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DETERMINATION OF OPTIMAL SIZES OF SENSORS MEMBRANE ELEMENTS BY MEASURING ELASTIC MODULES USING THE RESONANCE METHOD

Dyachok D. A., Lukashin V. V.*, Volchok N. A.*, Gorbachev V.E.**, Polyakov S.N.***

**South Ukrainian National Pedagogical University named after K. D. Ushynsky,*
26 Staroportofrankivska St., Odessa, 65020, Ukraine.
dyachok-dima@mail.ru
*** Odessa National O.S. Popov Academy of Telecommunications,*
1 Kuznechna St., Odessa, 65029, Ukraine.
physonat@gmail.com

ВИЗНАЧЕННЯ ОПТИМАЛЬНИХ РОЗМІРІВ МЕМБРАННИХ ЕЛЕМЕНТІВ ДАТЧИКІВ ШЛЯХОМ ВИМІРЮВАННЯ ПРУЖНИХ МОДУЛІВ РЕЗОНАНСНИМ МЕТОДОМ

Дячок Д.О., Лукашин В.В.*, Волчок Н.А.*, Горбачов В.Е.**, Поляков С.М.***

** Південноукраїнський національний педагогічний університет ім. К.Д.Ушинського,*
65020, Україна, м. Одеса, вул. Старопортофранківська, 26.
dyachok-dima@mail.ru
***Одеська національна академія зв'язку ім. О.С. Попова,*
65029, Україна, м. Одеса, вул. Кузнечна,1.
physonat@gmail.com

ОПРЕДЕЛЕНИЕ ОПТИМАЛЬНЫХ РАЗМЕРОВ МЕМБРАННЫХ ЭЛЕМЕНТОВ ДАТЧИКОВ ПУТЕМ ИЗМЕРЕНИЯ УПРУГИХ МОДУЛЕЙ РЕЗОНАНСНЫМ МЕТОДОМ

Дячок Д.А., Лукашин В.В.*, Волчок Н.А.*, Горбачев В.Э.**, Поляков С.Н.***

**Южноукраинский национальный педагогический университет им. К.Д.Ушинского,*
65020, Украина, г.Одесса, ул. Старопортофранковская, 26.
dyachok-dima@mail.ru
***Одесская национальная академия связи им. А.С.Попова,*
65029, Украина, г. Одесса, ул. Кузнечная,1.
physonat@gmail.com

Abstract. Introduction of the concept of the Internet of Things in telecommunication networks has caused a rapid number growth of new designs and technologies for manufacturing reliable sensors of physical quantities, in particular pressure and displacement sensors. In order to determine the optimal dimensions and rejection of unreliable working elements of membrane pressure and displacement sensors, the frequency dependence of natural transverse oscillations of biphasic steel plates on their length is investigated. The experimental frequencies values of plates of fixed thickness and of various lengths were determined by the resonance method. The measurement results were processed using the Spectra PLUS computer program. The analytical dependence of the disk natural oscillation frequency on the length for the fixed disk thickness is expressed by the exponential function. The theoretical values of the frequencies are well coordinated with the experimental data for plates 60-100 mm long. However, for lengths less than 30 mm, a significant discrepancy between the experimental and calculated data is observed. This can be explained by the difficulty of obtaining stable oscillation. The plates deformation by alternating bending decreases the disk natural oscillation frequency due to the appearance and development of residual damages in the forms of micropores and microcracks in the disks. It is proved by the direct observation over microstructures by means of electron-microscope investigation.

Key words: membrane sensor, elasticity, damage, oscillation, frequency, microstructure, resonance, cyclic deformation, micropores.

Анотація. Впровадження в телекомунікаційні мережі концепції Інтернету речей викликало бурхливе зростання числа нових конструкцій і технологій виготовлення надійних у роботі датчиків фізичних величин, зокрема, сенсорів тиску і зміщення. Для визначення оптимальних розмірів і відбраковування ненадійних робочих елементів мембранних датчиків тиску і зміщення досліджена залежність частоти власних поперечних коливань пластин двофазної сталі від їх довжини. Експериментальні значення частот пластин фіксованої товщини і різної довжини визначали резонансним методом. Результати вимірювань оброблялися за допомогою комп'ютерної програми Spectra PLUS. Аналітична залежність частоти коливань вільної пластини від довжини для фіксованої товщини пластини виражається ступеневою функцією. Теоретичні значення частот добре узгоджуються з експериментальними даними для пластин довжиною 60 - 100 мм. Однак для довжин менше 30 мм спостерігається суттєва розбіжність експериментальних і розрахункових даних. Це може бути пояснено труднощами в отриманні стабільних коливань. Деформація пластин знакозмінним вигином зменшує частоту власних коливань пластин за рахунок зародження і розвитку в обсязі матеріалу пластин залишкових дефектів у вигляді мікропор і мікротріщин. Це демонструють прямі спостереження мікроструктур методами електронної мікроскопії.

Ключові слова: мембранний датчик, пружність, пошкодженість, коливання, частота, мікроструктура, резонанс, циклічна деформація, мікропори.

Аннотация. Внедрение в телекоммуникационные сети концепции Интернета вещей вызвало бурный рост числа новых конструкций и технологий изготовления надежных в работе датчиков физических величин, в частности, сенсоров давления и смещения. Для определения оптимальных размеров и отбраковки ненадежных рабочих элементов мембранных датчиков давления и смещения исследована зависимость частоты собственных поперечных колебаний пластин двухфазной стали от их длины. Экспериментальные значения частот пластин фиксированной толщины и различной длины определяли резонансным методом. Результаты измерений обрабатывались с помощью компьютерной программы Spectra PLUS. Аналитическая зависимость частоты колебаний свободной пластины от длины для фиксированной толщины пластины выражается степенной функцией. Теоретические значения частот хорошо согласуются с экспериментальными данными для пластин длиной 70 – 100 мм. Однако для длин менее 30 мм наблюдается существенное расхождение экспериментальных и расчетных данных. Это может объясняться трудностями в получении стабильных колебаний. Деформация пластин знакопеременным изгибом уменьшает частоту собственных колебаний пластин за счет зарождения и развития в объеме материала пластин остаточных дефектов в виде микропор и микротрещин. Это демонстрируют прямые наблюдения микроструктур методами электронной микроскопии.

Ключевые слова: мембранный датчик, упругость, поврежденность, колебания, частота, микроструктура, резонанс, циклическая деформация, микропоры.

Introduction. When implementing the concept of the Internet of Things (IoT) in telecommunication networks, a special role is assigned to measurement tools that fill the computing environment with numerical information. This has caused a rapid growth in the number of new designs and technologies of the production of reliable sensors of physical quantities. In previous works [1, 2], we considered the construction of sensors for temperature, illumination, magnetic field, radiation as highly economical sensors of the IoT network.

In this paper, the working elements of membrane pressure and displacement sensors are investigated to improve their reliability and wear resistance. The main working element of such sensors is an elastic membrane, which is made of a steel plate. Regardless of the design of the pressure or displacement sensor, the measurement result is determined by elastic modules of its working element. In the process of operation, the diaphragms of sensors undergo cyclic deformations, as a result of which micropores and microcracks are formed on the surface and in the volume of the material that significantly change their elastic properties and affect the results of measurements.

In the Material failure theory, the process of mechanical failure of a body is divided into three stages. This is the birth of damage at the microscopic level, the coalescence of them at the mesolevel, the growth and spread of cracks at the macroscopic level. It is possible to observe visually the damage at the macroscopic level. To investigate the damage at the micro level, it is necessary to use microscopic equipment with high resolution (electron microscopy). To detect micropores and microcracks using electron microscopy, complex preparation of samples (ion polishing) is required. In addition, all these methods are destructive. In [3] it was shown that for viscous materials (from which membrane elements of sound equipment are usually made) with high accuracy, it is possible to determine the level of micro damages in the volume of a material if one analyzes the variation of elastic moduli in comparison with an intact standard. To do this, it is necessary to measure the Young's modulus change in the process of nucleation and growth of internal micro damages (discontinuities) with an adequate accuracy.

Young's modulus of structural materials *E* is usually measured in the course of mechanical tensile testing [4]. In this case, the loading of the sample under tension introduces a certain change in the structure of the material under study. In addition, during the tensile tests, residual plastic deformation always remains.

Young's modulus determines the propagation velocity of elastic waves in the material, as well as the frequency of natural oscillations of the solid-state sample [5]. Therefore, according to the results of measurements of the propagation velocity of elastic waves or the frequency of natural oscillations of samples in the form of plates, rods, membranes, it is possible to obtain information on the elastic moduli of the material and, accordingly, on changes of its structure during thermal or other processing, and also during operation under the influence of long-term cyclic deformation. Moduli defined in this way are called dynamic or adiabatic [6].

In practice, elastic elements of pressure sensors, bias or membrane elements of a sound equipment are made of materials with a high Young's modulus. Usually, to eliminate structural defects, they are subjected to heat treatment in the form of quenching and tempering. The newest technologies allow introducing two-phase steels into the industry, the structure of which is a mixture of plastic ferrite and durable martensite. Such materials have a complex of high strength and plastic properties [4].

The durability of the work and the efficiency of the response to the mechanical effects of membrane elements of the structures under constant mechanical stresses are determined not only by the elastic properties of the material, but also by the geometric dimensions of the working element, in particular the ratio of its longitudinal section and thickness.

The aim of the paper is to determine the optimal dimensions of flat rectangular samples of biphasic steel by analyzing the theoretical and experimental data on the frequencies of natural oscillations of plates after their forced cyclic deformation by alternating bending.

Dynamic elastic modulus of the plate. During the oscillations of elastic plates or membranes, the displacement occurs in the plane which is perpendicular to their longitudinal section or transversely to their axis. Therefore, the oscillations of such objects can be considered as oscillations of a system of material points with one degree of freedom [5].

The state of such a system is being described by an equation with one coordinate, and the initial condition is the equilibrium condition.

The kinetic *T* and the potential energy *V* of an elastic body for any position of a system with one variable (displacement *u*) is expressed as:

$$T = \frac{1}{2} m\dot{u}^2 \text{ и } V = \frac{1}{2}\mu u^2. \tag{1}$$

For transverse and longitudinal oscillations of systems, the deformation ε is related to the tensile force per unit sectional area of the plate σ by Hooke's law: $\sigma = E\cdot\varepsilon$, where *E* – is the Young's modulus of the plate material.

The Young's modulus, like the ρ density, is the main characteristics of a material of a plate that affects the frequency of its oscillations. For a plate or a rod of the constant cross section, the equation of the motion was obtained in the form [7]:

$$\frac{\partial^2 y}{\partial x^2} + b^2\chi^2 \frac{\partial^4 y}{\partial x^4} = 0, \tag{2}$$

where $b^2 = q / p$ – velocity of propagation of longitudinal waves in a rod; $\chi^2\omega$ – moment of inertia of the plate; ω – the cross-sectional area of the plate element.

The boundary conditions for a free plate have the form: $\frac{\partial^2 y}{\partial x^2} = 0$, $\frac{\partial^3 y}{\partial x^3} = 0$.

Assuming that the displacement of points of a plate of length l along the y axis is described by the harmonic function $y = u\cos[\chi b/(ml)^2 \cdot t]$, the solution of the equation of motion (2) will have the form:

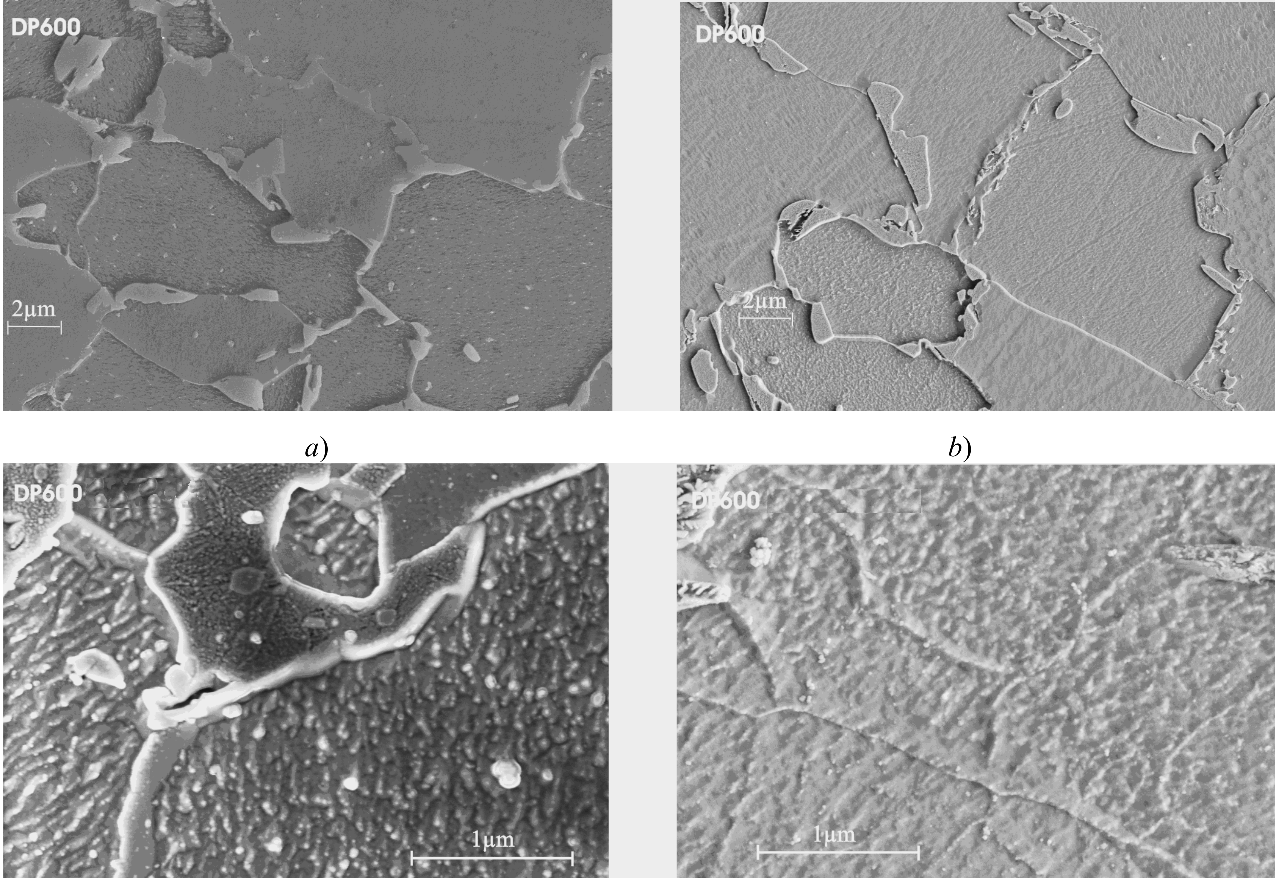
$$E = \frac{48\pi^2}{m^4} \cdot \rho \frac{l^4}{d^2} \nu^2, \qquad (3)$$

where m – some constant; d – plate thickness; ν – oscillation frequency.

Thus, for plates of fixed dimensions, there is a unique relationship between the natural frequency of a plate and its Young modulus.

Investigations and results. Experimental studies of the influence of heat treatment and forced cyclic deformation by an alternating bend at the frequencies of the natural transverse oscillations of plates of different lengths were carried out on samples of a two-phase steel sheet DP600 of Salzgitter Flachstahl with the following impurity composition: C – 0,10 %; Si – 0,15%; Mn – 1,4%; P – 0,007%; S – 0,008%; N – 0,009%; Al – 0,02 - 0,06%; Cr-Mo-Ni – 1%.

Cards of 100 x 100 mm in size were cut out from sheets 1 mm thick. One lot of cards was in the original delivery condition and was not subjected to any impact. Another batch of cards was annealed before the recrystallization process began at a temperature of 250 °C for 72 hours in an atmosphere of the neutral gas. In Fig. 1 microstructures of DP600 steel sheets in the initial state of delivery conditions and after annealing at various magnifications are shown.



a) *b*) *c*) *d*)

Figure 1 – Microstructure of DP600 steel in the initial state of delivery conditions *a*) and after annealing at the temperature of 250 °C for three days in the neutral atmosphere *b*) at × 5000 magnification; the same samples at × 30000 magnification *c*) and *d*)

In the photographs obtained at × 5000 magnification, the grains of ferrite and martensite are clearly seen. However, at this magnification in the microstructure, the steels in the initial state and after a long annealing differ little from each other. At × 30000 magnification, the significant changes in the microstructure after annealing are already noticeable. It can be seen that martensite is located along the boundaries of ferrite grains and in the form of small inclusions directly in the grains. In the initial state pores that disappear or become substantially smaller after annealing can be seen on the surface of the martensite grains. The fine grains of martensite interspersed with ferrite appear smaller in size and in smaller quantities after annealing.

To investigate the natural frequency dependence of the transverse oscillations of annealed samples on their length experimentally, three rectangular plates with the width of 12 mm and the length of 100 mm were cut out from cards 100 × 100 mm in size. All samples were processed in a package to ensure the same size. Firstly, the frequency values were measured for samples with the length of 100 mm, then the samples were shortened by 10 mm and the measurements were repeated. The measurements were carried out using a special measuring system consisting of a personal computer and a resonant mechanical part, the circuit of which is shown in Fig. 2.

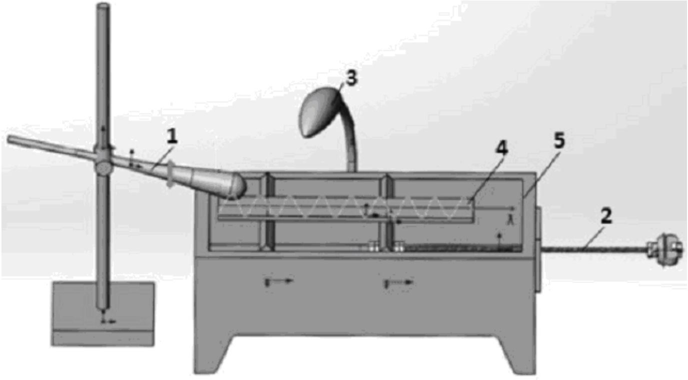


Figure 2 – Scheme of the resonant part of the installation for measuring the frequency of the natural transverse oscillations of a plate:
1 – the vibrator; 2 – the distance adjustment screw between the sample supports; 3 – the microphone, 4 – a sample; 5 – the resonator

Principle of operation of the measuring system. To measure the frequency of natural oscillations, a steel sample in the form of a plate is mounted on two prism-supports. The vibrator excites mechanical oscillations of the sound frequency in the sample. With the help of the adjusting screw, it is necessary to achieve the position of the plate, in which the prisms would be at the nodes of the standing wave arising in the sample. The maximum amplitude of the oscillations corresponds to the natural frequency. The oscillating plate excites sound waves in the resonator, which are recorded with a broadband microphone. The signal from the microphone is fed to the computer and processed using a special program SPECTRA PLUS. The natural frequency value of the plate corresponds to the maximum of the sound level recorded by the microphone.

Static processing of the frequency measurement results was carried out according to ASTM E1876-09-2009 protocol, according to which the accuracy of measuring the natural frequency of plates with the confidence probability of 0,95 is ± 0,01 Hz.

For comparison the theoretical values of the frequencies of natural oscillations of an elastic solid body in the form of a rectangular parallelepiped of appropriate dimensions were calculated according to formula (3). In our paper [8], it was shown that the Young's modulus of the DP600 steel can take the value from 190 to 218 GPa, depending on the type of processing, texture and the grain structure. The calculations were carried out for the Young's modulus of 204 GPa that corresponds to its average value for the annealed samples.

In Fig. 3 the experimental dependence of the natural oscillations frequency of plane-shape steel samples on their length is shown. As follows from the graph, the function $\nu = f(l)$ is power-law. In Fig. 3 the theoretical values of the natural oscillations frequencies of an elastic mechanical solid body in the form of a rectangular parallelepiped of appropriate dimensions are also shown (3). As can be seen from the graph, the results of experimental measurements are well agreed with theoretical values only in the range of 70 - 90 mm. For experimental values of the natural oscillation frequencies of samples with a length less than 40 mm, the discrepancy with the experimental data is very significant.

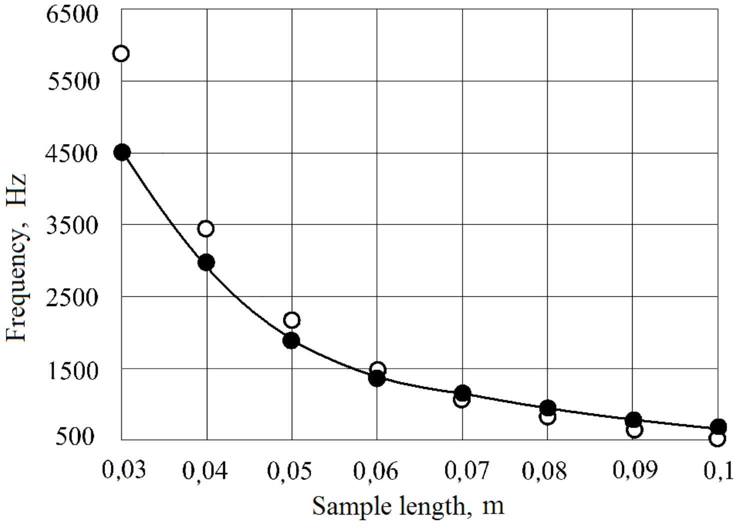


Figure 3 – Frequency dependence of natural transverse oscillations of rectangular steel samples on their length: ● – experimental, ○ – theoretical data

For samples of less than 30 mm of length, it was difficult to measure the frequency with the method described above, since it is difficult to achieve stable oscillations at this specified length and thickness of the 1 mm sample. Some discrepancies in the frequency values for samples with lengths greater than 90 mm may be associated with the appearance of more numbers of lateral harmonics with increasing plate sizes. Samples with lengths greater than 100 mm were not investigated due to limitations in the dimensions of the membrane elements of industrial products.

To investigate the impact of mechanical effects on the frequencies of natural transverse oscillations of plates, the selected batch of cards 100 × 100 mm in size after annealing was tested concerning the deformation by alternating bending on a roller with the diameter of 50 mm during one, three and twelve cycles. One cycle consisted of bending in one direction, straightening, bending in the other direction and straightening.

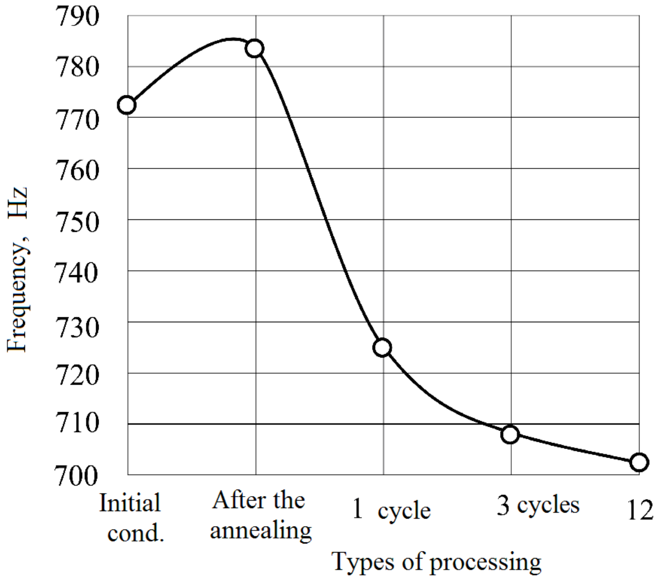


Figure 4 – Changing the frequency oscillations of plates 100 mm long after their annealing and deformation

After deformation, three rectangular plates with the width of 12 mm and the length of 100 mm were cut from the cards. All samples were processed in a package to ensure the same size. First, the natural oscillation frequencies of the samples in the initial state of the delivery conditions were measured, then after annealing. After that, the cards were tested by the action of forced deformation by alternating bending of varying intensity, and the frequencies of natural oscillations were again measured. Average values of the oscillation frequencies of plates 100 mm long for each type of processing are given in Fig. 4.

It can be seen from the presented graph that annealing increases the frequency of natural oscillations, and the deformation by an alternating bending leads to its decreasing. The frequency of natural oscillations decreases sharply already with a small number of deformation cycles by bending, but the values of the natural frequency tend to stabilization with increasing the number of cycles.

This decreasing the frequency of the natural oscillations of the plates during deformation by alternating bending is associated with the appearance of damages in the form of micropores, microcracks and other structural discontinuities, both on the surface and in the plate volume.

This fact is confirmed by a photograph taken with the help of an electron microscope, which shows the surface of the longitudinal volume section of the plate after 12 cycles of deformation by alternating bending (Fig. 5).

In the photo of the microstructure of the volume section, the micropores are clearly visible. Such micropores were absent in the photographs of the plates microstructures before deformation.

Investigations of the effect of cyclic deformation on samples of different lengths have shown that plates of greater length, as expected, are the most resistant to external mechanical actions.

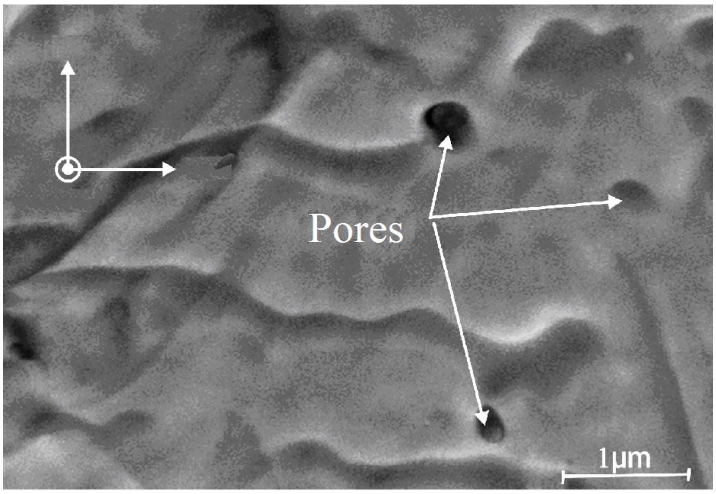


Figure 5 – Microstructure of DP600 steel after 12 cycles of deformation by alternating bending at the × 30000 magnification

Conclusions:

1. The natural frequency of oscillations of a rectangular plate is determined by the value of the Young's modulus of the material, which in turn depends on the damage level of the structure.

2. The optimum length of 1 mm thick rectangular plate for measuring the frequency of its natural oscillations by the resonance method in the range of sound frequencies is 70 – 90 mm. The small dimensions of the plates prevent the formation of stable free oscillations in the plates.

3. The frequency of the proper transverse oscillations of rectangular plates depends on the number of cycles of testing the plates by deforming the samples by alternating bending. As the number of cycles increases, the frequency value decreases and shows the tendency to stabilizing after testing with 12 cycles of deformation.

4. The decreasing the frequency of natural oscillations of the plate as a result of an action of cyclic deformation is caused by the generation of microdamages in the material volume in the form of micropores and microcracks, so the deviation of the value of this frequency in comparison with the reference sample can be used to reject the elastic elements of the membrane sensors of pressure and displacement.

5. When having a fixed thickness and width of the steel plate, there is an optimal length of the steel plate that provides the best response to mechanical actions with minimal intensity of defects formation in the structure of the membrane during an operation.

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