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Heat Conductivity of the Material Obtained by Melting Steel on the Flame Supersonic Jet of Mix of Air–Propane

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In this article presented results of measurements of heat conductivity coefficient of the porous material, obtained by melting industrial steel grade 'Steel 3' in the range of temperatures from −140 to +400°C measured on ИТ-λ-400 installation. Comparison of the obtained results with data existing in scientific literatures on porous steel became with various degrees of porosity, showed their good agreement. Heat conductivity of such porous samples unlike well-known mechanisms (electronic and phonon) heat conductivity of metals. Heat transfer in this material is explained by mechanisms, which include transfer through solid pore walls and through gases being inside pore.

Key words: mix of air–propane, supersonic jet, flame, steel, heat conductivity, pore, electron, and phonon.

У статті наведено результати вимірювань коефіцієнта теплопровідности пористого матеріялу, одержаного при топленні промислової криці марки «Сталь 3» в діяпазоні температур від −140 до +400°C, виміряного на установці ИТ-λ-400. Порівняння одержаних результатів з наявними в науковій літературі даними з пористої криці з різним ступенем пористости показали їх добрий збіг. Теплопровідність таких пористих зразків відрізня-

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ється від добре відомих механізмів (електронної та фононної) теплопровідности металів. Теплопередача в цьому матеріялі пояснюється механізмами, які включають передачу через тверді стінки пор і через гази, що знаходяться всередині пор.

Ключові слова: суміш повітря–пропан, надзвуковий струмінь, полум'я, криця, теплопровідність, пори, електрони та фонони.

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1. INTRODUCTION

In modern materials science, interest is gradually growing in obtaining new materials with predetermined properties and their application for solving various applied problems. Certain successes have been achieved in the technology of obtaining porous materials with unique physicochemical, mechanical, electrical, and magnetic properties. Although there are various natural porous materials in nature, in recent years, the interest of researchers around the world is riveted to the artificial synthesis of such materials by various methods [1]. There are many types of porous and foamy materials with properties not typical of conventional materials, such as low density and high specific surface area [2]. These materials are used for the manufacture of lightweight structures, as biomaterials for medical orthopaedics, various filters, thermal insulators, catalysts, heat carriers, electrodes, vibration and acoustic energy dampers, shock energy absorbers, *etc.* [3]. Porous materials with such properties are successfully used in various thermal installations as heat exchangers, heat transfer fluids for heat pipes [4].

2. EXPERIMENTAL DETAILS

To study the temperature dependence of the thermal conductivity of the porous materials synthesized by melting steel on the flame supersonic jet of mix of air-propane based on industrial steel grade 'Steel 3', was used an IT-λ-400 device designed to measure the thermal conductivity of solid materials. The measurement technique and processing of their results are described in detail in [5]. With this measurement technique, the relative measurement error was 3–5%.

For the synthesis of a porous material based on industrial steel, a special furnace made of refractory bricks was used. For moulding, special cylindrical shapes were made based on fine-grained graphite or from refractory bricks with a height of 3 mm and a diameter of 16 mm, which was firmly mounted on the focus of the burner flame.

After that, a special burner was installed in front of the furnace, so that the focus of the flame of the supersonic flow exactly coincided with the centre of the cylindrical shape.

After that, using a special nozzle creating a supersonic flow of gases, a mixture of air and propane was ignited in a flame of which the temperature can reach up to 2300°C. (For melting steel, depending on the grade, a temperature in the range of 1550–1600°C is required).

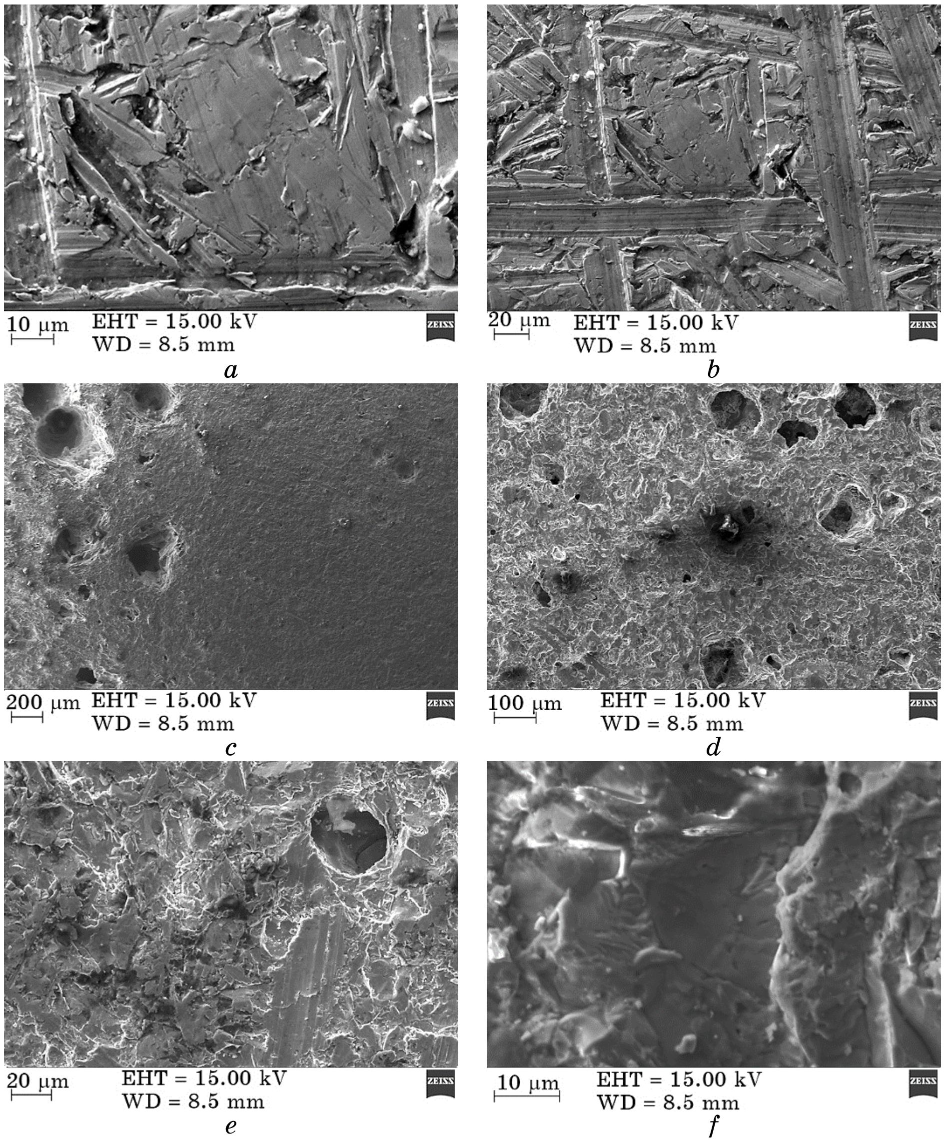
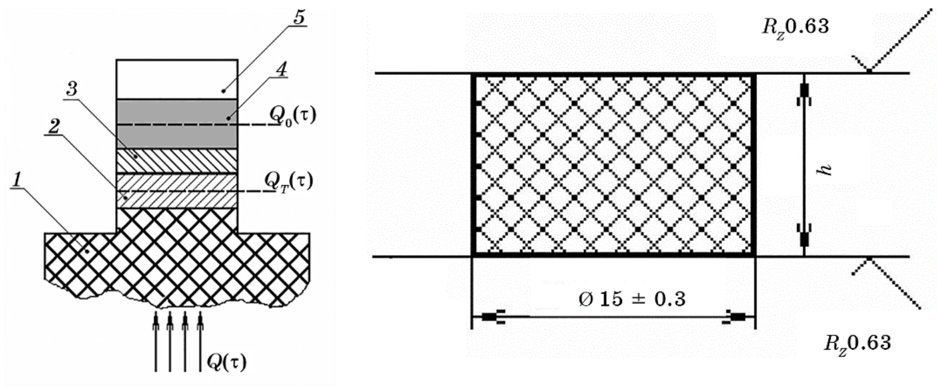


Fig. 1. Images of the surface topology obtained using a scanning electron microscope: *a*, *b*—the sample of initial steel before melting; *c*, *d*, *e*, *f*—images pores with differed resolution.

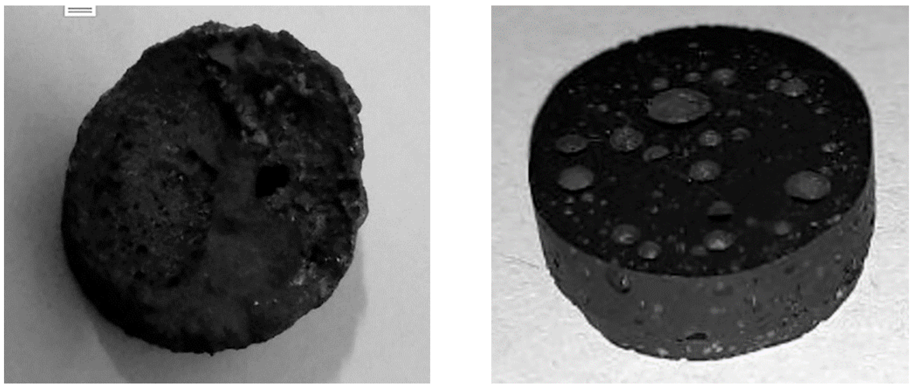


a *b*

Fig. 2. Scheme of heat flow propagation in the chosen method: *1*—base, *2*—plate, *3*—pin plate, *4*—test sample, *5*—rod (*a*); the requirement for the size (diameter) and the smoothness of the sample surface (*b*).

After melting, the liquid steel flows into the mould and fills it. After extinguishing the flame, the mould filled with liquid metal is cooled naturally to room temperature and then the shaped sample is taken out of the mould. At the same time, the synthesized samples had a porous structure (Fig. 1). Measurement of their porosity according to the standard technique showed 68% of the porosity of the samples obtained.

To study the temperature dependence of the synthesized porous material based on steel, samples were made with the form and geometric dimensions shown as in Fig. 2, *b*. For this, cylindrical shape samples



a *b*

Fig. 3. Images of the synthesized samples: immediately after demolding (*a*); after mechanical cutting with a diamond disc (*b*).

with dimensions $h = 2 \pm 0.1$ mm and $d = 15 \pm 0.3$ mm were made using a 3D diamond cutting machine (Fig. 3).

To ensure good thermal contact between the elements of the cell and the test sample, the surface of the sample was polished to a level of ± 0.65 μm.

To reduce the harmful effect of the roughness of the contacting surfaces of the standard and the sample on the measurement accuracy, as well as to improve their thermal contact, a high-temperature paste was used.

3. RESULTS AND DISCUSSION

In Figure 4 presents the results of experiments on the temperature dependence of the thermal conductivity coefficient of porous steel samples with different degrees of porosity (60 and 68%) synthesized by melting industrial steel grade 'Steel 3' in the flame of a supersonic flow of an air-propane mixture. In the same Figure, for comparison, the temperature dependences of the thermal conductivity coefficient of porous steel with different degrees of porosity obtained by other technologies are shown. Data taken from [3].

As can be seen from Figure 4 the thermal conductivity coefficients of the porous steel samples synthesized by us with a porosity of 60 and 68% are less than 1.3 and 2.6 times in comparison with the thermal

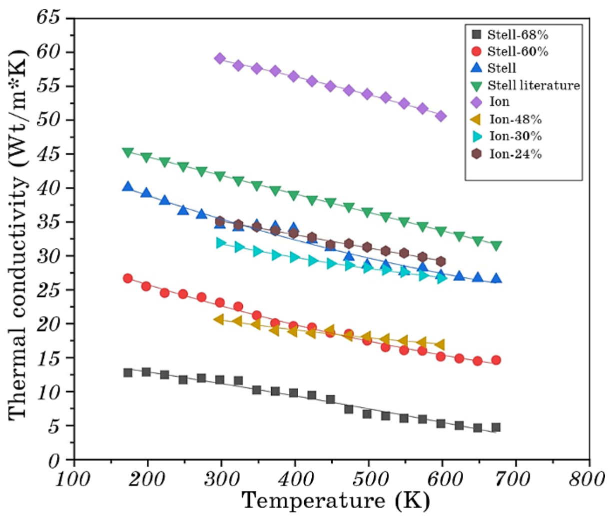


Fig. 4. Temperature dependences of the thermal conductivity coefficient of the synthesized samples with porosity of 60% and 68% and the initial steel. Here are the published data [3] of the temperature dependence of steel grade 'Steel 3'.

conductivity coefficient of the initial 'Steel 3' steel sample, respectively. In addition, the curves of the temperature dependences in the investigated temperature region of the porous samples synthesized by melting steel on the flame supersonic jet of mix of air–propane and the porous samples synthesized by other technologies is described by different dependences. So, for example, the temperature dependence of a steel sample with 48% porosity obtained by hot pressing can be approximated by a functional dependence of the form $Q(t) = 26.33 - 0.0213t + 1.275 \cdot 10^{-0.5}t^2$, while those for the porous samples synthesized by melting steel on the flame supersonic jet of mix of air-propane are approximated dependence of the form $Q(t) = 0.0403t + 1.7972 \cdot 10^{-0.5}t^2$. It should be noted that there is some similarity in the general form of these dependences, and this, in turn, shows the similarity of the mechanisms of thermal conductivity and temperature dependences of the thermal conductivity coefficients of the above samples. The difference in the thermal conductivity coefficient of a porous sample synthesized in a supersonic flame of an air-propane mixture with a porosity of 60% compared to porous steel with the same porosity, but synthesized by other methods, turned out to be about 1.33 times less.

To explain the obtained results, it is necessary to take into account the dependence of the thermal conductivity of materials on the following important thermodynamic and acoustic properties, such as: temperature conductivity, heat capacity, density, speed of sound propagation. The effective coefficient of thermal conductivity of materials can be calculated using the above parameters.

Predicting the thermal conductivity of porous materials, even after many theoretical simplifications, is a difficult and sometimes impossible problem. The thermal conductivity of porous materials mainly depends on the pore structure (opening or closing of the cell), their geometric configuration (spherical, cylindrical, *etc.*), the relative orientation of the pores, location and distribution, pore size, type of crack, *etc.* and therefore theoretical modelling heat transfer processes and predicting is a very difficult problem.

It is known that the process of heat transfer in solids mainly depends on their crystal structure, electrical and magnetic properties and is transmitted mainly by phonons and free electrons [13]. The thermal conductivity of porous materials is transmitted by three mechanisms: electronic and phonon, along solid matrix (pore walls) [6–10], convective, through gases filling the pores [11, 12], and radiant mechanisms [14–17]. The thermal conductivity of metals is well explained using of the classical electronic theory [13, 18]. The observed discrepancy between theory and experiments was eliminated using the Fermi–Dirac quantum statistics for an electron gas [19]. From the beginning, for the theoretical description of the thermal conductivity of such materials, a model was applied, according to which these materials consist of hard spheres with the same radii filled with gas, and with this approximation, expressions were obtained for calculating their thermal conductivity coefficient [24]. With the further development of the theory, based on a number of theoretical approximations, expressions were obtained, the calculation results for which are close to the experimental results [20–23]. It should be noted that there is no complete theory describing the mechanisms of thermal conductivity of porous materials.

The processes of heat transfer and thermal conductivity of porous samples synthesized in a flame of a supersonic air–propane (or air–methane) mixture are complex phenomena due to the presence in its volume of heterogeneous phases: gas-filled spherical regions and solid crust covering these spherical regions. The lower values of the coefficient of thermal conductivity of porous steel in relation to the original metal steel is associated with a large difference in the coefficients of thermal conductivity of metals and gases, as well as the process of heat transfer between them and the pressure of gases in the pores. These processes are associated with various structural parameters, such as density, pore size distribution, the possibility of connecting cells, open or closed cells, surface roughness *etc.*, which are very difficult to measure accurately and generalize.

To explain the mechanisms of thermal conductivity of porous materials synthesized in a supersonic flame of an air–propane (or air–methane) mixture is difficult due to the lack of comprehensive detailed

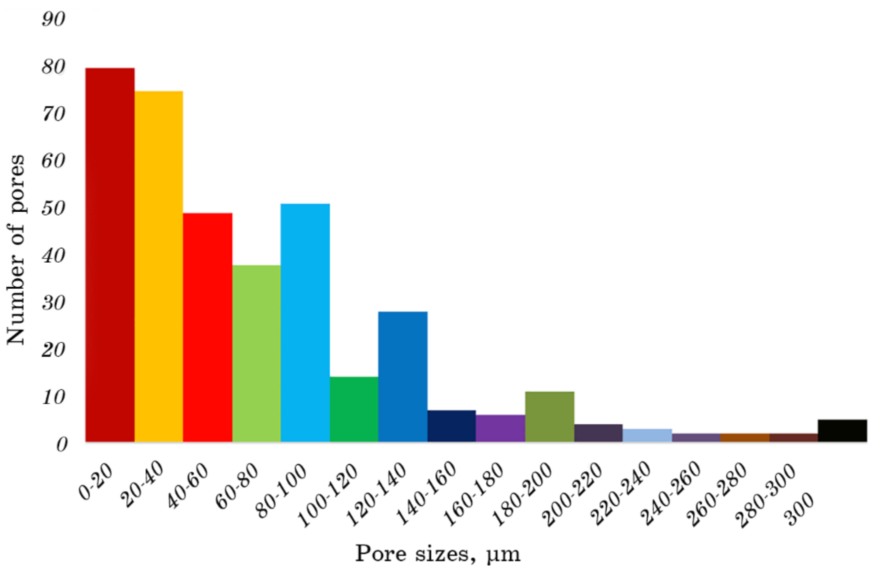


Fig. 5. Pore size distribution on the surface of the synthesized sample.

studies to determine and control the degree of porosity, the shape and size of pores, as well as the pore volume distribution. In our opinion, the above parameters depend on the outlet pressure of the gas mixture, the ratio of the concentration (pressure) of the gas mixture in the flow, the temperature of the liquefied steel, the delay time of the steel in the liquid state, the cooling rate, *etc*. Concerning, it is of interest to study the pore size distribution to explain the thermal conductivity of the porous steel synthesized by melting steel on the flame supersonic jet of mix of air–propane. The pore size distribution on the surface of porous steel sample is shown in Fig. 5. These distributions were constructed by multiple measurements of the pore sizes of various samples and their averaging.

As can be seen from Figure 4 the pores on the surface of the sample are distributed in a complex manner. There are four maxima on the distribution, which lie in the range of pore sizes 0÷20, 80÷100, 120÷140, and 80÷100 μm. The number of pores corresponding to the maxima is in the ratio 1:1.6:2.7:8. As mentioned above, the pore size plays a key role in the thermal conductivity of porous materials. If due to the pore size distribution of the investigated samples, it can be concluded that in the process of heat transfer, the key role plays pores with sizes lying in the range of 1–140 μm. Based on the foregoing, it can be assumed that in the studied porous samples, heat is mainly transferred along solid walls of pores by electronic and phonon mechanisms, and also through gases filling the pores, by convective mechanism.

4. CONCLUSIONS

Based on the analysis state of art in thermal conductivity of porous materials and the experimental studies came to the following conclusions:

– thermal conductivity coefficients of the porous steel samples synthesized by melting steel on the flame supersonic jet of mix of air-propane with a porosity of 60 and 68% are less than 1.3 and 2.6 times in comparison with the thermal conductivity coefficient of the initial 'Steel 3' sample, respectively. In addition, the curves of the temperature dependencies in the investigated temperature region of the studied porous samples and the porous samples synthesized by other technologies are described by different dependencies. It should be noted that there is some similarity in the general form of these dependences, and this, in turn, shows the similarity of the mechanisms of thermal conductivity and temperature dependences of the thermal conductivity coefficients of the above samples;

– on base the pore size distribution of the investigated samples, it can be concluded that in the process of heat transfer to the investigated samples the key role plays pores with sizes lying in the range of 1–140 μm and it can be assumed that in the porous samples, heat is mainly transferred along solid walls of pores by electronic and phonon mechanisms, and also through gases filling the pores, by convective mechanism.

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