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Effect of surface modification by selective laser melting on heat transfer during pool boiling and microjet cooling with water

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Heat transfer on a surface with a relief obtained by selective laser melting of copper powder was experimentally studied under conditions of pool boiling of saturated water and microjet cooling with a subcooled liquid. Microjet cooling was carried out by a distributed system of impact microjet water at subcooling to a saturation temperature of 80°C. In the experiments, 36 impact microjets were used, the nozzles of which, with a diameter of 174 μm, were located at a distance of 1 mm from the modified surface. It has been established that under conditions of saturated boiling, the heat transfer coefficients on the modified surface are 3.5 times higher, and the critical heat flux is 2.8 times higher than for a smooth surface. Under microjet cooling conditions at a jet speed of 1 m/s, the intensification of heat transfer from the modified surface was 35%, and an increase in the maximum heat flux was achieved from 493 W/cm^2 to 770.3 W/cm^2.

Keywords: selective laser melting, heat transfer, critical heat flux, saturated boiling, microjet cooling.

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For operation of electronic equipment it is necessary to remove heat fluxes exceeding 1000 W/cm^2 [1] which will allow maintaining the temperature of heat-stressed devices below a certain limit for ensuring the performance of prospective microprocessors, power electronics of hybrid cars, X-ray medical equipment, since overheating results in a decrease of device performance and their failure. Active methods of heat removal from heat-stressed devices based on the use of microchannels, impact jets and sprays, including boiling jets [2], can remove high heat fluxes and reduce temperature heterogeneity at low mass velocities [3–5]. The advantage of impact jets is the possibility of applying a large subcooling to the saturation temperature, which significantly increases the critical heat flux (CHF) in case of boiling [6].

The use of two-phase impact jets is a promising technology for dissipation of the heat from small-sized sources, which allow maintaining the required temperature at high thermal load due to the latent heat of vaporization. It was found in [7] that the CHF does not exceed 25 W/cm^2 in case of cooling of a flat surface with impact jets of a dielectric liquid HFE 7100, which is significantly less than the value necessary to ensure the operability of promising heat-stressed devices (1000 W/cm^2). A promising coolant for removing large heat fluxes is water. The CHF reached 450 W/cm^2 at a liquid velocity in jets of 3.54m/s for a system of 2×2 water jets with a diameter of 1 mm and underheating of 8°C [8].

Boiling determines the heat transfer in the conditions of high thermal loads, and the methods of intensification of the heat transfer in case of boiling can be used to intensify heat transfer during cooling by impact jets. For instance, the intensification of heat transfer during boiling of water on a surface with porous copper columns obtained by sintering powder in a furnace was studied in [9].

The values of CHF of 435 W/cm^2 and the heat transfer coefficient of 200 kW/(m$^2 \cdot$ K) were obtained. This shows the potential of using porous surfaces with a modulated structure to increase the CHF. The analysis of literary sources [10] shows that the problem of increase of the CHF for heat-stressed devices- is still relevant, and it is necessary to use of modern methods of modification of the cooled surface to solve it.

The aim of this paper is to experimentally study the effect of surface modification using additive layer-by-layer melting/sintering of copper powder materials (SLS/SLM method) on the critical heat flux and heat transfer coefficients for saturated pool boiling as well as for cooling by a distributed system of water micro-jets The specific features of the work performed include the use of additive 3D technology for metal [11] for obtaining a modulated porous structure on the surface, a small distance from the nozzles to the cooled surface equal to 1 mm, a jet velocity of 1 m/s and subcooling of the liquid to the saturation temperature of 80°C.

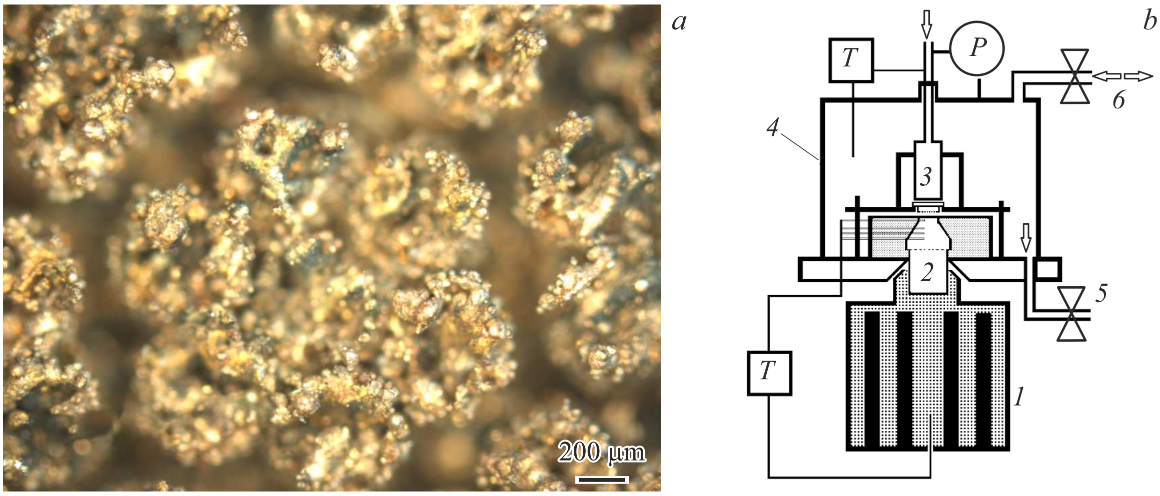

Figure 1. Experimental setup. *a* — the image of the structure element. *b* —the layout of the experimental site. *1* —the heating system, *2* — the measuring unit, *3* —the jet shaper, *4* — the outer casing, *5* —the drain valve, *6* — nitrogen supply — the steam release (in experiments on boiling in pool boiling).

The structure of the modified surface is a hexagonal ensemble of seven closely spaced protrusions made by SLS/SLM-method and located on a porous substrate. Cylindrical protrusions with a height of 250 μm are located on a substrate with a thickness of 250 μm. The diameter of the zone of sintering of a single protrusion is 0.5 mm, the distance between the centers of adjacent protrusions in a single cell is 0.6 mm, the distance between the central protrusions in adjacent cells is 1.8 mm. The photographic image of the surface is shown in Fig. 1, *a*. This structure is formed on the surface of the measuring unit used to measure the heat transfer. The powder of JSC „Polema" from PR-BrX alloy with a copper content of more than 99% and a dispersion of 30–60 μm was used to form the structure. The following processing parameters were used: plot raster 50 μm, layer thickness 100 μm, scanning speed 0.5 m/s, size of the focused laser spot in the processing plane 70 μm, laser radiation power 150 W. The measurement of surface characteristics on an optical interferometer showed that the height difference at the projections is 70 μm.

The setup for experiments is a closed circuit with a plunger pump, a pressure pulsation damper, a filter, a turbine flow sensor, a heat exchanger setting the temperature of the coolant, a working section and a liquid cooler. The working section is a flange closed by a casing, to which a heat supply system with a measuring unit is connected from below through a paronite gasket, above which a microjet shaper is located (Fig. 1, *b*).

A casing with a diameter of 100 mm and a height of 100 mm forms a working chamber in which temperature and pressure are measured. A nitrogen atmosphere with a pressure close to atmospheric is maintained in the work area for preventing any contact of the hot work surface with atmospheric oxygen. Heaters and additional thermal insulation are placed on top of the casing. There are holes for measuring pressure and temperature and for supplying liquid and nitrogen at the upper end of the casing.

The heat supply system constitutes a copper cylinder into which eight heating cartridges are pressed with a maximum heat dissipation capacity of 220 W each and a maximum operating temperature of 700°C. There is a landing hole in the upper end of the system for replaceable measuring units with modified surface. The measuring unit is thermally insulated with a fluoroplastic washer with a diameter of 40 mm and sealed with a high-temperature sealant. The measuring units are made in the form of a M1 grade copper cylinder with a tapered upper part. The outer diameter of the cylinder is 19 mm, the diameter of the cooled surface is 8 mm. There are four measuring insulated thermocouples with a diameter of 0.5 mm along the axis of the tapered part. The average temperature T_w and the heat flux q_w on the heat transfer surface are determined by the measured temperature gradient based on the solution of the thermal conductivity equation for a given geometry.

The heat transfer characteristics are acquired for two measuring units. The first unit with a flat surface was additionally coated with a nickel protective coating with a thickness of 5 μm. The second unit had a modified heat transfer surface. The temperature and heat flux on the unit with the modified surface were determined on the base surface on which the structure was applied.

The microjet shaper has 36 evenly distributed nozzles with a diameter of $174 \pm 3\,\mu$m, located at a distance of 1 mm from each other, its detailed description is provided in [4]. The gap between the microjet shaper and the cooled surface is 1 mm. The measuring system is vacuum-treated and filled with nitrogen prior to the experiments, after which it is refilled with distilled water that was degassed by vacuuming. The microjet shaper was

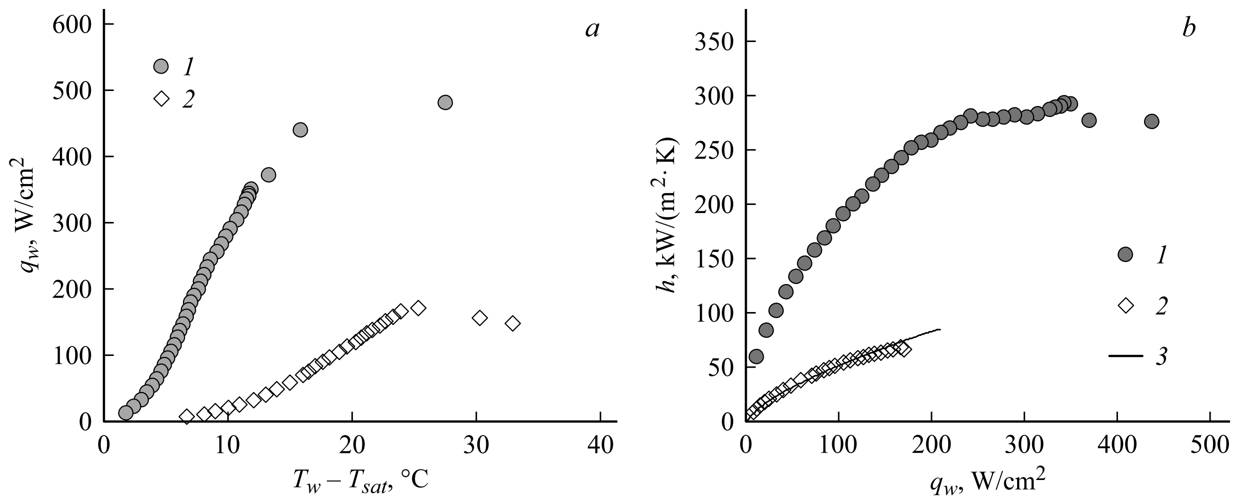

Figure 2. Pool boiling heat transfer. *a* — the dependence of the heat flux on the wall overheating. *b* — the dependence of the heat transfer coefficient on the heat flux. Points *1* — the surface with structure, points *2* — the flat surface, line *3* — calculation according to [12].

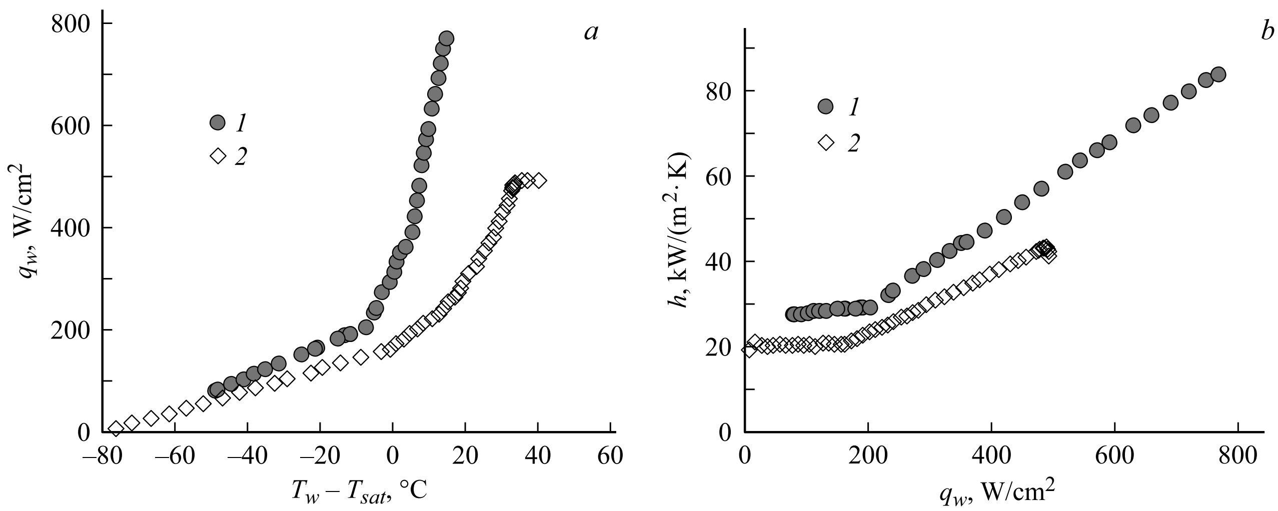

Figure 3. Heat transfer in case of cooling by submerged impact micro-jets at a velocity of 1 m/s. *a* — the dependence of the heat fflux on the wall overheating. *b* — the dependence of the heat transfer coefficient on the heat flux. Points *1* indicate the modified surface, points *2* indicate the flat surface.

removed from the site when measuring pool boiling heat transfer, the volume of the measuring site was completely filled with liquid which was heated to the saturation temperature.

Fig. 2 *a* shows the boiling curves acquired for modified and flat surfaces. The CHF for the flat surface is 170 W/cm^2, and the CHF for the modified surface is 480 W/cm^2, which is 2.8 times more than CHF for the flat surface. Fig. 2, *b* shows the dependence of the heat transfer coefficient h, defined as $h = q_w/(T_w - T_{sat})$ (where T_{sat} is the saturation temperature at the measured pressure) on the heat flux. It can be seen that the heat transfer coefficients in case of boiling on the modified surface significantly exceed the heat transfer coefficients for the flat surface.

The dependences of the heat flux on the overheating of the wall for flat and modified surfaces in case of cooling by impact microjets are shown in Fig. 3, *a*. The initial velocity of the liquid in the jets is 1 m/s, the coolant temperature is 23 ± 1°C. It can be seen that the boiling on the modified surface takes place with significantly lower surface overheating than in the case of the flat surface. The CHF in case cooling of the flat surface by impact microjets is 493 W/cm^2 when the wall is overheated relative to the saturation temperature of 35°C. The CHF was not achieved in case of cooling of the modified surface because of the limitation of the temperature of the heating system, the maximum heat flux was ~ 770 W/cm^2 in case of the wall overheating of 14.7°C. Fig. 3, *b* shows the dependence of the heat transfer coefficients, defined as $h = q_w/(T_w - T_0)$ (where T_0 — the temperature of the liquid jet entering the shaper) on the heat flux for flat and modified surfaces. It can be seen that the heat transfer coefficient for the modified surface is up to 40% higher than the heat transfer coefficient for the flat surface.

These data demonstrate that the developed structure of hexagonal porous protrusions, mad using the SLS/SLM method, significantly reduces wall overheating and increases heat transfer coefficients by 3.5 times for saturated pool boiling of water. The achieved heat flux in case of boiling is 10% higher, and the heat transfer coefficients are 1.5 times higher than the maximum values obtained in [9] for the modulated surface with porous copper columns. Hexagonal porous protrusions also demonstrated high efficiency in case of cooling of the modified surface with a distributed system of impact microjets. The achieved value of the heat flux exceeds 770 W/cm^2 for the velocity of liquid 1 m/s in jets. Such a heat flux for the flat surface is achieved at a significantly higher jet velocity, which results in an increase of the energy costs for the formation of jets and an increase of the dynamic impact on the cooled device. This shows the prospects of the proposed surface modification method for intensifying heat transfer and increasing the maximum heat fluxes necessary to ensure the performance of prospective heat-stressed devices, including microelectronic devices.

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Conflict of interest

The authors declare that they have no conflict of interest.

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