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PAPER

Conditions for the open pores formation in medical textile materials for the treatment of wounds using iron oxide nanopowders

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Abstract

One of the tasks of dressings in the process of wound treatment is to remove exudate. In the optimal case, this intensity is determined individually for each wound. Active medical textiles take advantage of the capillary effect that occurs in thin channels. For these purposes, medical materials are created from porous structures. To create back pressure in foamed medical materials, the pores must be in the form of channels, which is not realized with conventional technologies. The purpose of this study is to analyze the performance of magnetic nanopowders on the pore structure in the production of porous materials. Research methods include methods of chemical synthesis, methods of microscopic analysis, methods of modeling, statistical analysis. The main result is the study of the formation of necessary forms in foamed materials during the use of magnetic nanopowders as additives. This effect makes it possible to increase the efficiency of foam structures when used as medical materials.

1. Introduction

A significant trend in modern textile science is the development of special textile materials for medical applications [1, 2].

One of the urgent tasks in this direction is the creation of textile materials for the treatment of wound infections. For example article [3] is devoted to selection of appropriate wound dressing for various wounds. Modern dressings use innovative technologies [4, 5]. Such methods as, bioengineering, advances in textile materials science, smart technologies and nano technologies are used for this purpose.

Wound healing is a complex multifunctional process. One of the tasks of dressings in this case is to remove exudate [6, 7]. In this case, the intensity of exudate removal should not be too fast or too slow. In the optimal case, this intensity is determined individually for each wound [8].

In most cases, active medical textiles exploit the capillary effect that occurs in thin channels [9]. Special medical materials are created for these purposes from porous structures [10, 11].

The order of operation of such materials is considered in a number of studies [12]. Also, researches are devoted to the technology of creating porous and foamed materials [13].

The creation of capillary effects may not automatically occur during the formation of pores. Closed pores can hold certain volumes of liquid, but it is difficult for liquid to enter such pores. At the same time, most of the existing technologies provide the formation of closed pores. The capillary effect for creating negative pressure implies the presence of extended pores that have a clear exit on the surface of the material.

Various technologies and compositions involve the creation of porous materials of various shapes and sizes. In most cases, closed pores are realized (figure 1(a)). Most often, their shape is close to spherical.

The formation of long open cavities is actual for the task of creation capillary effects (figure 1(b)). The study [14] presents data on the effect of magnetic nanopowders on the dynamics of pore formation in foamed materials. A significant dependence of the pore size on the magnetite content was shown, although the shape of the formed cavities was not investigated.

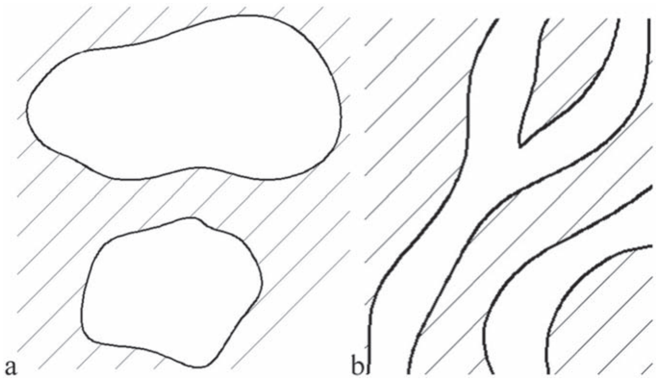

Figure 1. Structures of porous materials. (a)- closed, (b)- open.

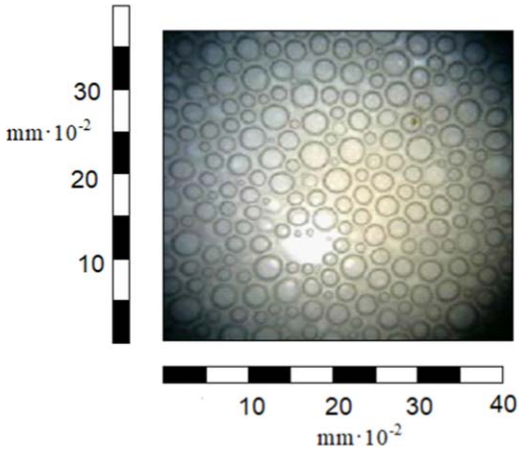

Figure 2. Formation of closed cavities during foaming.

Important characteristics of medical textile materials for wound treatment are their hygienic, bactericidal, bacteriostatic properties [15, 16]. A number of studies [17, 18] show the effect of metallic nanomaterials. Experiments with magnetic nanopowders in the composition of textile materials [19, 20] have shown that the introduction of powders based on Fe_2O_3 significantly improves bacteriostatic properties.

Thus, the use of magnetic nanopowders in the composition of medical textile materials can potentially significantly improve their properties.

The purpose of this article is to study the conditions for the formation of long open pores in medical textile materials using magnetic nanopowders for effective remove exudate from wounds.

2. Methods and materials

Polyurethane was chosen as the main material for research. The manufacturing technology of polyurethane foam involves the connection of two main elements. These substances are isocyanate and polyol. When they are combined and heated, microcapsules filled with air are formed and the mixture foams [21, 22].

With a magnification of 40 times, the micrograph of the resulting structure looks like figure 2.

The main method for improving the structure of porous materials in our case was the use of magnetic nanopowders. The technology for obtaining such nanomaterials has been substantiated in a number of studies [14, 20].

Installation shown in figure 3 was developed for the manufacture of magnetic nanomaterials.

1. Mixture of $FeSO_4$ and $FeCl_3$ solutions, 2. Reactor for performing of chemical reactions, 3. Heat insulation, 4. Electric motor, 5. Stirring device, 6. Device rotation, 7. NH_4OH solution, 8. NH_4OH drops, 9. Alkaline sensor 10. Alkaline environment recorder.

The starting materials for obtaining magnetic nanomaterials are aqueous solutions of two substances. The first substance is ferrous sulfate, the second is ferric chloride.

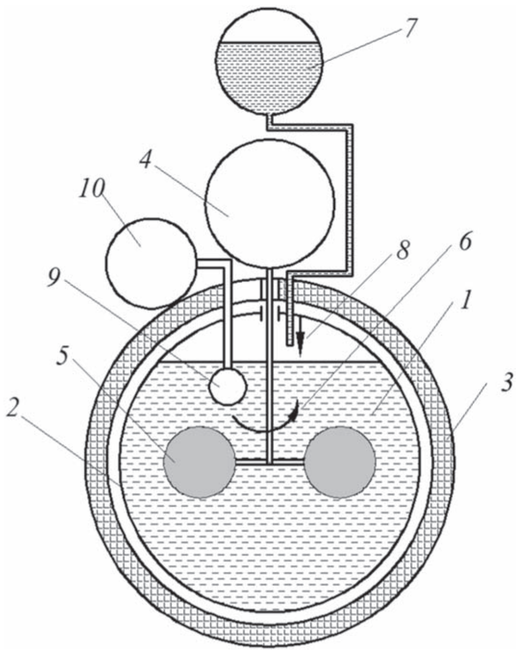

Figure 3. Installation for the manufacture of magnetic nanomaterials.

These solutions are mixed in reactor 2, which is protected by heat insulator 3. Electric motor 4 drives mixing device 5 into rotation 6. A solution of NH_4OH 8 is supplied dropwise from vessel 7 to the solution.

The first substance reacts 12

The first substance enters the reaction [12], which is described by equation

$$FeSO_4 + 2NH_4OH \rightarrow FeO + (NH_4)_2SO_4$$

The second substance implements successive reactions

$$FeCl_3 + 3NH_4OH \rightarrow Fe(OH)_3 + 3NH_4Cl$$

$$2Fe(OH)_3 \rightarrow Fe_2O_3 + 3H_2O$$

The sensor 9 registers the appearance of an alkaline medium in the mixture, this is displayed by the registrar 10.

The resulting nanopowder has magnetic properties and includes components of iron oxides with different valences.

In the process of foaming polymers, a magnetic nanopowder was added to the prepared mixture, based on preliminary data on its effect on the formation of cavities in the foamed material.

To study the effect 0.1%, 0.2%, 0.3% magnetite in the form of nanopowder was added to the initial mixture for the manufacture of foamed material. A foaming agent was introduced into the mixture. After thickening, samples were prepared for further microinvestigations of the structure. To determine the actual structure of the samples were prepared in different directions of the foamed material. In particular, samples were prepared in two mutually perpendicular directions.

During the research, the structure of foamed materials was studied. The shape and size of pores and their distribution were determined.

The currently accepted methods for studying porous materials are microscopic morphology methods [23, 24].

Processing of these pore formation processes is carried out by the methods of mathematical statistics [25] and mathematical modelling [26].

Research methods of this study include methods of chemical synthesis, methods of microscopic analysis, methods of modeling, statistical analysis.

In further studies, it is planned to use Infrared spectrometry to clarify the content of organic and inorganic substances, to identify probable changes in the composition of the obtained materials.

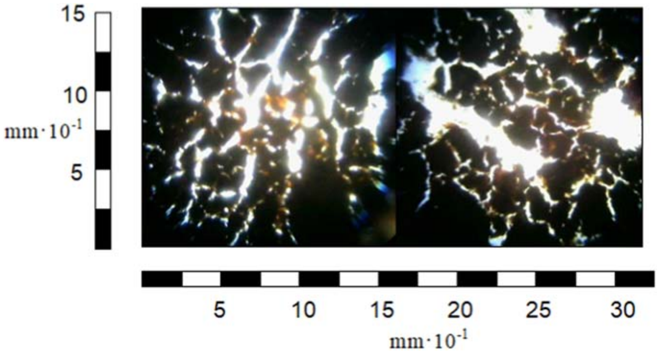

Figure 4. Formation of open pores during foaming with the addition of magnetic nanopowders.

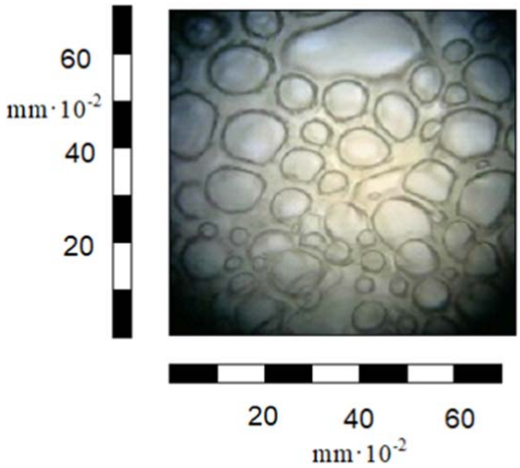

Figure 5. Pore formation with the addition of conventional powders.

3. Results

These results show that foaming under normal conditions provides the formation of a structure in the form of closed cavities of approximately spherical shape (figure 2).

As already mentioned, this structure cannot be used as a material for creating negative capillary pressure.

The addition of a magnetic nanopowder to a polymeric material during foaming fundamentally changes the structure. Figure 4 shows micrographs of a porous material obtained by foaming polyurethane containing magnetite.

Closed spherical shapes are gone. Instead of them, long branched pores of an open structure appeared. Although different clusters of the obtained material show different shapes and sizes of the resulting pores, in general, their elongated open shape should be noted. For such pores, one can introduce the concept of length, flow section, and conditional diameter of this section. Such structures will have a capillary effect. They will have the ability to suck up liquid, creating a negative pressure.

To test the effect of the proposed powders on the structure of foamed materials, foaming experiments were also carried out with the addition of conventional chemically and physically neutral fine powders (sand). Figure 5 demonstrates the fact that the overall pore structure in the material does not change. It is likely that the shape and size of the pores change to some extent, but this is of no fundamental importance for the purpose set.

Let us try to explain the reasons for the fundamental change in the mechanism of pore formation in materials with the addition of magnetic nanopowders.

Under normal conditions, the process of increasing closed pores can be represented in the model of viscous-fluid deformations under the action of internal gas pressure (figure 6(a)). In this case, the increase in the cavities will increase until the internal stresses in the material balance the gas pressure in the cavity. Since the mechanical characteristics of the material are approximately the same, the learned cavities will be the same (figure 5).

The introduction of magnetic nanopowders into the material changes its mechanical characteristics. The material becomes quasi-brittle to a certain extent. In this case, the cavity does not expand indefinitely, but after reaching a certain pressure it breaks. In this case, the cavity can be connected to an adjacent cavity, which has

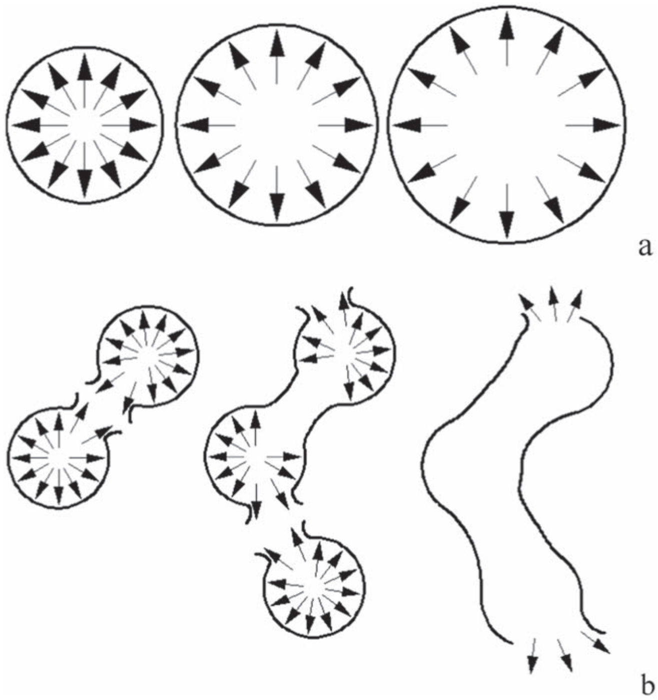

Figure 6. Mechanisms of pore formation (a) - closed, (b)—open.

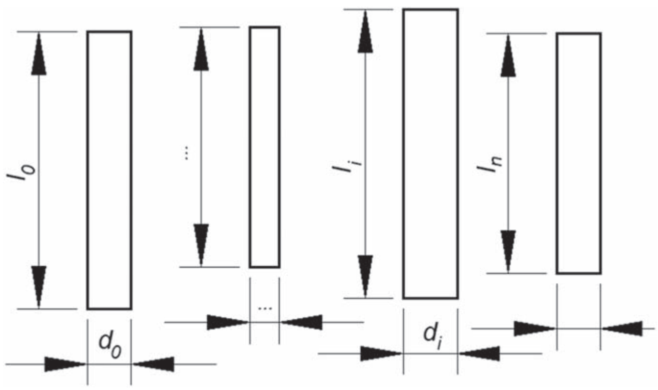

Figure 7. Capillaries in porous bodies with open pores.

undergone a similar destruction. A further system of destruction leads to the formation of a complex structure of cavities, which is a system of connected destroyed micropores (figure 6(b)).

As a result, the structure takes the form of a system of open pores - capillaries capable of creating back pressure to remove liquid [27, 28].

Each individual pore can be represented as a pipe, which has its own length and diameter (figure 7).

The capillary pressure is determined by the average capillary diameter d and the wetting angle Θ [29].

$$\Delta p \leftarrow \frac{\cos \Theta}{d}$$

In the process of studying of the system of pores in a material containing nanopowders (figure 4), intervals of change in their diameters were identified. At the same time, the lengths of pore-capillaries were determined, for which a given diameter is characteristic. The data obtained for the foam samples are shown in the table 1.

Figure 8 shows a histogram of the distribution of capillary diameters.

The study of the distribution law makes it possible to find out the most probable sizes of pore-capillaries, and as a result, to determine the magnitude of the negative pressure that is created by the porous material.

With known parameters of wetting and size distribution of capillary pores in the material, it is possible to estimate the amount of negative pressure to remove exudate from wounds.

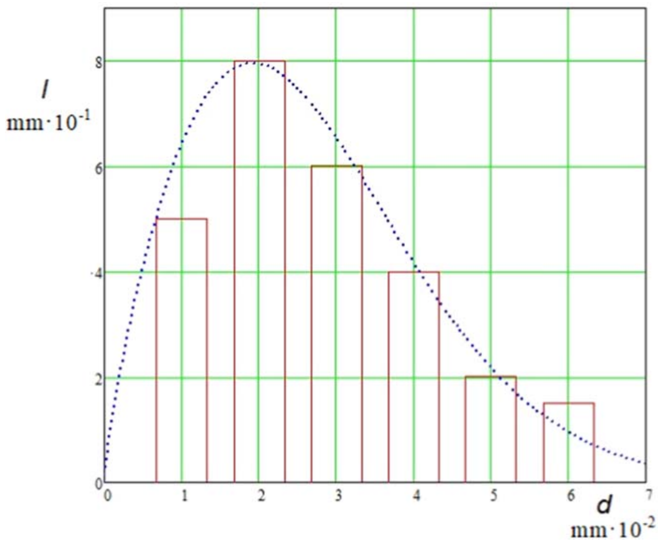

Figure 8. Distribution of capillary lengths by diameter size.

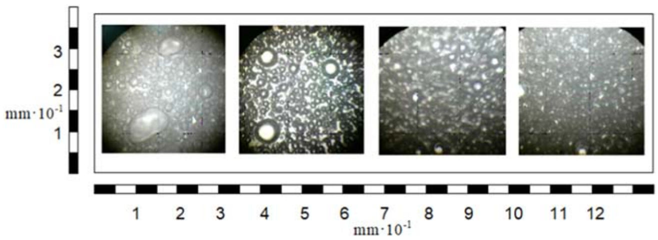

Figure 9. Distribution of pores depending on the content of nanopowder.

Table 1. Lengths of capillaries of various diameters.

d, mm·10^{-2}	d<1	1<d<2	2<d<3	3<d<4	4<d<5	d>5
l, mm·10^{-1}	5	8	6	4	2	

An actual task is to determine the required concentration of nanopowder to obtain the best effects. Additional studies were carried out on the effect of nanopowder concentration on the structure and size of pores. In this case, the pore formation process was carried out under the influence of a magnetic field. Figure 9 shows the distribution of pores without the content of nanopowder, as well as at a powder concentration of 0.1%, 0.2%, 0.3%. As the powder content increases, the average pore size decreases, and the size dispersion also decreases significantly. With an increase in concentration above 0.2%–0.25%, the effect slows down, which makes it possible to recommend this concentration for the formation of pores.

4. Conclusions

The effect of a fundamental change in the process of foaming polymeric materials using magnetic nanopowders has been revealed. The standard foaming procedure demonstrates the appearance of a system of hollow bubbles. This structure does not provide the conditions for the removal of exudate from purulent wounds. The addition of magnetic nanopowders to polymeric materials during foaming ensures the appearance of a capillary porous structure. Such foams can create the negative capillary pressure needed to remove exudate from wounds.

This effect makes it possible to increase the efficiency of foam structures in the process of use them as medical materials.

In the future, it is planned to study the influence of the parameters of magnetic nanopowders on the pore size, to determine the real parameters of capillary pressure, the effects of fluid removal from wounds, and to clarify bacteriological and bacteriostatic properties.

Additional studies for other magnetic nanopowders are also promising in order to identify the best conditions for the manifestation of the described effects.

The obtained results are considered as potentially effective for creating negative pressure in the treatment of wounds. For *in vivo* studies, it is planned to involve medical laboratories with subsequent publication in specialized medical journals.

Also, in further studies, it is planned to use Infrared spectrometry to clarify the content of organic and inorganic substances, to identify probable changes in the composition of the obtained materials.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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