UDC 672.32, 536.2.081.7

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CREATION OF EFFECTIVE METALLIC THERMAL INSULATION CONSTRUCTIONS

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СТВОРЕННЯ ЕФЕКТИВНИХ МЕТАЛЕВИХ ТЕПЛОІЗОЛЯЦІЙНИХ КОНСТРУКЦІЙ

Purpose. Creation of the heat-insulating structure (based on perforated metal plates set), which has simple manufacturing, optimal thermal and physical properties, and also allows using structural elements both from one material and a combination of different ones.

Methodology. The empirical laboratory studies of the proposed thermal insulation structure with varying of the pore size and the distance between them were conducted. The regression equation was constructed by the method for planning the experiment. The Student's t-test and Fisher's adequacy test were used for the statistical processing of the data. The Lagrange method with the Kuhn-Tucker conditions was used for finding the objective function minimum.

Findings. Dependence of the strength and effective thermal conductivity in the insulating material structure on the maximum pore diameter, and the distance between pore edges was found. An objective function on the basis of minimum heat conductivity and compressive strength of at least 100 MPa was received. The optimum plate perforation dimensions, at which the thermal conductivity is equal to 20.7686 W/(m·K) and the compressive strength equals to 100.235 MPa, were determined.

Originality. The optimal geometric parameters of the perforated plate set, for their use as elements of power equipment thermal protection, were determined. The thermal conductivity coefficient and hardness factor of the obtained material were found.

Practical value. A thermal insulation structure consisting of a metal plate set was proposed. The obtained metal thermal insulation can be used in different areas, among which are aircraft construction; rocket engineering; automotive and nuclear industry. Such a wide range of applications is due to a combination of thermo-physical and strength characteristics. The ability to use a variety of metals, whether they involve titanium for hulls in rocket construction or zirconium to isolate the core of a nuclear reactor is also important. The usage of this insulation structure instead of monolithic parts will lead to a decrease in total weight; heat losses and material costs.

Keywords: *metallic thermal insulation, metallic thermal protection, effective coefficient of thermal conductivity, compressive strength*

Introduction. Porous metal materials have a unique combination of properties that have been repeatedly considered by scientists from different countries [1, 2]. This combination of properties, contributes to the growth of the spread of these materials in exponential dependence. They have already found their application in various fields, including aerospace (titanium and aluminum sandwich panels); shipbuilding (hulls of passenger ships); automotive industry (structural elements); railway industry (dampers); medicine (implants in the human body).

Porous metal materials also can be used in a nuclear reactor core to reduce heat losses. They usually are made of zirconium dioxide. This thermal insulation serves to reduce energy losses and simultaneously to reflect neutrons, since the zirconium nuclei have a large scattering cross-section and a small capture cross-section, as well as a high atomic density. Based on the technological conditions this thermal insulation cannot be replaced by a non-metallic one.

Problem formulation. Despite various usages of porous metallic materials in different areas, their development is gradually decaying. The reason for this is one-sided development, the orientation of research only on the chemical composition of such materials and the overall porosity. While the location, size and shape of pores are hardly considered. This happens due to initial development vector, which is fundamentally reliable, but has exhausted itself over time. Also we should not forget about the difficulties associated with obtaining porous or highly porous material (with closed porosity) with identical forms of all pores located in the right order.

For further development in this area, it is necessary to develop a new porous metal material that will be simple in manufacturing, will allow achieving the identity of all pores, locating pores in the desired order and using a combination of different alloys without using expensive equipment.

Analysis of the recent research. A number of research studies on aluminum sponge production were carried out and analyzed in [2, 3]. The entire process of forming a spongy structure consists of three fundamental steps: preparation of the working capacity and packing it with filling (organic or non-organic); infiltration of backfill granules with metal (with or without external pressure); removal of pellets from frozen metal (leaching or heat treatment). The density of such material lies in the range of 900–1200 kg/m^3, porosity is 55–67 %. The main disadvantages of this method are: the complexity of the complete removal of the backfill; the presence of excess pressure for completeness; uneven distribution of the backfill in the volume. Moreover, the works do not consider the thermo-physical properties of the given material.

In [4], the method for obtaining intermetallic compound by the SHS method is considered. The powders of nickel, aluminum, cobalt, copper and manganese oxide were used as the initial components. An analysis of the microstructure of the samples, a test for strength and thermal analysis were carried out. The analysis showed that the physical and mechanical properties of the samples are different, depending on the composition of the mixture and the processing method. Such materials have a high melting point and low density. Due to the combination of these characteristics, their usage as thermal insulation, with certain parameters of porosity, in systems with high-temperature processes is promising.

In [5, 6], an analysis of porous metallic materials depending on the technology of their production is presented. Experimental samples obtained by the gas-eutectic method, foaming and casting are shown. The most interesting are samples obtained by casting, because this method allows achieving the same shape of all pores and their orderly arrangement. However, the creation of a mold for casting involves a number of difficulties, especially if it is necessary to achieve a circular or ellipsoidal cross-sectional shape of the pore. Also this method is limited by channel porosity.

In [7] the technology of obtaining a highly porous coating by chemical precipitation is presented and patented. The material with such a coating has plasticity and a compressive strength. However, the manufacturing process has a number of significant drawbacks including gases toxicity; combustibility and explosiveness of precursors; it is corrosively aggressive, features different evaporation rates of each precursor and in connection with this, the high cost of the equipment.

In [8], porous metals and foam metals made from powder are considered. The microstructure of the samples obtained by sintering without an applied excess pressure, selective laser sintering and various foaming methods is given. The influence of the oxygen content on foaming of aluminum powder at temperatures of 500 and 550 °C is shown. However, there is no analysis of the properties of such materials.

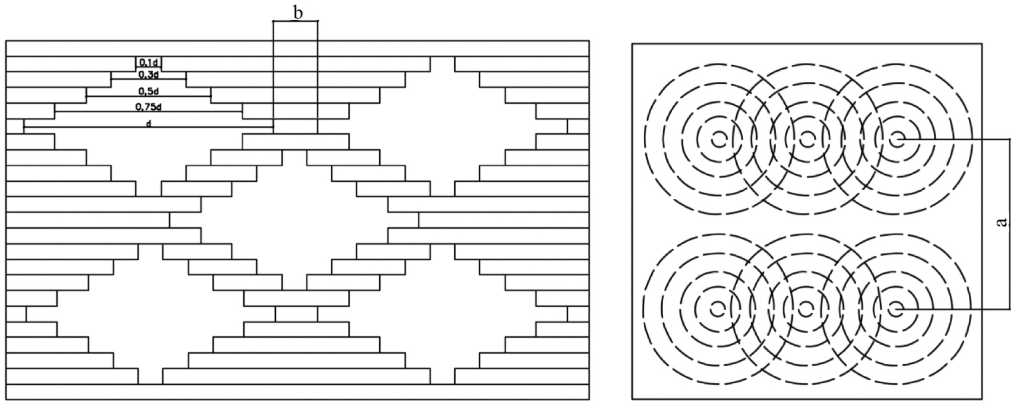
In [9], the influence of the size and pores location on the electronic thermal conductivity of metallic material was investigated. As the experimental samples perforated plates of stainless steel were used with the hole diameters of 3.2–15 mm. The dependence of the electronic heat conductivity coefficient on the diameter of the holes is shown for corridor and staggered arrangement. But this method makes it impossible to obtain the coefficient of effective thermal conductivity. Closed porosity was not considered as well.

In [10], cellular metals and foam metals are considered. The emphasis in this work is put on metals with lotus-porosity. Various methods of production are shown. The work considers the following: the mechanism of nucleation and pore growth in metals with lotus porosity; mechanical, chemical and physical properties; method for controlling the pore size and the total porosity of such metals. However, the shape of the pores in the proposed material is limited to an elongated cylinder with different cross-sections.

Objectives of the article. Creation of the power equipment thermal protection based on a set of perforated metal plates, which features simple manufacturing, has optimal thermal and physical properties, which allows using structural elements both from one material and a combination of different ones.

Presentation of the main research. The proposed method for thermal insulation porous metal material manufacturing for thermal protection, consists of perforated plates linked together. The perforation in the plates can be made in such a way that the plates being combined, the formed pore would have the shape and location required. The connection of the plates can be made by sintering under pressure, gluing or bolting. With a cold bonding method, dielectric paper can be used as a dielectric in the pores. Since the contact thermal resistance between the plates will significantly reduce the heat flux, the assembly of the plates must be carried out in such a way, that their connection lines are perpendicular to the heat flux. Since the largest overall pore size must also be perpendicular to the heat flux, the plates must be assembled according to the scheme given (Figure).

The groups of holes are arranged in rows at a distance a from the center of the pores. This pore location helps achieve a large total porosity of the sample. To determine the dependence of the strength and the effective coefficient of thermal conductivity on the determining dimensions of d and b, the method of experiment planning was used. Input parameters of the model are: d – the maximum diameter of the holes in the plate, the encoded value (X_1); b – the distance between the edges of pores in



a *b*

Fig. Assembled perforated metal plates: side view (a); top view (b)

one row, the encoded value (X_2); a – the distance between the centers of the rows of perforations, the encoded value (X_3). The output parameters of the model are Y_1 – the thermal conductivity of the collected sample, W/(m·K) and Y_2 – the compressive strength, MPa. The levels of variation with the input parameters of the model are presented in Table 1.

Experimental part. In the experiment carbon steel of ordinary quality ST3sp with a compressive strength of 137 MPa and a thermal conductivity of 55 W/(m·K) was used. The thickness of one sheet was 0.8 mm. The dimensions of the sheet are 0.3 x 0.3 m. A dielectric paper in the form of a petal was inserted into pores after every six plates. The perforated plates were connected by point application of epoxy glue (cold welding) and by welding the ends of the sample with electric welding.

To obtain the quadratic coefficients of the regression equation, an orthogonal second-order plan with a core of 23 and with two "star" points was chosen (Table 2).

The coefficients of regression equation were calculated with the following formula [11]

$$a_i = \begin{cases} c_1 \cdot \sum_{j=1}^{N} x_i^j \cdot y^j, \ i = 1,\dots,n \\ c_2 \cdot \sum_{j=1}^{N} \left[(x_{i-n}^j)^2 - \beta \right] \cdot y^j, \ i = n+1,\dots 2n \\ c_3 \cdot \sum_{j=1}^{N} x_\mu^j \cdot x_\lambda^j \cdot y^j, \mu,\lambda = 1,2,\dots,n, \mu \neq \lambda, i = 2n+1,\dots,k \end{cases}.$$

The free regression coefficient was calculated by the following formula

$$a_0 = b_0 - \beta \sum_{j=1}^{n} a_{n+i},$$

where b_0 was calculated as the arithmetic mean value of the experimental data

$$b_0 = \frac{1}{N} \sum_{j=1}^{N} y^j.$$

Table 1

Variation levels of the model input parameters

X	-1.215	-1	0	+1	+1.215	Δ
X_1, mm	8.925	10	15	20	19.86	4
X_2, mm	2.57	3	5	7	7.43	2
X_3, mm	23.925	25	30	35	36.075	5

Table 2

The experimental design matrix and obtained results for experimental sample

№	X_1	X_2	X_3	Y_1	Y_2	№	X_1	X_2	X_3	Y_1	Y_2
1	+1	+1	+1	37.8	95.67	9	-1.215	0	0	34	110.73
2	-1	+1	+1	27.9	109.65	10	+1.215	0	0	31	90.38
3	+1	-1	+1	44.4	90.99	11	0	-1.215	0	21.1	99.39
4	-1	-1	+1	30	110.51	12	0	+1.215	0	30.3	101.71
5	+1	+1	-1	42.2	95.67	13	0	0	-1.215	24	101.25
6	-1	+1	-1	43.1	109.65	14	0	0	+1.215	28.3	102.25
7	+1	-1	-1	39.2	90.99	15	0	0	0	22.7	100.55
8	-1	-1	-1	41.6	110.51	16	0	0	0	22.8	100.1

According to [11], for the plan with the core 2^3, the following coefficients were taken: $\alpha = 1.215$; $\beta = 0.73$; $c_0 = 0.0667$; $c_1 = 0.0913$; $c_2 = 0.2298$; $c_3 = 0.1250$. After calculating of all regression equation coefficients and finding the non-significant coefficients with Student's t-test, the following equations were obtained

$$Y_1 = 20.979 - 1.9X_3 + 8.592X_1^2 + 3.985X_2^2 + 4.29X_3^2 + +3.45X_1X_2;$$

$$Y_2 = 100.284 - 8.375X_1 + 0.955X_2 + 1.01X_3^2 + 1.385X_1X_2.$$

Optimization and analysis. Proceeding from the fact that the thermal conductivity of the product should be minimal and the compressive strength should not be less than 100 MPa, a target function was obtained for optimization with restriction

$$\begin{cases} Y_1 = 20.979 - 1.9X_3 + 8.592X_1^2 + 3.985X_2^2 + 4.29X_3^2 + \\ +3.45X_1X_2 \to \min \\ Y_2 = 100.284 - 8.375X_1 + 0.955X_2 + 1.01X_3^2 + \\ +1.385X_1X_2 \ge 100 \end{cases}.$$

To determine the optimal mode of thermal treatment, the Lagrange function was compiled. The target function, which would be optimized, was as follows

$$F(X) = 20.979 - 1.9x_3 + 8.592x_1^2 + 3.985x_2^2 + +4.29x_3^2 + 3.45x_1x_2.$$

By rewriting the constraint with the ultimate strength in an implicit form we obtained the following

$$\varphi_1(X) = 100 - (100.284 - 8.375x_1 + 0.955x_2 + +1.01x_3^2 + 1.385x_1x_2) = 0.$$

The auxiliary Lagrange function was compiled by the following way

$$L(X,\lambda,\mu) = 20.979 - 1.9x_3 + 8.592x_1^2 + 3.95x_2^2 + 4.29x_3^2 + +3.45x_1x_2 + \mu(100 - 100.284 - 8.375x_1 + 0.955x_2 + +1.01x_3^2 + 1.385x_1x_2).$$

The necessary condition for extremum of the Lagrange function is the vanishing of its partial derivatives with respect to the variables X_i and undetermined factors. The obtained equations system is

$$\begin{cases} \partial L / \partial x_1 = 17.184x_1 + 3.45x_2 + \mu(-1.385x_2 + 8.375) = 0 \\ \partial L / \partial x_2 = 3.45x_1 + 7.97x_2 + \mu(-1.385x_1 - 0.955) = 0 \\ \partial L / \partial x_3 = -2.02x_3\mu + 8.58x_3 - 1.9 = 0 \\ \mu(100 - (100.284 - 8.375x_1 + 0.955x_2 + 1.01x_3^2 + \\ +1.385x_1x_2)) = 0, \mu \ge 0 \end{cases}.$$

The next step was to solve the following system of equations

$$\begin{cases} 17.184x_1 + 3.45x_2 + \mu(-1.385x_2 + 8.375) = 0 \\ 3.45x_1 + 7.97x_2 + \mu(-1.385x_1 - 0.955) = 0 \\ -2.02x_3\mu + 8.58x_3 - 1.9 = 0 \end{cases}.$$

Two options were considered:

a) $i \neq 0$,

$X_1 = (0.03675, -0.02414, 0.2181)$ $\mu = -0.0652$;

b) $\mu = 0$,

$X_1 = (0, 0, 0.2214)$.

Further, the conditions of Kuhn-Tucker were checked. The Kuhn-Tucker theorem says that in order to make the found plan X_0 a solution to the problem it is necessary and it is sufficient that there would exist such a vector μ^0, with which (X^0, μ^0) for all $X \ge 0$ and $\mu \ge 0$. Then $L(X, \mu^0) \le L(X^0, \mu^0) \le L(X^0, \mu)$. For a function of vector variables to have a saddle point, it is necessary and sufficient that the following conditions be satisfied

$$\frac{dL(X^0,\mu^0)}{dx_j} \ge 0; \quad x_j^0 \frac{dL(X^0,\mu^0)}{dx_j} = 0, \; x_j^0 \ge 0;$$

$$\frac{dL(X^0,\mu^0)}{d\mu_j} \le 0; \quad x_j^0 \frac{dL(X^0,\mu^0)}{d\mu_j} = 0, \; \mu_j^0 \ge 0.$$

Point X_1 was excluded, because μ has a negative value

$X_1 = (0.03675, -0.02414, 0.2181)$, $\mu = -0.0652$.

Point $X_1 = (0, 0, 0.2214)$ satisfies all conditions, the value of the function at this point $f(x) = 20.7686$.

Further, the form of the extremum was determined. For the function $L(x, \lambda, \mu)$, the Hessian matrix H_L was found. If the matrix HL is positive-definite, then the obtained point x is a minimum point, if the matrix is negative – then x is the maximum point. For the equations

$$L(x,\lambda,\mu) = 20.979 - 1.9x_3 + 8.592x_1^2 + 3.985x_2^2 + +4.29x_3^2 + 3.45x_1x_2;$$

$$F(X) = 20.979 - 1.9x_3 + 8.592x_1^2 + 3.985x_2^2 + +4.29x_3^2 + 3.45x_1x,$$

partial derivatives were found

$$\frac{\partial F(X)}{x_1} = 17.184x_1 + 3.45x_2; \quad \frac{\partial F(X)}{x_2} = 3.45x_1 + 7.97x_2;$$

$$\frac{\partial F(X)}{x_3} = 8.58x_3 - 1.9.$$

After the system was solved, the stationary point was obtained. $X_0 = (0, 0, 0.2214)$ The second partial derivatives are

$$\frac{\partial^2 F(X)}{\partial^2 x_1^2} = 17.184; \quad \frac{\partial^2 F(X)}{\partial x_1 \partial x_2} = 3.45; \quad \frac{\partial^2 F(X)}{\partial x_1 \partial x_3} = 0;$$

$$\frac{\partial^2 F(X)}{\partial^2 x_2^2} = 7.97; \quad \frac{\partial^2 F(X)}{\partial x_2 \partial x_3} = 0; \quad \frac{\partial^2 F(X)}{\partial^2 x_3^2} = 8.58.$$

The Hessian matrix is

$$G(X)=\begin{pmatrix}17.184 & 3.45 & 0\\ 3.45 & 7.97 & 0\\ 0 & 0 & 8.58\end{pmatrix}.$$

For point $X_0 = (0, 0, 0.221)$ the following values were obtained

$$\frac{\partial^2 F(X)}{\partial^2 x_1^2}(X^0)=17.184;\quad \frac{\partial^2 F(X)}{\partial x_1 \partial x_2}(X^0)=3.45;$$

$$\frac{\partial^2 F(X)}{\partial x_1 \partial x_3}(X^0)=0;$$

$$\frac{\partial^2 F(X)}{\partial^2 x_2^2}(X^0)=7.97;\quad \frac{\partial^2 F(X)}{\partial x_2 \partial x_3}(X^0)=0;$$

$$\frac{\partial^2 F(X)}{\partial^2 x_3^2}(X^0)=8.58.$$

The Hessian matrix at the point $X_0 = (0, 0, 0.221)$ is

$$G(0;0;0.221)=\begin{pmatrix}17.184 & 3.45 & 0\\ 3.45 & 7.97 & 0\\ 0 & 0 & 8.58\end{pmatrix}.$$

The obtained diagonal minors are:

$D_1 = a_1 = 17.184$;

$D_2 = a_{11}a_{22} - a_{21}a_{22}$;

$D_3 = 1072.9631484$.

Since diagonal minors have a positive value, G_f is a positive definite matrix. It follows that the function is convex. Moreover, the function is strictly convex and has a unique minimum point $X_0 = (0, 0, 0.2214)$. Based on the obtained values, the optimum dimensions of the assembled metal perforated plates are: d = 15 mm; b = 5 mm; a = 31.1 mm. The coefficient of thermal conductivity at such parameters is 20.7686 W/(m·K), and the compressive strength is 100.235 MPa.

Conclusions and recommendations for further research. A metal structure that can serve as thermal insulation of power equipment and consists of perforated metal sheets of ST3sp brand was developed. Optimal dimensions of metal plates perforation, at which the thermal conductivity coefficient was 20.7686 W/(m·K), and the compressive strength was 100.235 MPa, were obtained. The obtained design of the metal element of thermal protection of industrial equipment satisfies all the purposes. The technology of production of such a structure is simple and allows minimizing financial costs for the purchase of technological equipment. The obtained construction with the proposed analysis technique can be used in further studies, for example for carrying out experiments with plates of different metals. Moreover, on the basis of this research it is possible to create a heat-insulating composite material in which part of the plates will be made of non-metallic material.

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Мета. Створення теплової ізоляції (на базі набору перфорованих металевих пластин), що володіє простотою виготовлення, має оптимальні теплофізичні й міцнісні характеристики, котрі дозволяють використовувати конструктивні елементи як з одного матеріалу, так і комбінації різних.

Методика. Проведені емпіричні лабораторні дослідження запропонованої теплової ізоляції з варіюванням розміру пор і відстані між ними. Для побудови рівняння регресії використовувався метод планування експерименту. Для статистичної обробки даних використовувався метод t-критерію Стьюдента й перевірка адекватності за критерієм Фішера. Для знаходження мінімуму цільової функції використовувався метод Лагранжа з умовами Куна-Такера.

Результати. Знайдена залежність міцності та ефективної теплопровідності розглянутого теплоізоляційного матеріалу від максимального діаметра пори і відстані між краями пор. Складена цільова функція, виходячи з мінімальної теплопровідності й міцності на стиск не менше 100 МПа. Визначені оптимальні розміри перфорації у пластинах, за яких теплопровідність дорівнює 20,7686 Вт/(м·K), межа міцності на стиск – 100,235 МПа.

Наукова новизна. Визначені оптимальні геометричні параметри перфорованих пластин для використання їх в якості теплової ізоляції. Знайдено коефіцієнт теплопровідності й показник твердості отриманого матеріалу.

Практична значимість. Запропонована теплова ізоляція, котра складається з набору металевих пластин. Розроблена металева теплова ізоляція може бути використана в ряді галузей, серед яких: авіабудування; ракетобудування; автомобільна та ядерна промисловість. Настільки широка область застосування обумовлена комбінацією теплофізичних і міцнісних характеристик. Також важливою є можливість використання різноманітних металів, будь то титан для корпусів у ракетобудуванні або цирконій для ізоляції активної зони ядерного реактора. Використання даної конструкції замість монолітних частин у виробі призведе до зменшення загальної ваги, теплових втрат і витрат матеріалу.

Ключові слова: *металева теплоізоляція, ефективна теплопровідність, межа міцності на стиск*

Цель. Создание конструкции тепловой изоляции (на базе набора перфорированных металлических пластин), обладающей простотой изготовления, имеющей оптимальные теплофизические и прочностные характеристики, позволяющей использовать конструктивные элементы как из одного материала, так и комбинации различных.

Методика. Проведены эмпирические лабораторные исследования предложенной конструкции тепловой изоляции с варьированием размера пор и расстояния между ними. Для построения уравнения регрессии использовался метод планирования эксперимента. Для статистической обработки данных использовался метод t-критерия Стьюдента и проверка адекватности по критерию Фишера. Для нахождения минимума целевой функции использовался метод Лагранжа с условиями Куна-Такера.

Результаты. Найдена зависимость прочности и эффективной теплопроводности рассматриваемого теплоизоляционного материала от максимального диаметра поры и расстояния между краями пор. Составлена целевая функция, исходя из минимальной теплопроводности и прочности на сжатие не менее 100 МПа. Определены оптимальные размеры перфорации в пластинах, при которых теплопроводность равна 20,7686 Вт/(м·K), предел прочности на сжатие – 100,235 МПа.

Научная новизна. Определены оптимальные геометрические параметры составных перфорированных пластин для использования их в качестве элементов тепловой защиты энергетического оборудования. Найдены коэффициент теплопроводности и показатель твердости полученного материала.

Практическая значимость. Предложена конструкция тепловой изоляции, состоящая из набора металлических пластин. Разработанная металлическая тепловая изоляция может быть использована в ряде областей, среди которых: авиастроение; ракетостроение; автомобильная и ядерная промышленость. Столь широкая область применения обусловлена комбинацией теплофизических и прочностных характеристик. Также важна возможность использования разнообразных металлов, будь то титан для корпусов в ракетостроении или цирконий для изоляции активной зоны ядерного реактора. Использование данной конструкции вместо монолитных частей в изделии приведет к уменьшению общего веса, тепловых потерь и затрат материала.

Ключевые слова: *металлическая теплоизоляция, металлическая тепловая защита, эффективный коэффициент теплопроводности, предел прочности на сжатие*

Рекомендовано до публікації докт. техн. наук О. В. Явтушенком. Дата надходження рукопису 14.12.16.