STRENGTH FACTORS FOR GLASS FOAM

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ABSTRACT
It is shown how the macroscopic structure of material affect the mechanical strength of glass foam as well as the quantity and the size of a crystalline material presenting in the noncrystalline matrix of the interpore partition. It has been stated that the material having a hexagonal form of pores of 1-1, 5 mm in size and 40-50 μm in thickness of partitions, possesses maximum strength. In forming nanospheroids in the noncrystalline matrix of the foamed material partition, its strength reaches 4, 5 MPa that approaches to calculate strength values (5 MPa). In this paper, the degradation mechanism is described for foamed material using the equations of a synergetic model of amorphous body deformation.

1. Introduction

Mechanical properties of porous materials similar to glass foam are defined by its structure, i.e. the size, form, homogeneity of pore distribution, and also the thickness of the interpore partition and the composition of a noncrystalline component [1, 2, 3]. It is known that mechanical strength of amorphous phase is significantly increasing in presence of the crystal phase particles of micro and nanosizes, i.e. without stress concentration at the phase interface resulting in destruction [4, 5, 6]. The particles of this size can be obtained in glass by means of a partial crystallization or using a phenomenon of microliquation delamination [7, 8, 9].

A widespread glass foam technology is based on the use of flat and packing glass cullet or quenched cullet of the similar compositions which possess, as a rule, low crystallizability in the bulk. At sponging temperatures the ion diffusion and the crystal growth rate in the bulk significantly decreases. However, glass powder crystallization is much easier. In producing glass foam from glass powder blend and foaming agent, the specific surface of glass particles is relatively high and comes to approximately 6000 sm^2/g. Thus, even glasses whose crystallization is not observed in bulk at these temperatures also possess crystallization tendency in sponging. Due to this, crystallization can be found to a greater or lesser extent almost in any glass foam, more by token, that the temperature interval of sponging practically coincides with that one of crystallization of host glass.

The paper is aimed at detecting factors that affect the mechanical strength of glass foam material, the quantity and the size of crystalline material particles presenting in the noncrystalline matrix of an interpore partition.

2. Experimental

To analyze mechanical properties and to define ultimate resistance of the samples, tests were carried out using Test Machine ‘Instron 1185’ with the load range from 0-100 N to 0-100 kN. Precision of measurements is ± 0,25% of the load scale used. According to recommendations from the Federal standard P EH 826-2008 (Test method of compression properties), tests were carried out at the rate of 2 mm/min.

To determine the structure of the samples obtained, the optical and electron microscopy was used. The elemental composition of interpore partitions was detected with of high resolution scanning electron microscope JSM-7500FA and equipped with X-ray microanalyzer. Before re-

cording, the samples were covered with a thin platinum layer. Recording was carried out at the following modes: accelerating voltage of the electron beam of 10-15 kV; working distance of 20-50 mm; and magnification up to 100,000 times.

The X-ray structural analysis of the phase composition of quenched cullet and foamed material was carried out using DRON-3M diffractometer with Cu K_α radiation with monochromatization of a diffracted beam by a pyrolitic graphite crystal.

3. Results and Discussion

The foamed material production was carried out according to a two-stage technology developed by the authors [10, 11]. At the first stage the quenched culled was synthesized at temperatures of 850 – 950^{o}C that are significantly lower as compared to the glass melting (1400 – 1500^{o}C) used in a traditional glass foam technology. Such crystal and noncrystalline silica-containing rocks as silica sand, diatomite, flint, silica clay, perlite were sampled as a feedstock. A low-temperature synthesis of quenched cullet results in formation of residual silica in a vitrified material. At the second stage, a foam-forming mixture was being prepared from the quenched cullet powder and gas developing agent in sponging modes individual for each composition. Investigations carried out on glasses of Na_2O-CaO-SiO_2 system and containing Na_2O – 23%, CaO – 5%, SiO_2 – 72%, showed that the quenched cullet contains a residual crystalline material in a state of silica. The number and the size of particles of residual silica in a finished material are controlled by the composition of the initial mixture, technological modes of the quenched cullet synthesis and sponging.

By changing the technological mode and using various feedstock the foamed material samples were produced which contain the residual crystalline material from 5 to 20% in the bulk, that is supported by the results of X-ray structural analysis (Fig. 1). Optical investigations of the noncrystalline matrix of the foamed material partition showed the presence of particles with the strong interface (Fig. 2). Formation of particles can be explained by silica solution in the amorphous melt in sponging.

It has been stated, that the durability of the experimental samples increased from 1,8 to 3 MPa in changing the size of particles from 1000 to 300 nm in a crystalline material. On the basis of the experimental results, an isogram was designed for foamed material durability and the number of micro and nanoscale crystalline material dependence (Fig. 3). The results of calculations obtained by an interpolation method showed the maximum displacement of the foamed sample durability with the crystalline material particles of small sizes (300 nm) into the area of lower concentrations (5-7%).

For the samples with the fixed number of the residual crystalline material (5% on the average) and different sizes of its particles, the experimental dependence has been established (Fig. 4) which shows that the correlation between the strength and the size can be described by the simple exponential relationship $y = y_o + a_1 \times e^{-x/t}$ (correlation coefficient $R^2 = 0{,}98$). On the strength of assumption that the minimum particle size of the crystalline material corresponds to the size (10 nm) of heterogeneity areas presenting in the glass structure, the maximum theoretical durability of the foamed material was calculated by this dependence and comes to 5 MPa.

Controlling the technological mode of the quenched cullet synthesis and the sponging process so as to obtain a noncrystalline matrix in the interpore partition of residual silica of not over 5-7% in concentration and up to 100 nm in size, it is expected that the mechanical strength of the foamed material may achieve values exceeding 5 MPa. In case of the glass foam whose noncrystalline matrix does not contain the crystalline material this value does not exceed 1,5 MPa.

The foamed material samples selected for further investigations possess higher strength properties (Fig. 5). The macrostructure of these samples corresponds to the following parameters: hexagonal form of pores of 1-1,5 mm in size; thickness of the interpore partition 40-50 μm;

a high degree of the pore distribution homogeneity in the bulk of material; the crystalline material content not over 5% at its particles' size not exceeding 200 nm.

Electronic Microscope Image of the interpore partition of the foamed material shows spherical elements in size from 60 to 160 nm. Such structural elements (spheroids) have not been found in the interpore partition of the glass foam (Fig. 6). The bar chart of the distribution of spheroid sizes shows the average meaning of the sizes which is 89 ± 10 nm with the distribution maximum of 60 nm (Fig. 7).

The energy-dispersive analysis of the silica content in the noncrystalline matrix of partition showed its heterogeneous distribution. Maximum concentration was observed near the borders of partition; minimum – in the centre (Fig. 8). Electronic analysis of the Images has shown that the nanospheroids are the main siliceous structural elements which, generally, accumulate near the borders of the partition that strengthens it and explains the increased strength of the given samples.

A comparative analysis of deformation properties of the different foamed materials has shown that the generalized view of dependences $\sigma - f(\varepsilon)$ for the samples investigated, differs (Fig. 9). The value of ultimate strength of the samples containing nanoscale spheroids is considerably higher (2-3 times) in comparison with the sample strength which do not have such structural elements. It should be noted that in compressive testing of the foamed material, an abrupt destruction typical for brittle materials does not observed. With the load increase the sample starts to deform. The glass powder generating after that, sinks in cells which are destroying again with the following gradual destruction of the sample.

A synergetic approach was used to describe the process of deformation of foamed material presented in paper [12] for vitrification of liquid. In terms of synergetic equations for viscoelastic medium, a modified Maxwell equation (1) is in good agreement with the experiment. The first summand is responsible for dissipative process of stress relaxation to an equilibrium value; the second summand in this equation stipulates the self-organization process.

$$\sigma = -\sigma / \tau_\sigma + g \cdot \sigma \cdot \varepsilon \cdot T \qquad (1)$$

Thus, the most simple deformation curve $\sigma(\varepsilon)$ must possess not one but two areas. The first area is elastic, Hookean and has a wide angle of inclination; the second area is more flat and responsible for plastic deformation processes. Consideration of the deformation defect of the module with transition from Hookean stage to the flat area of plastic yield adequately reflects the vitrification process in terms of synergetic concepts. On a deformation curve of the foamed material really observed are two areas described by the synergetic model (Fig. 10). On the strength of the deformation curve analysis carried out according to the model of vitrification, the amorphous component of foamed material is strengthened by nanoparticles (residual silica), and defines both the high level of mechanical properties and the destruction process itself.

4. Conclusions

As a result of this research the factors affected the mechanical properties of the glass foam have been detected. In obtaining foamed materials with the increased mechanical properties the following factors should be taken into account:

1. Structure factor which detects the strength of the foamed material due to crystalline material nanoparticles presenting in the noncrystalline matrix. Maximum strength is observed in the samples with 5-7% concentration and the particle size of not over 300 nm. In forming a partition of the foamed material of nanoscale spheroids in the noncrystalline matrix, its strength reaches 4,5 MPa that approaches to the calculated strength values.
2. Technological factor which is detected by the production mode of the foamed material. From the viewpoint of strength, the mode which allows producing the structure of material with pore size of 1-1,5 mm and hexagonal form; interpore partition thickness of 40-50 μm, and the equilibrium distribution of pores in the bulk.

3. Deformation factor which is detected by a self-consistent behavior of the particle ensemble. It conditions the process of deformation and destruction of the foamed material in terms of synergetic concepts of vitrification of liquid. Upon testing the foamed material a gradual destruction of the samples is observed that was connected with strengthening of the interpore partition.

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Figure captions

Figure 1 – X-ray pictures of foamed material with the different content of crystalline material: *а – 5 %; б – 10 %; в – 15 %*

Figure 2 – Electronic pictures of interpore partition of foamed material obtained from the low-temperature quenched cullet

Figure 3 – Isogram of foamed material strength dependent from the size of particles of crystalline material: *1 – 3 MPa; 2 – 2,3 MPa; 3 – 1,8 MPa*

Figure 4 – Foamed material strength and particle size of crystalline material dependence.

Figure 5 – Pore form of foamed material with different strength

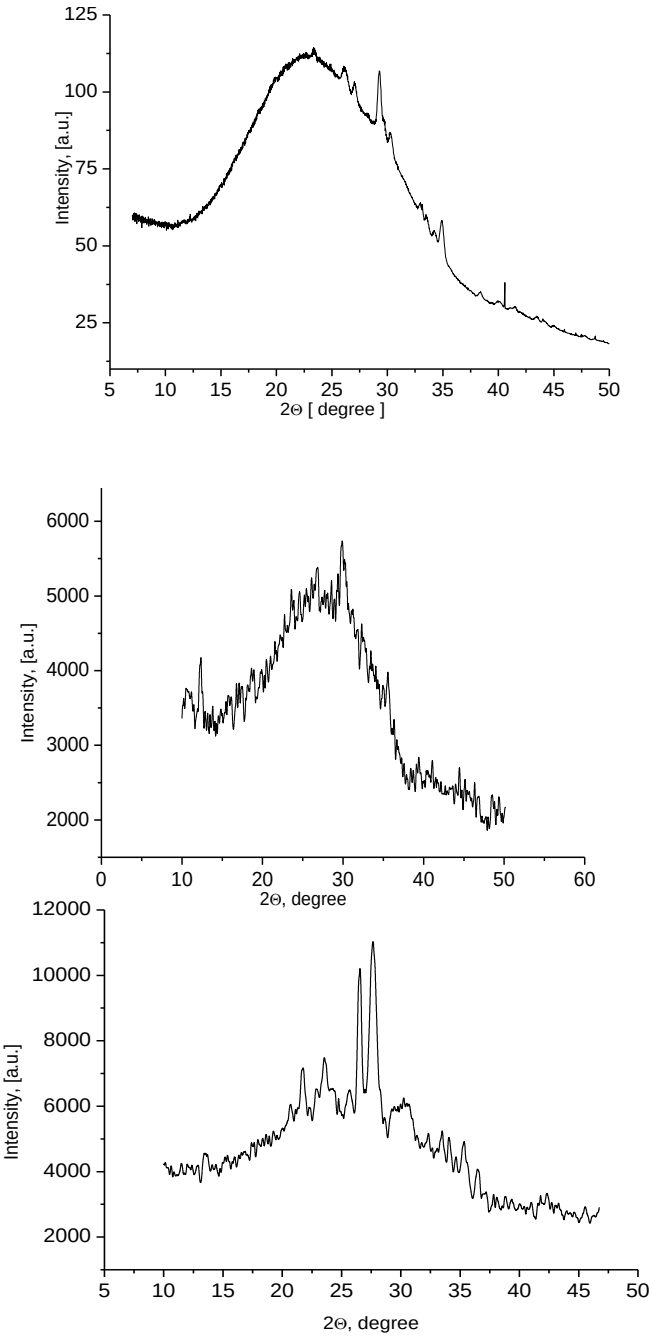
Figure 6 – Electronic Microscope Image of the interpore partition in foamed material

Figure 7 – Distribution of spheroids presenting in interpore partition by sizes

Figure 8 – Distribution of the silica content in the interpore partition

Figure 9 – Deformation curves of tensile tests: 1 – foamed material obtained on the basis of quenched cullet; 2 – industrial glass foam; 3 – laboratorial glass foam.

Figure 10 – Deformation curve (in the time) of foamed material.


Intensity, [a.u.]
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Intensity, [a.u.]
2Θ, degree
Intensity, [a.u.]
2Θ, degree

Figure 1

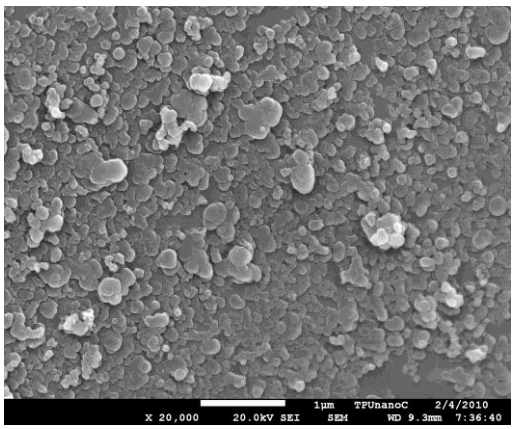


Figure 2

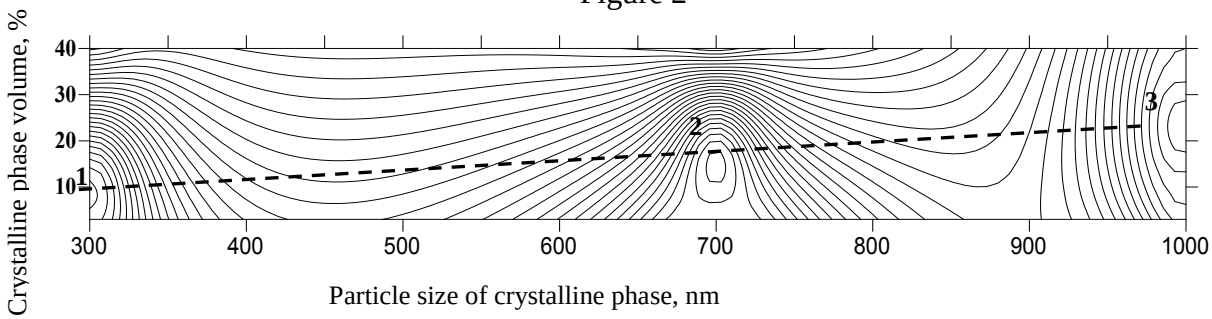


Figure 3

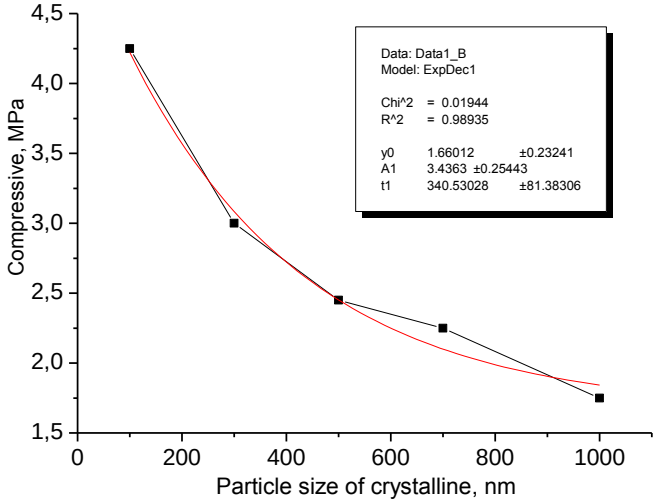


Figure 4

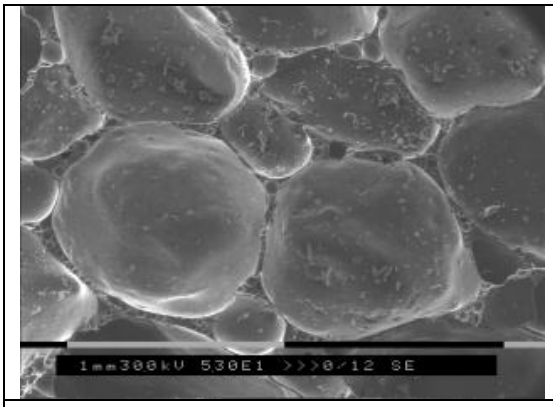
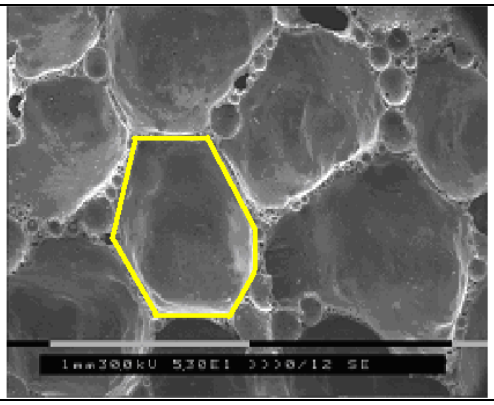
	
3,41 MPa	3,67 MPa

Figure 5

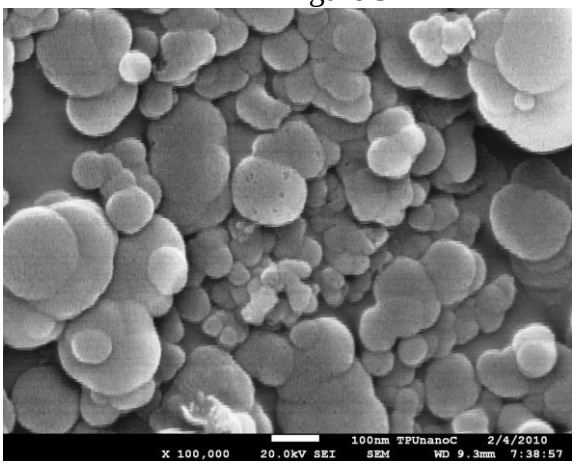


Figure 6

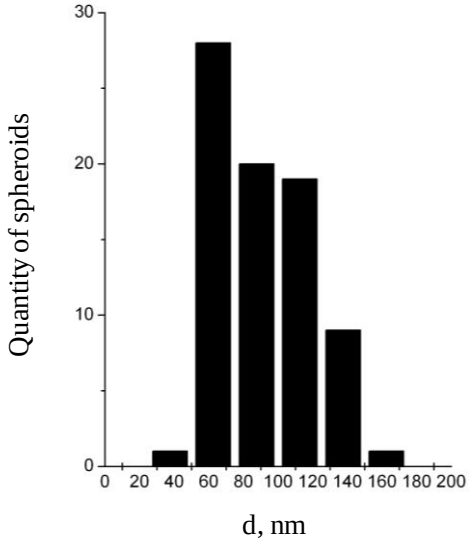
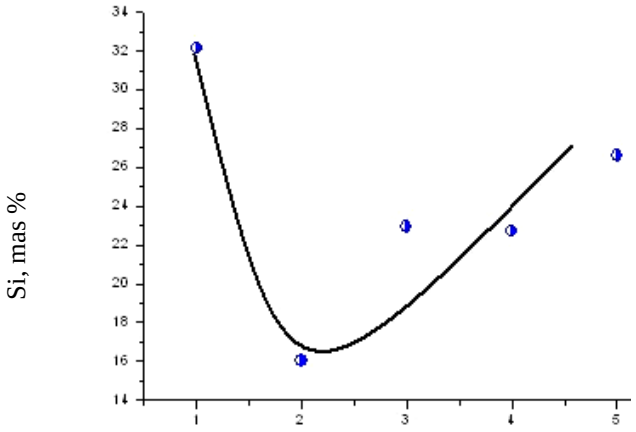


Figure 7



The numbers of measuring points of silicon concentration

Figure 8

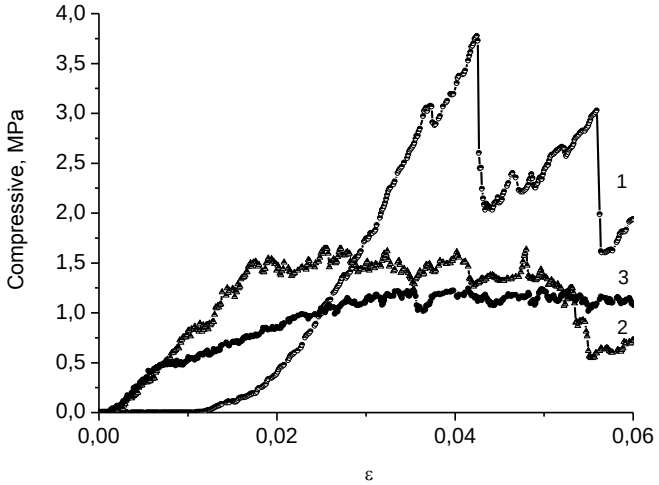


Figure 9

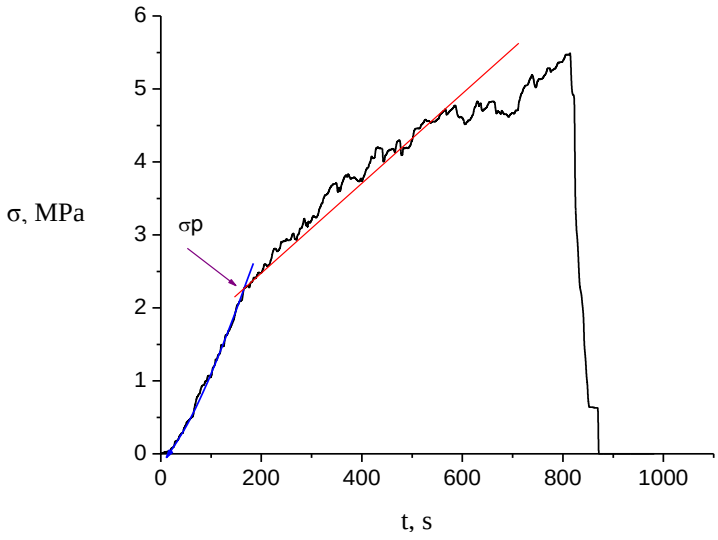


Figure 10

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