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PRODUCTION TECHNOLOGY AND PROPERTIES OF LAYERED COMPOSITE COATINGS USED FOR BOILING HEAT TRANSFER AUGMENTATION

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The paper presents the production technology and properties of layered metallic composites in view of their use for the creation of highly efficient phase-change heat exchangers. It discusses the experimental results of the boiling heat transfer of distilled water and ethanol under atmospheric pressure on copper substrates on which a metal mesh layer, which augments heat transfer via boiling, was applied by sintering. The sintering technology enables durable bonds to be obtained between the joined elements, which results in proper strength properties. The meshes used in the experiments were made of bronze, brass and copper. The heat transfer results indicate that all the samples with the additional layer showed better performance – they dissipated more heat at the same temperature difference in comparison to the smooth surface without any mesh applied onto it, while the copper mesh outperformed the others. It seems to be linked to the highest thermal conductivity of this material in relation to the copper alloys considered in the study.

Keywords: boiling heat transfer, composite heat exchangers, metallic layers

INTRODUCTION

Nowadays, the advances in the technology and development of devices that require a high level cooling (for example computer processing units, refrigeration systems) put pressure on scientists and engineers to search for more efficient methods of heat removal and much scientific effort is being made in the area of heat exchangers [1, 2]. Such novel devices are necessary so that higher heat fluxes could be dissipated. It can be achieved in many ways, for example, with nanofluids [3] or specially prepared surfaces that can enhance heat exchange processes especially during phase change, which is highly effective [4, 5]. Those surfaces are often prepared using mechanical means [6], plasma spraying [7], powder metallurgy [8] or the sintering technology of metal meshes. In the case of sintering, wire mesh layers of various metals are typically applied on substrates to produce a heat exchanging unit. This technology enables durable bonds to be made between the elements, and thus the heat exchangers are able to sustain vibrations and stress in their normal operational cycles. If meshes made of various metals are used, a composite heat exchanger is produced.

Orzechowski and Orman [9] analysed composite non-isothermal heat exchangers in the form of fins made with a copper base, on which two layers of mesh were applied: one was made of copper and the other of stainless steel. Both had a wire diameter of 0.20 mm and distance between the wires of 0.32 mm. Two samples were produced with different relative locations of the meshes on top of each other. It occurred that the sample with the copper mesh located directly on the copper base (with the steel mesh on top) performed better than in the case of the sample with the steel mesh situated directly on the copper base (with the copper mesh on top of the steel mesh). This observation was made with both water and ethanol as boiling liquids. In another paper by the same authors [10] the temperature gradient along a fin with a two-layer mesh coating of the same materials (copper and steel) was compared with a smooth fin. Significant improvement in the heat transfer coefficient was observed for both the composite heat exchangers in comparison to the smooth fin (without any meshes). Białek et al. [11] analysed the performance of a composite heat exchanger in the form of a copper disk covered with bronze mesh layers. The wire diameters of the meshes were 0.10 mm and 0.25 mm, while the distances between them were 0.16 mm and 0.40 mm, respectively. The brass alloy was composed of copper (65%), nickel (12%) and lead (23%). The system with the larger wire diameter proved to be more efficient in the case of both water and ethanol boiling. The comparison of this sample (0.25 mm wire diameter) with a pin-fin sample of the same height was conducted by Białek and Stokowiec [12]. The results indicated that the sample containing pin-fins (made of copper) dissipated more heat than the meshed surface (a composite with a copper base and brass mesh).

Kumar et al. [13] experimented with heat exchangers consisting of stainless steel tubes wrapped with different sizes of stainless steel wire mesh materials under water boiling conditions and heat flux up to 55 kW/m^2. It was found that the tubes with the mesh dissipated more heat than the plain tubes, but only at low heat fluxes (not exceeding 30 kW/m^2). The authors attributed the better performance to the improved retention time of the bubbles over the tubes and the increase in turbulence created around them. Orzechowski [14] performed tests on the non-isothermal surface of a copper fin covered with copper mesh 0.2 mm in wire diameter using FC-72 as the working agent. It was stated that the initiating point of nucleate boiling was reduced by 2-3 K in relation to the smooth fin. Moreover, the meshed fin dissipated more heat. The author concluded that the mesh anisotropic properties can affect the external surface superheat by up to 5 K.

At the same time, the combined effect of applying meshes and extended surfaces has also been investigated. Pastuszko [15] studied water and ethanol boiling on surfaces made of copper tunnels on which meshes were sintered and noticed that the heat transfer coefficients were even ca. three times larger than those typical of the tunnels without the meshes. On the other hand, the experiments in [16] on ultra-thin heat pipes with a single-layer wire mesh core showed that the maximal value of temperature fluctuation is affected by thermal loads, while the period of this fluctuation is an integral multiple of the working fluid flow within the heat exchanger. Very recently, Yin et al. [17] conducted research on copper surfaces with micro or micro/nanocomposite structures produced by sintering copper mesh, as well as thermal oxidation techniques. It was reported that the production method influenced the growth rate, departure frequency and diameter of the vapour bubbles, depending on the boiling agents used in the study.

The industrial use of composite heat exchangers is increasingly more common. Caccia et al. [18] discussed the use of ceramic-metal composites as high temperature heat exchangers for use in concentrated solar power plants. They were able to increase the efficiency of the whole system to over twenty percent, combined with the reduced costs. Generally, the renewable energy sector is an important market for efficient heat exchangers [19, 20]. Thus, much scientific interest is now seen there.

The present paper discusses the performance of composite heat exchangers made of copper and its alloys (brass and bronze) under pool boiling conditions of water and ethanol, as well as the mechanical and technological aspects of the production and operational stages. The insight into this issue could provide the basis for the development and practical use of composite phase change heat exchangers.

The sintering process enables strong bonds to be formed between metals/alloys that turn into a uniform structure. In the paper three types of materials, namely copper and its alloys, were used to make metal matrix composites. The compositions of these materials are presented in Table 1.

PRODUCTION TECHNOLOGY OF THE COMPOSITE HEAT EXCHANGERS

TABLE 1. **Composition of copper and its alloys**

Copper [21]:								
Ni	Sn	Sb	Pb	Zn	Fe	As	Bi	Cu
≥ 0.002	≥ 0.002	≥ 0.002	≥ 0.005	≥ 0.003	≥ 0.005	≥ 0.002	≥ 0.001	99.9

Bronze [22]:							
Cu	Ni	Sn	Pb	Zn	Fe	P	Other
92	≤ 0.2	5.5 ÷ 7.0	< 0,02	< 0.2	≤ 0.1	0.01 ÷ 0.4	≤ 0.2

Brass [22]:						
Cu	Zn	Ni	Sn	Pb	Fe	Al
62.3	37	≤ 0.3	≤ 0.1	≤ 0.1	≤ 0.1	≤ 0.02

The composite structures were made using sintering technology in a special furnace in a reduction atmosphere of a controlled composition. A detailed diagram of the sintering apparatus was presented by the authors in [23]. The process consisted in enabling the flow of liquid ammonia into an electric furnace through a filter into a vaporizer. The ammonia flowed to a retort with a catalyst. During the process, heat was released due to diffusion. After sintering, the samples were mechanically moved in the moulds to the cooling zone, where the same reduction atmosphere was maintained to prevent oxidation. Cooling to ambient temperature was conducted using a coil-type heat exchanger, inside which tap water circulated. The cooling time was about 25 – 30 minutes. The parameters regulating the sintering process were the flow rate of the gas and temperature in the heating zone. The temperature was set at 0.8 of the melting temperature of the material that has the lowest melting temperature. The sintering activity rose with the increase in the contact area between the base material and the mesh, as well as the sintering temperature and duration. The values of the production parameters were determined experimentally and used for all the samples in the experiment.

DISCUSSION OF THE STRENGTH PROPERTIES OF THE COMPOSITE HEAT EXCHANGERS

The quality of the bonds generated during the sintering of various metallic materials influences the strength properties of the produced samples. High production quality means that the heat exchangers produced during the process will be resistant to mechanical factors, which is important as they operate in various technological devices, machinery, vehicles and can be subjected to vibrations or various forms of stress and loading. Preventing detachment of the microstructure from the base is particularly important. Table 2 presents the results of the assessment of adhesion strength of the copper base with the meshes of different materials (brass, bronze, copper).

TABLE 2. **Adhesion strength (S) of metallic composite materials (copper and its alloys)**

Material	S (N)
Copper base	60-78
Copper base with the copper mesh	53
Copper base with the bronze mesh	32
Copper base with the brass mesh	27

The flow of heat [24] caused by the development of the surface (for example due to a rapid increase in the contact area between the base and the meshes) can lead to the creation of internal thermal pathways. Those thermal pathways are in permanent contact and act as reinforcement [25]. A sudden increase in conductivity as the share of one phase rises is linked with reaching the percolation threshold [26], defined as a certain critical number of percolation joints that lead to the development of a thermal layer which is formed from macroscopic parts of the material.

The meshes of various copper alloys are responsible for additional thermal phenomena related to their composition in the composite structure [27]. Additional mechanisms of heat storage and release occur, for example, as a consequence of phase transition [28]. Even in the case of an initially uniform material, when the phase change occurs within the boundary of individual phases, a loss of its uniformity takes place and complex heat transfer is initiated. Despite the many similarities of the meshes made of copper and copper alloys which were sintered onto the copper disks, they have different properties. Pure copper is quite resistant and has high strength properties, while some of the phosphor bronze components impact its tensile strength and resistance to wear.

The area of the smooth surface can be extended using the sintering process, during which structures made of copper and its alloys are applied onto the base material (in this case copper). Figure 1 presents the cohesion strength (S) of the copper structure determined in the tensile test (as discussed by the authors in [23]).

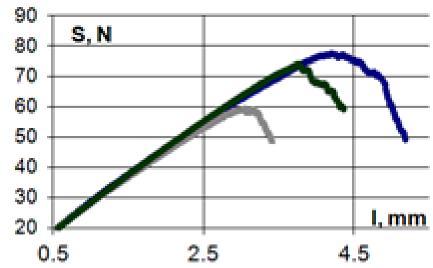


Fig. 1. Cohesion strength of copper element (three measurements) [23]

The introduction of the bronze and brass meshes onto the copper substrate reduced the adhesion properties of the composite structures (Table 2). The cohesion strength of the same type of copper structure was 71.3 N [23], while the strength of the porous structure with the copper mesh was reduced by ca. 25%. Higher reduction levels were observed in the case of applying the bronze and brass meshes (by 40% and 60%, respectively). First, destruction of the mesh occurs (alloys first, then pure copper). The strength of the copper capillary-porous layer is higher than that of the sintered copper mesh.

After reaching maximal loading (cohesion strength), the mesh did not detach from the copper base. During deformation of the structure, stress increases within a given volume. First, it leads to destruction of the weakest element of the structure (which is the location where the mesh is attached to the copper base), followed by destruction of the whole sample. It results from the combined influence of both the components of the structure according to Hook's law.

In the process of sintering, diffusion bridges are created; metallographic analyses enabled the number and quality of the bonds developed between the copper substrates and the meshes to be studied. The analyses were performed at random sites within the structures. The distribution of the width of the bridges occurred to be normal.

SAMPLES AND HEAT TRANSFER EXPERIMENTAL METHOD

The investigations focused on determining the heat flux released from the heat exchangers, which were made on a copper base (a disc 3 cm in diameter) on which copper, brass and bronze meshes were applied by sintering. The wire diameter of the meshes was 0.28 mm, while the aperture (distance between the wires) was 0.5 mm. Figure 2a presents a photo of the brass mesh applied onto the copper surface, while Figure 2b shows the details of the connection between the mesh and the base.

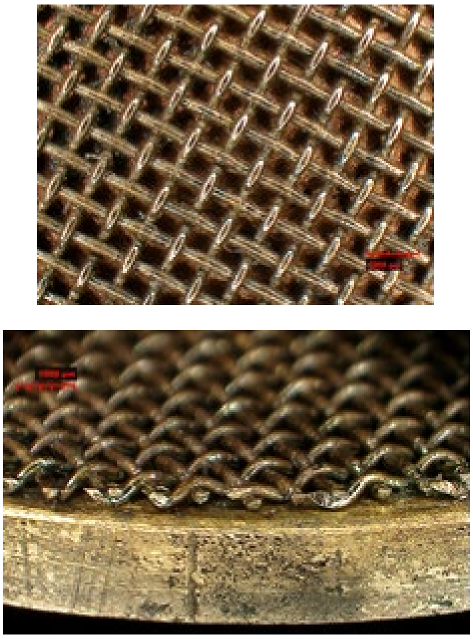


Fig. 2. Brass mesh sintered on copper base

The measurements were made on an experimental stand where the investigated element of the heat exchanger (no. 8) is located on the heating block (Fig. 3). The energy is supplied from below, where an electric heater generates heat which is conducted through the copper block (no. 7) to the sample. The temperature of the liquid (distilled water and ethyl alcohol) in the vessel above the sample is increased slowly until it reaches the saturation temperature (T_b) and starts to boil. The idea behind the experiment is to record the performance of the sample in such a way that for the increased thermal energy from the electric heater (heat flux – q), the temperature of the sample (T_s) also increases in certain steps. Both of these parameters are used to draw boiling curves, which are a graphic representation of the thermal performance of the heat exchangers.

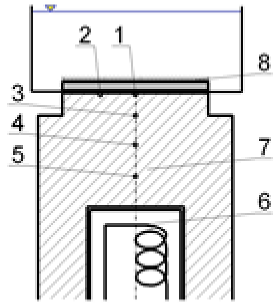
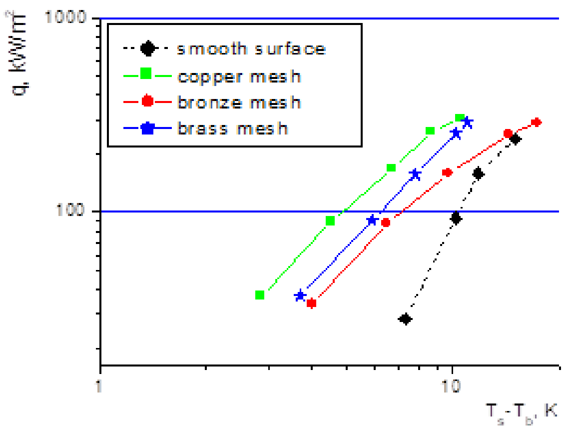


Fig. 3. Main experimental unit, where 1, 2 are thermocouples under the sample, 3, 4, 5 – thermocouples in heating block axis, 6 – electric cartridge heater, 7 – main copper block, 8 – investigated meshed sample

After each increase in the heat flux, some time is needed for the surface temperature to stabilize. The temperature readings were made only after the steady state was reached. In the course of the experiment vapour was generated; however, due to cooling of the condensate, the level of liquid in the vessel remained constant.

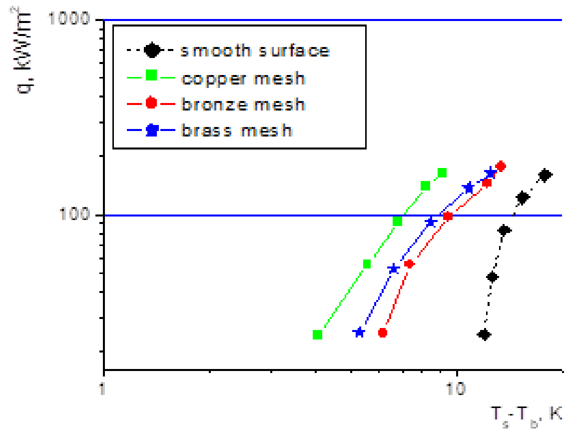
HEAT TRANSFER TEST RESULTS

The experiments consisted in increasing the thermal power supplied to the sample (which raised the temperature of the sample (T_s) over the saturation/boiling temperature of the liquid (T_b) – this difference is referred to as superheat). Figure 4 presents the performance of the samples for two boiling agents: water and ethanol.



a)

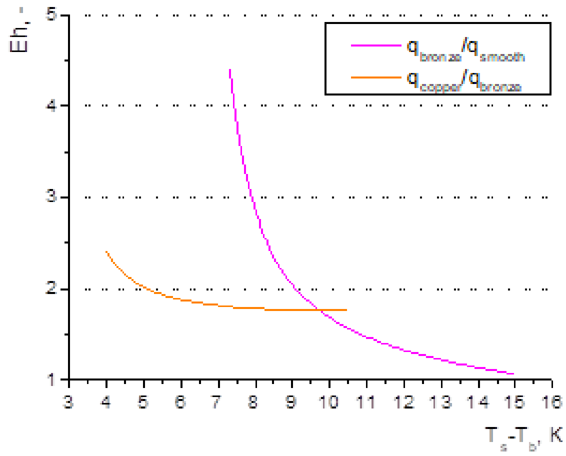
Fig. 4. ⟶



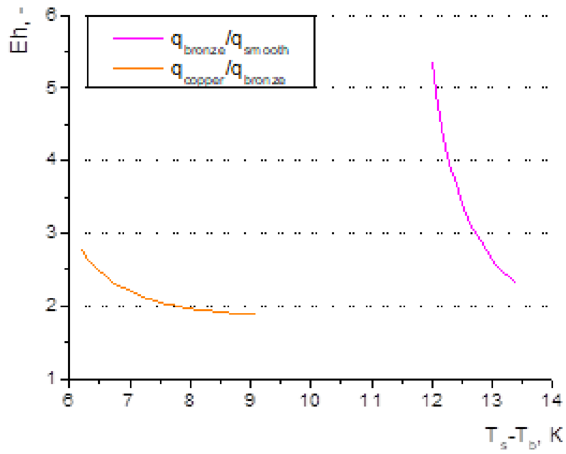
b)

Fig. 4. Dependence of heat flux as a function of superheat for: a) distilled water, b) ethyl alcohol

As can be seen, all the samples with the mesh showed better performance – they dissipated more heat at the same value of superheat (which is defined as the difference between surface temperature T_s and boiling temperature T_b) in comparison to the smooth surface without any mesh applied onto it. Nevertheless, this augmentation effect is best visible for small temperature differences (for a low temperature of the sample) and, as the temperature and heat flux grow, the performance of the meshed samples seems to become more similar to the performance of the smooth surface. The details of this phenomenon can be seen in Figure 5. It shows the ratio of the values of heat flux transferred from the samples to the liquid pool at the same value of superheat. At the same time, Figure 4 shows that the bronze sample proved to be the least efficient from all the meshed surfaces, while the copper mesh outperformed the others. It seems to be related to the thermal conductivity value, which equals 393 W/(mK) for copper, while for brass it is 120 W/(mK) and for bronze 50 W/(mK) [22]. Thus, it can be concluded that if the geometrical parameters of the meshes are the same, the most efficient heat transfer from the base of the sample and afterwards through the mesh is attributed to the performance of the heater made with the copper base and the copper mesh.



a)



b)

Fig. 5. Enhancement ratio of bronze mesh over smooth surface and copper mesh over bronze mesh for: a) distilled water, b) ethyl alcohol (based on data from Fig. 4 after data smoothing procedure, which involved determining equations for heat flux with least-squares fitting method – based on data points in Fig 4 for each sample, and then calculating Eh with a step of 0.1K)

The bronze sample proved to be the least efficient of all the meshed surfaces, nonetheless, it still outperformed the smooth surface. The heat flux dissipated from the bronze mesh was up to 4.4 and 5.3 times higher than that of the smooth surface for water and ethanol boiling, respectively. The differences in the heat flux transferred from the copper and bronze mesh were not so significant, however noticeable. The enhancement ratio, defined as the ratio of heat fluxes of different surfaces at the same temperature difference (Fig. 5a and b) in this case was up to 2.4 and 2.8 for water and ethanol, respectively. Here, the largest differences occurred in the range of low superheat values as in the previous case. It needs to be noted that at high temperatures and heat fluxes the boiling phenomenon is very intense. A considerable number of vapour bubbles are created, causing large mixing currents in the vessel. Thus, convective forces might be more dominant here as opposed to the conduction mode of heat transfer, which seems to be more vital in the low range of superheats.

A different problem is proper modelling of the thermal properties of composite heat exchangers during boiling. Various methods are used [29, 30] and many models are available in the literature. Selection of the most accurate one depends on a number of factors. A new study by the authors is being developed with regard to the heat transfer model of boiling that would be designed for composite heat exchangers.

The main limitation of the present study is the use of two boiling agents. The results obtained for other agents (natural or chemically synthesized) could be different; nevertheless, the general trend of the results and the applicability of the conclusions should not differ significantly. Moreover, the experiments were limited to the nucleate boiling mode of heat transfer. This mode is of most practical potential in the design and operation of heat exchangers and, although this might also be considered as a limitation, conducting the tests in the transition or film boiling regimes would not be justified from the engineering point of view.

CONCLUSIONS

The production of composite heat exchangers using sintering technology offers a number of advantages. The durability of the structure enables its application in various technological devices, while the heat augmentation potential makes it a viable option for phase-change heat exchangers. It was determined that for both boiling agents (water and ethyl alcohol), the heat flux values recorded for the surfaces of the meshes were higher than for the reference surface without any coating. The largest impact was observed for smaller temperature differences, while at higher ones this effect seemed to diminish. The performance of the heat exchangers depended on their thermal properties and thermal conductivity seems to be the most crucial parameter. The mesh material having the highest conductivity outperformed the others.

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