The study of the liquid metal drops fragmentation

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Abstract. The main models of the fragmentation of liquid metal droplets in a steam explosion based on thermal stress, shock-acoustic effects and explosive boiling water inside the melt were analyzed. Experimental installations are described and research results are presented. The experiments were carried out with samples of various metals (tin, nickel, zinc, stainless steel), which were heated in levitation mode using an inductor. The maximum temperature for heating a sample of ball-bearing steel did not exceed 1600 °C. Then, in the molten state, the samples (droplets) fell into a cell filled with distilled water at room temperature. In the experiments, the temperature of the melting sample was monitored and the crushing process was recorded. An experimental material indicating the diversity of the forms of the fragments being formed was obtained. The latter circumstance confirms the assumption of the existence of various fragmentation mechanisms, including the method of breaking drops under the action of intense sound waves caused by the collapse of vapor formations. The results of numerical estimates are given, which indicate that the rate of cooling of particles formed in the process of fragmentation can reach values from $10^9$ to $10^{10}$ K/s. These values are quite sufficient for obtaining various alloys with an amorphous structure. The possibility of destruction of vapor shells around hot drops under the action of pressure pulses caused by the collapse of adjacent vapor-gas formations has been experimentally confirmed.

1. Introduction
Currently, due to increased safety requirements for nuclear power plants, interest in studying the causes of thin fragmentation of droplets of hot liquid metal falling into cold water has increased again [1, 2]. Such a process is one of the key stages of a steam explosion, and its mechanism is not clear enough. In addition, due to the explosive nature of the process, the rate of cooling of the resulting fragments is sufficient for the formation of amorphous metals (metal glasses). Therefore, we can assume that this method of crushing is promising for creating an original technology for the production of amorphous metals. The following summarizes the literary status of these two questions, the experimental setups are described, and some of the results of the research are presented.

In the literature, for example [3, 4], one can find a large number of various hypotheses devoted to the description of possible mechanisms for melt fragmentation during its interaction with a low-boiling liquid in the regime of film boiling crisis. Among them, the so-called “hydrodynamic” jet model, in which the coolant jets penetrate into a hot liquid, for example, a liquid metal drop, is developed in the scientific literature most fully. Such jets are generated during the collapse of steam bubbles formed during boiling up of a cooler on a superheated surface. The cooler (usually water) penetrates into the hot drop and boils explosively in it, which leads to the fragmentation
of the volume of the melt. In our opinion, the hypothesis described above is excessively complex to be suitable for a reliable description of the melt fine fragmentation process course. In another common hypothesis regarding the mechanism of melt fragmentation, it is assumed that during the collapse of the vapor shell around a drop, there is an intense cooling of a strongly overheated liquid metal surface. This process leads to instantaneous solidification of the surface layer of the melt, which is accompanied by the appearance of tensile thermomechanical stresses in the solid shell and growing up of the pressure inside the drop liquid core. These processes initiate the formation of cracks in the hardened surface layer and the emission of hot liquid jets into the cooler. This hypothesis due to the relative slowness of the course of the thermomechanical processes (tens of milliseconds and above) underlying it is unsuitable for describing explosive fine fragmentation of the melt. However, as evidenced by the results of experiments, the model adequately describes the crushing process, as a result of which large fragments in the shape of “hedgehogs” are obtained (figure 1).

In connection with the foregoing, it can be assumed that for a reliable explanation of the phenomenon of thin fragmentation of the melt, approaches based on other physical principles are required. In particular, with high probability it can be assumed that the explosive fragmentation with the production of fine fragments is due to the cavitation- acoustic effect associated with the generation of high-frequency intense pressure pulses during the collapse of steam bubbles that are formed when hot and cold heat transfer media, see figure 1(c). Such impulses propagate both in the environment of the cooler and inside the drop by means of sound (shock) waves. The reflection of waves from the surface leads to the appearance of a train of rarefaction pulses inside the drop. In their amplitude and duration, these pulses can reach values sufficient for the emergence of fast-growing cavitation cavities inside the hot coolant and its fragmentation [5–7].

One of the objectives of the presented research is to obtain additional experimental information on the substantiation of the possibility of the occurrence of fragmentation under the shock-wave scenario.

The important question also touched upon in the report is connected with the possibility of obtaining amorphous alloys by the steam explosion method. As mentioned earlier, the crushing process during steam explosion is characterized by a significant cooling rate of droplet fragments, which, combined with the simplicity and relatively high productivity of their production, makes this method promising for the industrial production of amorphous metals [8]. In addition to the well-known magnetic and mechanical characteristics, such materials possess a number of remarkable properties. In particular, it is known that amorphous materials are capable of absorbing 50% more hydrogen than crystalline alloys [9]. Such a formulation of the question is

Figure 1. Schemes of (a) jet and (c) shock-wave melt fragmentation; (b, d) photographs of the formed tin fragments: 1—water; 2—melt; 3—steam; 4—shock wave; 5—steam bubble; 6—melt jet; 7—contact spot melt-cooler; 8—pressure impulse; 9—reflected pressure impulse; 10—drop destruction (spall).
Figure 2. Scheme of the setup (a) and photograph of the inductor with a levitating drop (b): 1—levitating drop of the metal; 2—cone-shaped inductor; 3—working chamber; 4—vessel with water.

new and requires additional research, in particular, with the assessment of the cooling rate of fragments formed during fragmentation.

2. Experimental installations and measurement technique
Schemes of two types of experimental facilities designed to study the fragmentation mechanisms of hot liquid metal droplets immersed in a cooler—distilled water are shown in figures 2 and 3. In the process of smelting, a metal sample located inside the inductor either levitates (see figure 2) or is located on the substrate (see figure 3) and at the same time is heated in an inert gas medium, argon, that fills the working chamber. Then the power supply of the inductor is turned off and the red-hot drop either falls into the vessel with water, or is immersed in the cooler by gradually filling (from below) the working chamber with water. In both cases, with a certain degree of probability, the process of its fragmentation occurs. The filling of the working chamber with distilled water and argon is carried out using a special gas-water system. Samples made from various metals (tin, nickel, zinc, stainless steel) were used in the experiments. Melting and fragmentation processes are monitored with video cameras and temperature and pressure sensors.

With high probability, it can be assumed that the process of primary contact of a hot body with a cooler for solid and liquid samples proceeds in a similar way. Therefore, in order to obtain additional information about the initial stage of fragmentation, in addition to experiments with liquid metal drops, experiments with solid metal bodies were also carried out. Information on the methods of carrying out such experiments and descriptions of experimental installations are presented in detail in [10].

3. Analytical and numerical estimates
To assess the applicability of the above approach, we solved the model problem of cooling a body with a fluid flow in the following formulation, a steel ball with a radius of \( r_0 \), an initial
temperature \( t_0 = 1500 \, ^\circ\text{C} \) and thermal diffusivity \( a = 4 \times 10^{-6} \, \text{m}^2/\text{s} \) is considered, the ball is flown around the fluid flow (water) with temperature \( t_f = 20 \, ^\circ\text{C} \) with a velocity \( W \), and a boundary condition of the third kind is realized on the surface. The one-dimensional heat conduction equation without internal sources can be written as

\[
\frac{\partial t}{\partial \tau} = a \left( \frac{\partial^2 t}{\partial r^2} + \frac{2}{r} \frac{\partial t}{\partial r} \right),
\]

(1)

where \( t \) is the temperature, \( \tau \) is the time, \( r \) is the current radius. Its solution is

\[
\Theta = \sum_{n=1}^{\infty} \frac{2(\sin \mu_n - \mu_n \cos \mu_n) \sin(\mu_n R)}{(\mu_n - \sin \mu_n \cos \mu_n) \mu_n R} \exp(-\mu_n^2 Fo),
\]

(2)

here \( \mu_n \) is the root of the characteristic equation

\[
\tan \mu_n = -\frac{\mu_n}{\text{Bi} - 1},
\]

(3)

also \( \Theta = (t - t_f)/(t_0 - t_f) \) is the dimensionless temperature; \( R = r/r_0 \) is the relative radius; \( \alpha \) is the heat transfer coefficient; \( \lambda_f = 0.6 \) and \( \lambda_s = 30 \, \text{W m}^{-1}\text{K}^{-1} \) are the thermal conductivities of the water and the steel respectively; \( Fo = a \tau/r_0^2 \) is the Fourier number; \( \text{Bi} = \alpha r_0/\lambda_s \) is the Biot number; the Nusselt number for the flow around the ball is written as \( Nu = 2\alpha r_0/\lambda_f \); the relation with the velocity and properties of the fluid is expressed by the Ranz–Marshall formula:

\[
Nu = 2 + 0.6\text{Re}^{0.5}\text{Pr}^{0.33}.
\]

(4)

Here \( \text{Re} = 2W r_0/\nu \) is the Reynolds number, where \( \nu = 10^{-6} \, \text{m}^2/\text{s} \); \( \text{Pr} \) is the Prandtl number for water; we took \( \text{Pr} = 7 \).

Assuming that the speed of dispersion of fragments \( W \) is in the range of 1–50 m/s, it is possible to obtain cooling curves and determine the characteristic rate of cooling of the sample. We consider the center of the ball. Since the cooling rate varies with time, it was calculated...
Figure 4. Dependence of the cooling rate on the radius of the ball at different velocities of flow: 1 (1), 10 (2) and 50 m/s (3).

as the ratio of the temperature difference $\Delta t = 100$ °C to the time $\tau_0$ during which the body cooled to this value. Thus, it is possible to determine the cooling rate as follows:

$$V_t = \frac{\Delta t}{\tau_0}.$$  \hfill (5)

Some results of this determination are shown in figure 4.

4. Research results and its analysis

The results of experiments to study the process of fragmentation of droplets made of tin, zinc, ball bearing steel and nickel indicate the diversity of the forms of the fragments. This circumstance confirms the assumption of the existence of various fragmentation mechanisms, which to a significant degree depend on the initial temperature of the melt. In particular, the coarse type of fragmentation of tin drops with the formation of fragments in the form of “hedgehogs”, see figure 1(b), most likely proceeds by a thermomechanical mechanism. A similar type of crushing is observed at the initial melt temperature below 400 °C.

At the drop temperatures $t$ of 400–700 °C, fine melt dispersion takes place, combined with the formation of a porous structure, see figure 1(d). It is known that a similar structure is observed during the fragmentation of viscous media under the action of shock waves propagating in their volume. Therefore, we can assume that in this temperature range the cavitation-acoustic mechanism of droplet fragmentation prevails. At the temperature $t \geq 700$ °C, there is practically no fragmentation, which is apparently due to the formation of a thick layer of oxides on the surface of tin drops in the process of their relatively long cooling in water in the film boiling mode.

A distinctive feature of some of the resulting fragments is their hollow form. The formation of such a form can be associated with the specificity of the interaction of a hot drop with the free surface of the cooler. It is also possible that this is due to the shock-wave effect.

To test the latter assumption, a preliminary numerical simulation of the propagation of pressure waves inside a liquid metal drop when interacting with a cooler using the StartFlow (fluid dynamics numerical simulation software) was carried out. It was shown that the wave fronts from the high-pressure source [figure 5(a)], simulating the collapse of the vapor bubble,
move along the interface to the opposite side of the drop, where they overlap (acoustic lens) and a secondary high-pressure area appears [figure 5(b)]. The latter circumstance can lead to the formation of jets of liquid metal. In the experiments, we observed breaks of the liquid drop with the formation of a funnel and the ejection of the material [figure 5(c)].

Based on the results of the experiments, including the works [11,12], the characteristic values of the parameters describing the process of melt fragmentation were determined. Some of them are presented in table 1. The experimental data given in the table allow us to estimate the cooling rate of the formed fragments—the determining parameter in the technology for producing amorphous metals.

The question of the possible fragmentation of a group of neighboring droplets under the action of pressure pulses caused by the explosive destruction of the vapor envelope around one of them is important for clarifying the mechanism of the flow of a spontaneous steam explosion. Therefore, in addition to experiments with liquid metal drops, experiments were carried out on
Table 1. Typical values of parameters: $P$ is the maximum amplitude of impulses arising during the collapse of the vapor bubble; $\tau$ is the time of this pulse; $D$ is the diameter of the fragments formed during fragmentation; $W$ is the velocity of the fragments during explosive fragmentation.

| $P$, MPa | $\tau$, $\mu$s | $D$, $\mu$m | $W$, m/s |
|----------|----------------|-------------|----------|
| 1        | 10–50          | 1–1000      | 1–10     |

the study of the characteristics of the flow regimes of film and transitional boiling of underheated water in a group of closely located hot bodies. The working section of the installation was a thermally insulated cylindrical copper block heated electrically. On the lower end surface of the block, samples were placed with hemispherical working surfaces on which vapor films were formed when they were immersed in hot water. The process of vanishing steam films was observed using digital video cameras and recorded according to the readings of thermocouples embedded in hemispheres. The obtained video materials and oscillograms figure 6. of the temperatures of three working hemispherical samples confirm the assumption of the possible simultaneous destruction of the vapor shells of several closely located hot bodies under the action of a spontaneous collapse of one of them. It was established that the delay time and the nature of the process of destruction of vapor shells largely depends on the sample temperature at which an initial initiating pressure pulse is observed.

5. Conclusions

Our findings are as follows:

- The process of fragmentation of droplets is random in nature and can occur under a variety of scenarios, which are based on different (thermomechanical, shock-wave, etc) crushing mechanisms. This is evidenced by the diversity of the forms of the fragments being formed. The scenario in which the crushing process can develop depends on the temperature of the drop, the degree of oxidation of its material, and the presence of the free surface of the cooler when interacting with the melt (the entrance of the falling drop into the water, flooding below the vessel in which the fixed drop is located).
- The cooling rate of particles formed in the process of fragmentation, as shown by numerical estimates, can reach values from $10^9$ to $10^{10}$ K/s. These values are quite sufficient for obtaining various alloys with an amorphous structure, including metal hydride materials.
- The possibility of destruction of vapor shells around hot drops by pressure pulses that are generated during the collapse of neighboring steam-gas formations has been experimentally demonstrated.

Acknowledgments

The work was partially supported by the Russian Foundation for Basic Research (grant No. 18-08-01497). The authors are grateful to S N Vavilov for assistance in carrying out experiments.

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