Features of intensive evaporation of liquid-metal steel drops heated in a high-frequency inductor

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Abstract. The paper presents the results of experimental studies of the processes of intense melting in air of samples (solid balls) made of metals, primarily various steels. It is shown that the heating of some steels is accompanied by intense sparking - the ejection of small secondary droplets (sparks) from the primary droplet heated up to 2500 K into the surrounding space. A possible mechanism of this process is proposed and described at a qualitative level. Possible reasons for the explosive fragmentation of secondary droplets are indicated and experimentally confirmed. The vibration process of molten samples shell, caused by the vortex motion and evaporation of the melt inside the droplet, is described. The influence of spark formation on the stability of the induction melting process is demonstrated.

1. Introduction

Liquid metals are actively used in various energy and cooling devices. For example, sodium and lead in a liquid state are used as coolants in fast-neutron reactors [1, 2]. On the other hand, due to tough measures to prevent carbon dioxide emissions in industrialized countries and especially in Europe, work is underway to use metals (aluminum, magnesium, iron, etc.) as alternative fuels [3]. The latter circumstance increases interest in the study of the processes of melting, intense evaporation, boiling, and combustion of liquid metals. The same issues are relevant for aeronautics and are associated with the development of effective methods for heat removal under zero gravity conditions (liquid metal heat pipes [4]), as well as with the disposal of space debris, consisting mainly of metallic parts. The results of experimental studies devoted to the investigations of some specifics of intense evaporation and combustion of steels in air are presented below. These issues are related, inter alia, to the problems of general fire safety of industrial installations [5] and the prevention of severe, beyond design basis, accidents at nuclear power plants [6].

2. Experimental set and measurement technique

The scheme of the experimental setup is shown in Figure 1. A solid-state sample 1 (usually a steel ball 10 mm in diameter) was placed on a ceramic support 4 in the center of a single-turn ring inductor 2 powered by a high-frequency electric generator. The temperature of the molten sample, the maximum value of which reached 2300 K, was measured using a spectrometer 7 of the Ava Spec-3648 type. For
video recording of the processes of melting, evaporation and combustion, two high-speed video cameras 5 with a maximum shooting speed of 960 frames/s were used. For the video recording the light filters and reflective glasses were used. It made it possible to observe the vortex motion on the lateral surface of the molten droplet. In the experiments, the samples produced mainly from ball bearing steels of grades ШХ15 (analogous to US steels: 52100, G52986, J19965) and 95X18-Ш (440B, 440C, 440FSe, A756) were used. In order to study the hydromechanical vibrations of the samples in a high-frequency electromagnetic field the copper drops were used.

The power for the inductor was provided by the induction melting furnace HT-15kWt power supply (frequency 30-60 kHz), as well as by a specially designed laboratory high-frequency inverter. In order to improve the operational characteristics, the produced device was extended with a phase-locked loop system and a high-speed protection of power transistors against overcurrent, as well as with a special pulse regulator that allowed to control the inverter power with a personal computer. Such modifications make it possible to ensure the stable operation of a high-frequency (250 kHz) inductor and to conduct research on the melting process of various metal samples in laboratory conditions at temperatures of ~ 2000 °C.

![Figure 1. The scheme of experimental setup](image)

1 - a metal sample of an annular inductor; 2 - annular single-turn inductor; 3 - high-frequency power supply; spectrometer; 4 - ceramic support; 5 - video camera; 6 - optical diaphragm; 7 - spectrometer; 8 - PC.

As it was mentioned above, the temperature of the sample was determined by the spectral method. Spectrum processing (Figure 2a) was carried out according to the well-known technique [7], in which the flame temperatures of heated metals were determined from the angle of inclination of the linear portion of their spectrum, presented in the Wien coordinates (Figure 2b): \[ Y = \ln(I\lambda^5), \quad X = C_2/\lambda. \] Here \( I \) is the radiation intensity, \( \lambda \) is the wavelength, \( T \) is the temperature, \( C_2 = 14388 \mu \text{m K} \).
3. Experimental results
The results of the experiments showed that high-temperature induction heating of steels in an oxidizing environment has a number of characteristics associated with intense sparking (Figure 3) - the ejection of luminous small splashes from the molten sample with an initial diameter of 0.1 - 1 mm. The initial velocity of the outgoing sparks is in the range of 0.5-3.5 ms. Secondary droplets, when moving in the environment, decrease in size due to evaporation and fragmentation, and their final diameter varies from 0.01 to 0.4 mm.
The analysis of the recorded video showed that the fragmentation of the emitted secondary droplets into the environment, apparently, can proceed: 1) without visible sources of impact (Figure 4a, b); 2) when particles collide with each other (Figure 4c, d) and, third, due to an external trigger associated with the explosive fragmentation of adjacent secondary droplets (Figure 4e, f, g). The fragmentation mechanism of secondary droplets depends on which of the two (solid or liquid) states they are in at the moment of contact. The temperature estimates based on the spectral experimental data require clarification and are close to the value of the melting temperature of steel (~1450 °C),

![Figure 5. Typical vertical and horizontal sections of a cooled steel specimen](image)

The emission of sparks, contributing to an intensive decrease in the droplet mass, was observed over its entire surface, which consists of oxides. It can be assumed that the heating of the melt by induction currents was carried out inside the volume bounded by this shell. Metallic vapor was generated inside this porous shell and was thrown out either through the formed passages (Figure 5b), or by explosive destruction of most of the droplet. Ultimately, in most cases, droplets of this melt, when solidified, turned into a hollow cavity of metal oxides (Figure 5a). For other materials used in the experiments, the process of "ordinary" evaporation of liquids from their outer surface took place.

For a more detailed study of the spark formation mechanism, an X-ray diffraction analysis of both secondary droplets-emissions and the shell material was carried out. The study of the phase compositions of the samples after fragmentation was carried out by the method of X-ray structural analysis according to the standard technique on a domestic setup of the DRON-2 type (CuKα radiation). It was found that the material of the secondary droplets consists of amorphous and crystalline components. The crystalline part of the sample contains four phases: \( \text{Fe}_3\text{O}_4 \), \( \text{FeO} \), \( \text{Fe}_2\text{O}_3\cdot\text{H}_2\text{O} \) and austenite (a solid solution based on \( \gamma-\text{Fe} \)). The \( \text{Fe}_3\text{O}_4 \) phase occupies 16% of the sample volume, \( \text{FeO} - 8\% \), \( \text{Fe}_2\text{O}_3\cdot\text{H}_2\text{O} - 5\% \), austenite - 8%. The average size of the coherent scattering regions (CSR) of \( \text{Fe}_3\text{O}_4 \) is 43 nm, \( \text{FeO} - 46 \text{ nm, of austenite and iron hydroxide } \text{Fe}_2\text{O}_3\cdot\text{H}_2\text{O} - \text{ not less than } 100 \text{ nm. The rest of the material is in an amorphous state. It is not possible to determine the phase composition of an amorphous substance by X-ray structural analysis.}

The results of the analysis of the shell material showed that it also has both an amorphous and a crystalline structure. The crystalline part of the sample contains two iron oxides (\( \text{Fe}_3\text{O}_4 \), \( \text{Fe}_2\text{O}_3 \)) and ferrite (\( \alpha-\text{Fe-based solid solution} \)). According to a rough estimate, the share of \( \text{Fe}_3\text{O}_4 \) accounts for 17% of the volume, \( \text{Fe}_2\text{O}_3 - 5\% \), ferrite - 7%. The average CSR size of these phases is: \( \text{Fe}_3\text{O}_4 - 43 \text{ nm, ferrite - 24 nm, Fe}_2\text{O}_3 - \text{ not less than } 100 \text{ nm. The rest of the primary droplet shell material is in an amorphous state.}

It is important to note that the melting process of the samples in the inductor is accompanied by relatively intense mechanical vibrations of the melt volume with accompanying waves on its surface. Such effects are caused in particular by vortex convective flows inside the droplet which are caused by the forces of Archimedes and Ampere acting under conditions of intense phase transformations of low-boiling liquids present in the melt. The results of purely numerical MHD studies [8] indirectly confirmed by the type of longitudinal sections of solidified samples (Figure 5a), indicate that toroidal vortices are formed inside the droplet facilitating mixing of the liquid and suction of the surrounding
humid air to it. The vortex motion of metal oxides (copper) on the surface of the molten sample also confirms this phenomenon (Figure 6).

Figure 6. Time variation of the sample contour (copper cylinder 8 × 20 mm) upon heating in an inductor. Time interval between frames (from left to right) 1/50 s.

4. Conclusion
The paper presents the results of an experimental study of the physical effect associated with the burnout of molten metal samples through sparking - the release of secondary incandescent drops into the environment. The samples were melted in air using induction heating. On the basis of the obtained experimental material the following possible mechanism of this phenomenon can be proposed which is based on the formation of a porous oxide film (shell) on its surface during the melting of a sample. Inside this shell the processes of combustion of steel components intense evaporation or boiling of low-boiling substances (for example, water) can take place. These substances can be in the melt in a dissolved state or penetrate into the inner volume of the shell from the external environment. Intense vaporization in a limited volume created by the vapor shell leads to an increase in pressure and the release of hot vapor through passages in the porous surface. The results obtained, in addition to specialists in general fire safety and nuclear power plant safety, may be of interest to researchers in the field of volcanology and astrophysics.
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