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SHORT COMMUNICATIONS

Explosive Fragmentation of Melts in Contact with a Solid Surface in Subcooled Water[1]

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Abstract—An experimental study on the explosive fragmentation of strongly heated lead melt inside a steel cup in distilled subcooled has been conducted. Analysis of high-speed video recordings of the process showed that an explosion can be initiated both with complete and partial hardening of the upper lead melt layer. The observed phenomena are described. The results may be useful for the determination of causes of the initiation of a steam explosion when the melt contacts with a solid surface or is partially crystallized.

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INTRODUCTION

Historically, experimental studies of steam explosions can be divided into two groups by the techniques and approaches used. The first group includes large-scale experiments close to real conditions that are mostly connected with the nuclear industry (e.g., [1, 2]). This approach results in data on the explosion pressure in a vessel similar to a certain technological installation, which is of interest to the designers of specific equipment. The significant differences between the experimental series do not allow the results of measurements and observations to be analytically generalized.

The second group includes experiments on cooling singular molten droplets. These studies (e.g., [3, 4]) focus on the influence of certain regime parameters on the probability of explosive phenomena occurring. Such parameters include the degree of liquid subcooling and the amount of uncondensed gas dissolved in it, the thermophysical properties, the initial temperature, and the method (the effect of oxide films) of melt preheating. At the same time, the transfer of data obtained in these studies directly to the fragmentation of a significant melt mass is complicated due to the specifics of the experimental conditions.

Therefore, due to the technical limitations above, the entirety of the data obtained in both groups does not allow us to solve adequately all of the problems associated with the steam explosion. One of the questions is the degree of influence of melt contact with a solid surface has on the explosive fragmentation. The bottom of a cooling liquid container or a part of an already solidified melt may be such a surface. This paper contains the preliminary results of the authors' studies focused on the solution of this problem.

EXPERIMENTAL SET-UP AND TECHNIQUES

The experimental set-up (Fig. 1a) used in this work consisted of the following elements: a container *1* with subcooled water; an induction heater *2*; a test section *3* fixed on a linearly movable device *4*; a lighting system *5*; a high-speed video camera Phantom 2012 *6*; and a mirror *7*. A more detailed scheme of the set-up (albeit slightly differently arranged) can be found in [5, 6]. The water container was made of stainless steel and had a rectangular shape and a size of 530 × 250 × 230 mm. To enable backlighting and video recording of the ongoing processes, a glass window was built into one of the side walls of the container. The water temperature was measured with a mercury thermometer with an error of 0.2 K and was maintained at the level required in a given experiment with an electric heater, which was connected through an autotransformer; the cooling was due to the loss of heat to the environment.

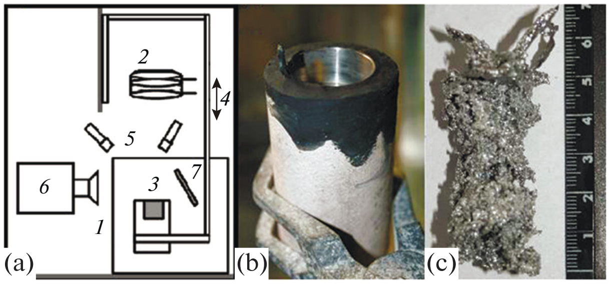

Fig. 1. Experimental set-up (a), test section (b), and view of the lead crust with a porous structure attached underneath (c).

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[1] Supplementary materials are available for this article at DOI: 10.1134/S0018151X18060020 and are accessible for authorized users.

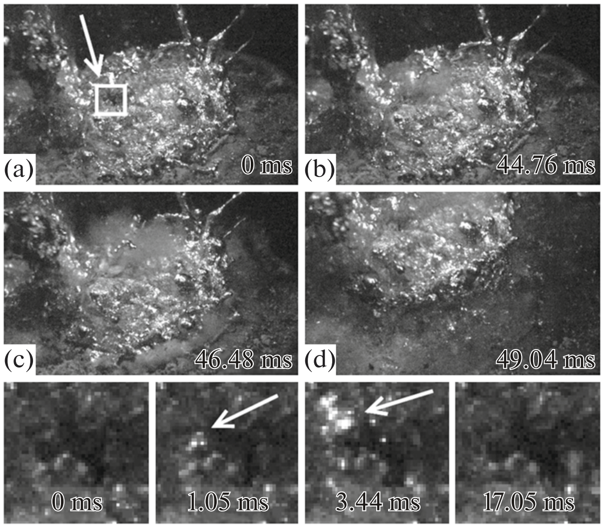

Fig. 2. Initiation of lead melt fragmentation in the case of its crystallized upper part (frames a–d); the formation and drawing in of the vapor bubble in the cavity (at the bottom).

The test section consisted of a vertical ceramic tube with a diameter of 50 mm plugged at the bottom with a fluoropolymer plug (Fig. 1b). The tube volume was filled with asbestos crumbs; a stainless steel cup with a depth of 15 mm and an inner diameter of 22.4 mm was roughly centered at the upper part of the tube. The top edges of the cup and the tube were at the same level, and the space between them was filled with a high-temperature sealant based on kaolin, liquid glass, and glass fibers. A chromel-alumel thermocouple was resistance-welded to the bottom of the cup, and its thermoelectrodes were brought out through the bottom plug. The melt material was placed flush inside the cup (high grade lead was used at this stage).

The melting and the subsequent heating of the melt was conducted in a double-turn inductor. Upon reaching the desired temperature level, the entire test section was submerged into subcooled water to a depth of about 50 mm with a linearly movable device. A high-speed video recording (100 kHz) of the occurring processes was made through a mirror tilted in two directions. Tilting of the mirror horizontally made it possible to obtain an image of the heat-dissipating surface; it was necessary to tilt it vertically so that the optical ray did not repeatedly pass the convection zone.

RESULTS

The experiments on two-phase cooling of a lead melt placed in a steel cup in subcooled water showed that fragmentation might have occurred when the initial melt temperature (as estimated from readings of the thermocouple welded to the bottom of the cup) was above 700°C. In addition, fragmentation was proved to be possible when the top melt layer is completely solidified, which can be seen on the video in the materials accompanying the article. Figure 2 also illustrates this process. Frame in Fig. 2a shows a previously solidified lead crust with some off-shoots from the main body, which have no effect on further events. In the region marked by the white rectangle, there was a cavity allowing the cooling liquid to flow under the crust and to contact the still uncrystallized part of the melt (a similar smaller cavity was located near the edge of the cup). This contact resulted in an explosion. Frames in Figs. 2b, 2c show the initial stage of the development of this explosion. Then, because of the sharp vaporization, the lead crust separated from the glass with the melt (Fig. 2d). As the crust rose, new contacts of underheated water with melt became possible, which led to repeated explosions. There were four explosions total (the initial explosion, the second explosion after 9.88 ms, the third after 12.65 ms, and the final one after 23.3 ms). This resulted in the structure depicted in Fig. 1c.

The lower part of Fig. 2 shows in close-up the processes occurring between frames in Figs. 2a, 2b in the mentioned region, which is marked in Fig. 2a by the white rectangle. The left frame, which corresponds to Fig. 2a, presents the initial state of the cavity. It is characterized by the absence of any notable phenomena. The central frames show the formation of a vapor bubble, which is indicated by white arrows. Upon reaching a certain size, the bubble was drawn into the cavity, which can be seen on the right frame. The surrounding fluid then began to be drawn in together with the nearby particles of lead oxides (the conclusion about the liquid movement was made from observation of the vapor bubble and these particles). The rapid boiling up of the liquid caught under the lead crust evidently led to the subsequent explosion of the remaining melt.

One possible answer to the question of the nature of the force causing the surrounding liquid to rush into the cavity may be the following. After crystallisation the upper part of lead directly exposed to the water, the formed crust has a good grip on the edge of the cup with respect to the active forces and cannot be pushed in. As the lower layers of the melt gradually cool, they undergo a volume compression. Thus, the lower molten part of the lead can separate from the upper part, which is already solidified, i.e., cavities appear. If there are holes or pores in the upper crust, they might merge with such a cavity at some point in time, and the described liquid intake can occur because of the obvious difference in pressure between the environment and the cavity. A more detailed theoretical analysis involving numerical methods is required to verify this or other possible assumptions, which is a task for future research.

It should also be noted that explosive fragmentation could as well occur in similar experiments with partial crystallization of the upper part of the melt. In that case the process was initiated on still-liquid areas of the heat-dissipating surface. This picture is generally confirmed by the results of previous experiments on two-phase cooling of singular droplets of various melts [5].

CONCLUSIONS

An experimental study on the explosive fragmentation of strongly heated lead melt inside a steel cup in distilled subcooled water was conducted. It was found that the explosion can be initiated both with complete and partial hardening of the upper melt layer. In the first case, the video analysis showed that the surrounding liquid is drawn under the hardened upper crust of the melt before the explosion. This phenomenon presumably occurs when cavities form under the crust due to the volume compression of the lead when it cools. In the second case, the observed processes generally complied with the processes occurring in two-phase cooling of singular droplets.

The obtained data provide additional information on possible causes of the initiation of a steam explosion, since similar phenomena can also occur when a considerable mass of melt enters the subcooled water and sinks to the bottom of the container before the fragmentation; some part of it crystallizes with gradual cooling.

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