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Type the title of your paper here Effect of the focused light from the xenon arc lamp on the surface tension of the molten enamel

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Abstract. The effect of exposure to the focused light from the xenon arc lamp on the surface tension of molten enamels was studied with a designed light beam setup as compared to that observed in conventional heating in a resistance furnace. The objects under investigation were enamels No. 261, UES-200 and UES-300. The power density of the light beam was varied in the range of (30–80) W/cm^2. When exposed to light, the surface tension is shown to be an order of magnitude lower than that obtained in conventional furnace heating.

1. Introduction

Glass-enamel coatings of metal products are the most effective protection against corrosion and, in addition, they provide the surface of enameled metal products with a number of useful properties inherent in oxide glasses, namely, hardness, smoothness, acid and alkali resistance, attractive appearance and durability [1]. Along with viscosity and linear temperature expansion coefficients, the surface tension of enamels is an important technological parameter. For successful enameling, the surface tension of enamels at temperatures close to the firing point (750–1050 °C) should be no more than 230–340 mN/m [1]. It is known that decreased surface tension improves the wettability of the surface of the metal oxidized with molten enamel which facilitates release of gas bubbles from the melt and increases coating adhesion. That is, the decreased surface tension of the melt provides high-quality defect-free coating [1]. Conventional technology for producing enamel coating involves heating in resistance furnaces. A setup for treating the material with the focused light from the xenon short-arc lamp (XSAL) DKsShRB-10000 is described in [2–3]. This setup provides local heating to temperatures of about 1000 °C. This type of heating can be used for enameling small metal parts, and it is promising for repairing imperfections and re-enameling cast iron products [3]. To optimize the enameling modes, the effect of the XSAL focused light power density on the surface tension of the molten enamel should be studied.

This paper aims to study the effect of the XSAL focused light power density on the surface tension of the molten enamel of different composition.

2. Experimental procedure

We investigated enamels No. 261, UES-200 and UES-300. These enamels are acid and alkali resistant that determines their wide practical use. They can be used in liquid media with pH values from 1 to 14. The composition of the studied enamels is presented in Table 1.

Table 1. Chemical composition of acid and alkali resistant enamel frits (mass%).

Oxide	No. 261	UES-200	UES-300
Li_2O	5	4	4
Na_20	14	13.34	13.34
K_2O	1	4.38	4.38
CaO	4	2.28	2.28
MgO			
CoO	0.30	0.30	2.5
TiO_2	1		
ZrO_2	3	8	9.5
Cr_2O_3	4.7	2.2	
$Si0_2$	64	62	62
B_20_3	2	2	2
Al_2O_3			
P_2O_5			
Na_2SiF_6	1		
Na_3AlF_6			

2.1. The value of the surface tension coefficients of enamels studied under conventional furnace heating

For conventional furnace heating, the surface tension (σ) of the molten enamel of specific composition can be calculated by known methods based on the principle of additivity. Each component of the enamel contributes to the total property of this complex substance. This contribution is proportional to the content of each of the component. The proportionality factor takes into account the interrelation of the components, and it is called a partial coefficient [4]. The most precise calculation for the studied enamels can be obtained by the method of A. Dietzel [1]. The formula for calculation of the enamel surface tension according to Dietzel is as follows:

$$\sigma = \sum c_i * \sigma_i \tag{1}$$

where c_i is the mass fraction of the component (%) and σ_i is the partial coefficient according to Dietzel. Data for calculation of the enamel surface tension according to Dietzel (900 ºC) are shown in Table 2.

Table 2. Data for calculation of the enamel surface tension according to Dietzel (900 ºC) [1]

Oxide	σ_i, (mN/m)	No. 261		UES-200		UES-300	
		c_i	$c_i * \sigma_i$	c_i	$c_i * \sigma_i$	c_i	$c_i * \sigma_i$
$Si0_2$	340	64.00	217	62	211	62	211
CaO	480	4.00	19	2.28	11	2.28	11
B_20_3	80	2.0	1	2.0	1	2.0	1
K_2O	10	1.00	0.1	4.38	0.43	4.38	0.43
Na_20	150	14.00	21	13.34	19.5	13.34	19.5
Li_2O	460	5.0	23	4.0	18.5	4.0	18.5
TiO_2	250	1.0	2.5	-		-	
ZrO_2	410	3.0	10.5	9.5	39	8.0	33
CrO_3	-590	5.0	-29.5	2.2	-13	-	-
CoO	450	-		0.30	1.5	4.0	18
Na_2SiF_6	130	1.00	1	-	-	-	-
		$\sum c_i * \sigma_i$	265.5	$\sum c_i * \sigma_i$	289	$\sum c_i * \sigma_i$	312

For the temperature of the furnace roasting of 900 ºC, the calculated value of the surface tension of molten enamel No. 261 was 265.5 mN/m, that of UES-200 enamel was 289 mN/m, and for UES-300 enamel, it was 312 mN/m.

2.2. Experimental determination of the surface tension of the studied enamels in light beam heating

The falling-drop method was used to experimentally determine the coefficient of the surface tension of the enamels under light beam heating.

The experimental setup [2–3] providing continuous exposure was used as a source of light beam heating. An optical schematic of the setup is shown in Fig. 1.

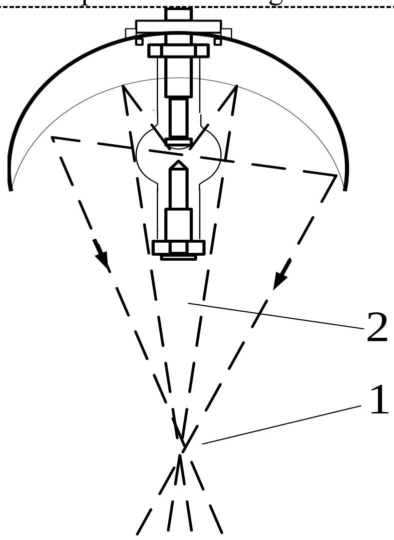

Figure 1. Optical schematic for focusing the light from the xenon arc lamp: area of highest light concentration (1), shadow cone (2).

This optical schematic allows placement of the main part of the enamel rod in the shadow cone under the lower lamp electrode, and that of the bottom end of the rod in the area of the highest light concentration. When arranged this way, the molten drop is formed at the bottom end of the rod under heating by XSAL focused light. It provides an opportunity to study the effect of the XSAL focused light power density on the surface tension of the molten enamel. The technique for determining this dependence is as follows.

The initial length of the rod with the diameter d_1= (1.5–1.8) mm is chosen equal to 10 cm. The shadow cone length is 9 cm. The initial position of the enamel rod is set largely in the shadow cone. The bottom end part of the order of (3–5) d_1 is placed in the area of the highest light concentration. When exposed to XSAL focused light, as the molten drop grows, the rod is moved down to keep the molten drop in the peak-heated region. When the weight of the drop exceeds the surface tension at the point of its detachment from the rod, the drop falls. This process can be described by the expression:

$$\sigma \pi d = mg, \tag{2}$$

where σ is the surface tension of the molten enamel, d is the diameter of the drop neck at the instant of its detachment, m is the drop mass and g is the acceleration of gravity. Hence, the surface tension of the molten enamel can be calculated by the expression:

$$\sigma = \frac{mg}{\pi d} \tag{3}$$

Since the diameter of the drop neck at the instant of its detachment is smaller than the diameter of the enamel rod (d_1), the surface tension of the molten enamel can be experimentally determined by the formula:

$$\sigma = \left(\frac{mg}{\pi d_1}\right)\left(1 + \frac{d_1}{d_2}\right), \qquad (4)$$

where m is the average mass of the drop, d_1 is the diameter of the enamel rod and d_2 is the average diameter of the enamel drop.

After drop detachment, the rod is kept moving down until the formation and subsequent detachment of the next drop. Falling drops are collected in a container filled with water located at a distance of about 1 m under the installation. After that, the average drop diameter for a given XSAL focused light power is measured. The dimension of the drop diameter is taken to determine the surface tension of the molten enamel at a given XSAL focused light power density by formula (4). This procedure is repeated for heating similar enamel rods at different XSAL focused light power densities. After that, the value of the surface tension of the molten enamel is plotted against the XSAL focused light power density.

3. Experimental results and discussion

For each of the enamels, the measurements were performed at lamp currents equal to 10, 15 and 20 A. In the experiment, the diameter of the light spot (1 in Fig.1) was maintained equal to 1 cm. The setup efficiency of the conversion of electrical energy into light is 10%. Therefore, at a current density of the lamp equal to 10 A, the XSAL focused light power density (q) in the area of the highest light emission concentration was about 38 W/cm2, at a lamp current of 15 A, it was 57 W/cm2, and at 20 A, it amounted to77 W/cm2. For enamel No. 261, at 77 W/cm2, the experiment failed as the enamel was melting too fast.

Fig. 2 shows the graph of the experimental results.

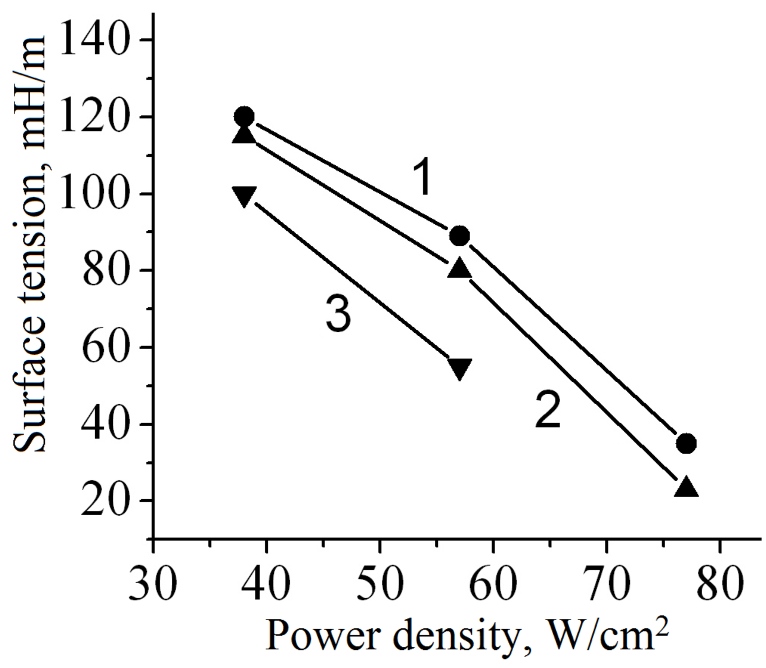

Figure 2. The coefficient of the enamel surface tension versus the light flux power density. UES-300 (1), UES-200 (2) and enamel No. 261(3).

The calculated and experimental values of the enamel surface tension are shown in Table 3.

Table 3. Correlation of the calculated and experimental coefficients of the enamel surface tension

Enamel	σ_1 (mN/m)	$q \approx 38$ (W/cm^2)		$q \approx 57$ (W/cm^2)		$q \approx 77$ (W/cm^2)	
		σ_2	σ_1/σ_2	σ_2	σ_1/σ_2	σ_2	σ_1/σ_2
No. 261	265.5	96	2.7	55	4.8	-	-
UES-200	289	115	2.5	80	3.6	28	10.3
UES-300	312	120	2.6	89	3.5	35	8.9

Note σ_1 is calculated coefficients and σ_2 is experimental coefficients of the enamel surface tension.

Surface tension is a thermodynamic characteristic of the surface of the interface between two phases determined as a portion of the internal energy of the substance. [5] In this case, it is the characteristic of the interface between the molten enamel and gas mixture of vapors of enamel and air. It is known that in conventional furnace heating, the surface tension of the molten enamel depends on the composition of the gaseous mixture above the molten enamel surface. The presence of the water vapor reduces the surface tension of the melt, and high content of carbon dioxide increases the surface tension of the molten enamel [1].

Therefore, the surface tension of the molten enamel depends on the state of the enamel and gaseous mixture of vapors of the enamel and the air above the melt, primarily, on the temperature of the melt and gaseous mixture [6]. The emission spectrum of the xenon short-arc lamp consists of 10% of ultraviolet radiation, 35% of visible radiation and 55% of infrared radiation. This spectral range is effective for heating both metals and metal oxides.

The features of the high-energy effect of exposure to the focused light from the arc source are determined, primarily, by a significant portion of ultraviolet radiation in the polychromatic light flux generated by XSAL. Enamel melting in exposure to the light-beam is accompanied by both strong ionization of the air above the melt and the molten enamel. As the power density increases, the degree of excitation of the melt and the air grows. This explains an anomalous decrease in the surface tension of the molten enamel in heating by polychromatic light.

4. Conclusions

It is found that in light beam heating, the surface tension of enamels is strongly dependent on the power density of exposure, and it can be more than 10 times less than that obtained in furnace heating. When the power density of the light beam is 38 W/cm2, the value of the enamel surface tension is 2.5–2.7 times less than that obtained in furnace heating at 900 ºC, and at a power density of 77 W/cm2, the ratio increases by 8–10 times.

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