phenomenon. On the other hand it can be related to the fracture development in the cold quartz under the external impact on its boundary. Fused quartz represents a very brittle medium, so the spallation under the tension induced by the hot plasma expansion causes the development of deep cracks propagating into the bulk of solid medium. In such a case the hot plasma can expand into the volume of fracture with the maximum available speed. Due to this the establishment of highest possible propagation speed takes place at lower laser radiation intensities compared with the calculations predictions.

It is useful to note that although there are distinctions between the numerical and experimental data the basic physical mechanisms defining the development of fracture processes in the fused quartz under the action of intense laser energy pulses are reproduced well enough in the calculations. One more
Figure 3. (left) Dependence of absorption wave speed on the intensity of energy flux (speeds are shown for the case of the sinusoidal signal). Blue line represents the data for slow regimes. Red dashed line — for fast regimes. For comparison, the experimental data from [1] and [6] are presented with the yellow signs (slow regimes) and green signs (fast regimes). Black dashed line represents the interpolation of experimental data. For convenience, we used the same units as in [1]. Vertical thin lines show the margins between three regimes: I — slow regime; II — transient regime (in case of the sinusoidal signal) or fast regime (in case of the step-wise signal); III — fast regime. A horizontal thin line shows the value of the maximal speed of absorption wave propagation at high intensities.

Figure 4. (right) Dependence of spatial scales related to the spallation of the medium on the intensity of energy flux. Vertical thin line shows the margin between regimes II and III for comparison with figure 3. Confirmation of this thesis is provided by the analysis of spallation scales obtained numerically and experimentally. Figure 4 shows the dependence of characteristic wavelengths arising in the process of quartz spallation associated with the propagation of absorption wave. The characteristic sizes of fragments measured experimentally in [6] for $I_0$ from the range between 2.0 and 4.0 W/µm$^2$ was found to be of the order of 0.1–1.0 µm that correlate well with the obtained numerical data for the fast regimes. In case of slow regime, the spatial scale of experimentally observed fractures was reported in [7] as 8.0 µm. Close scales were obtained experimentally in [1]. As one can clearly see, there is a steep change in the spatial size of fragments with the transition from the slow regime to the high-speed one. The spatial size decreases from the value of ∼ 10 µm to the value ∼ 2 µm and further decreases exponentially with the increase in radiation intensity.

4. Conclusion
As a result of detailed numerical analysis of the hydrodynamic processes associated with the absorption of intense laser pulses the basic mechanisms defining the solid medium spallation and absorption wave propagation are formulated. The slow regime is mainly determined by the heat transfer from the energy absorption region to the cold solid quartz. The localized heating caused by the heat transfer leads to the expansion of the heated medium and its subsequent spallation. Herewith, the characteristic spatial scale related to spallation is of the order of absorption length which correlates well with the laser wavelength. At higher intensity of laser radiation the hydrodynamic expansion of the hot plasma generated in the energy absorption zone causes significant tension and subsequent spallation of the cold solid quartz directly at the interface between the expanding plasma and cold medium. As a result the high-speed regime of absorption wave propagation is observed. The absorption front coincides with the interface between the expanding plasma and the cold medium. In the framework of the model considered here the
front of fracture wave is driven by the plasma expansion. Therefore, spallation takes place exactly at the absorption front. Herewith, the maximum speed of the complex consisting of the absorption front and fracture front is limited with the sound speed in the hot plasma. In reality, the spallation at the interface of such a brittle medium as quartz causes the generation of magistrate cracks propagating with the near transversal sound speed [8]. In case of quartz, transversal sound speed equals to 3.4 km/s while the sound speed in the hot plasma equals to 3.0 km/s. Since the speed of magistrate crack occurs to be higher than the maximum speed of hot plasma expansion, the speed of wave propagation in a fast regime equals to the sound speed in the hot plasma. This fact was numerously observed experimentally [1, 2, 6, 7], and the mechanisms formulated here explain well enough the high-speed regime of fracture wave propagation through the fused quartz under the action of intense laser impulse. The results are obtained in the one-dimensional approximation. However, despite in reality the dynamic processes develop in the three-dimensional geometry (including Gaussian distribution of the intensity in the cross section of core) the obtained results seem to be quite realistic in view of weak transversal rarefaction due to the fact that the energy is absorbed inside the narrow channel covered by a thick shell made of strong quartz.

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