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Mechanism of high energy absorption by foamed materials–foamed rigid polyurethane and foamed glass

TOSHIO KURAUCHI, NORIO SATO, OSAMI KAMIGAITO, NOBORU KOMATSU
Toyota Central Research and Development Laboratories Inc., 41-1, Aza Yokomichi, Oaza Nagakute, Nagakute-cho, Aichi-gun, Aichi-ken, 480-11, Japan

Energy absorbability of foamed rigid materials, polyurethane and glass, was studied under a compressive load. The brittle materials were proved to absorb much energy in a manner similar to ductile materials. A mechanism for such high energy absorption was proposed, based on a fracture model in which crushing of cells initiates at the weakest cell followed by propagation to cells lying in the layer containing the weakest one and lying in a direction perpendicular to the compressive force; then the crushing propagates to another layer under the compressive force after the completion of the first layer crushing. In the period of one layer crushing, the strain energy stored in the period of compression prior to the crushing is temporarily released, and it is stored again in the period of compression after the crushing. The store and release of strain energy is assumed to be repeated until all cell layers are crushed. This mechanism of layer-by-layer crushing allows the cells to absorb strain energy repeatedly, and causes high energy absorption in the brittle foamed material. The calculated energy based on the mechanism agrees well with the observed one.

1. Introduction

The emphasis on safety in automobiles has increased the need for more information on the energy-absorbing materials. To protect a driver from injury in a traffic accident, the compressive behaviour of a material should be ingeniously utilized for design of energy-absorbing structures. Foamed rigid polyurethane is particularly useful as an energy-absorbing material, because it has a wide plateau in the compressive stress–strain curve; the wide plateau contributes to the increase of the area under the stress–strain curve, which is usually defined as the energy absorbability of materials.

The mechanical properties of foamed rigid polyurethane, such as compressive strength, tensile strength and Young's modulus, have been extensively studied and reviewed by Hilyard [1]. From these studies, the outline of the properties of the material is well understood. Moreover, some theoretical studies of some of the properties have been made, and as a result the elastic modulus of the polyurethane can now be evaluated theoretically with rather high accuracy [2, 3]. The compressive and shear strength of the polyurethane foams have also been studied, and the semi-theoretical formula is given, in which the strengths are described as a function of the density of foamed materials [4]. The absolute determination of the strength, however, is not given in the study due to the complicated structure of the foamed materials. The deformation of several flexible and rigid foamed materials under compressive stress has been studied by Rusch [5–7], and the non-linear stress–strain curve was dealt with by the introduction of an empirical function, "shape function". The behaviour under compressive stress was also studied by Miltz and Gruenbaum [8], as well as by two of the present authors, under high speed impact and static load [9, 10]. In these studies, the material was proved to deform in a ductile manner similar to a ductile metal and polymer, and to absorb much energy in spite of the fact that the foamed material is composed of brittle substance.

The presence of the plateau or the nonlinearity in the compressive stress–strain curve, which is responsible for the high energy absorption of the material, is dealt with in these studies as a remarkable property of the material. The mechanism of occurrence of the plateau or the high energy absorbability of the material, however, seems to be unexplained in the studies made so far.

The object of the present research is to make an experimental study of the energy absorbing behaviour of foamed rigid polyurethane and clarify the mechanism of the high energy absorption of the foamed structure made of brittle material. To achieve this object, the deforming behaviour of some foamed glass was also studied, and the validity of the proposed mechanism was examined.

2. Experimental details

2.1. Preparation of specimens

Polyol containing fluorocarbon was well mixed with isocyanate with a stirrer. The amount of each component was 50 wt %. The mixture was poured into a 40 mmϕ x 300 mm aluminum mould with a small opening, at room temperature. Immediately after pouring, the opening was shut to maintain the pressure. The mixture gave foamed rigid polyurethane after 1 h. The specimens for compression tests were made by cutting the polymer into disks of 30 mmϕ x 20 mm.

Also, two types of foamed glass, Celoam and Foam Glass, were used to examine the validity of the postulated mechanism of the high energy absorption by brittle foamed material. Celoam was supplied by the Toyota Spinning and Weaving Co. Ltd, Japan, and is composed of low density foamed glass (density $\simeq$ 190 kg m^{-3}). Foam Glass was purchased from Corning Glass Works, USA. Its density is about 130 kg m^{-3}. The cell size of both types of the foamed glass is about 1 mm. The specimens for compression tests were made by cutting them into cubes of 50 mm x 50 mm x 50 mm.

2.2. Apparatus

The specimens were compressed uniaxially with an Instron universal testing machine. The cross-head speed was 0.0017 m sec^{-1}. The load for compressing was recorded against the displacement of the cross-head. From the load–displacement curve, the energy absorbability of the specimens was obtained.

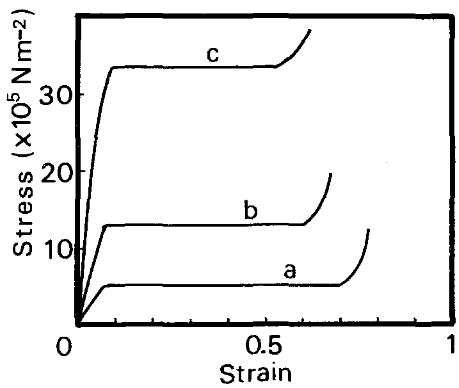

Figure 1 Typical stress–strain curves of foamed polyurethane: (a) 50 kg m^{-3} density, (b) 100 kg m^{-3}, (c) 200 kg m^{-3}.

Under these types of loads, the specimens were crushed. The occurrence and propagation of the crushing were observed under a microscope, and recorded on a photograph. Moreover, the fragments were observed microscopically.

3. Results and discussions

Typical stress–strain curves of foamed polyurethane under compression are given in Fig. 1 for specimens of various densities. As shown in the figure, the stress applied to the foamed polyurethane specimens increases with the strain of the specimen, and reaches a nearly constant value (plateau stress, σ_p) for strains exceeding the elastic strain limit (ϵ_p). The plateau stress, σ_p, is larger for higher density (Fig. 2), while the elastic strain limit is nearly constant against specimen density and about 8% (Fig. 3). The total energy absorbed up to the end of the plateau region of stress–strain curve is shown in Fig. 4. The figure shows

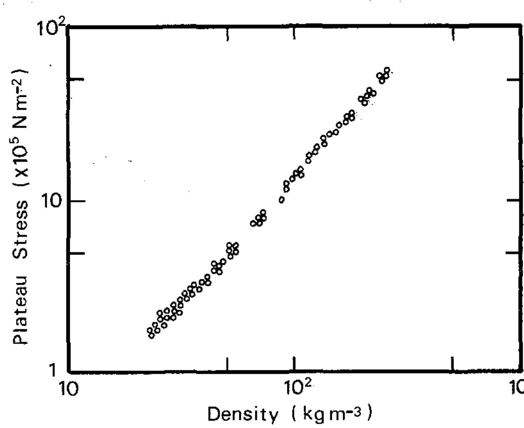

Figure 2 Influence of density on plateau stress σ_p for foamed polyurethane.

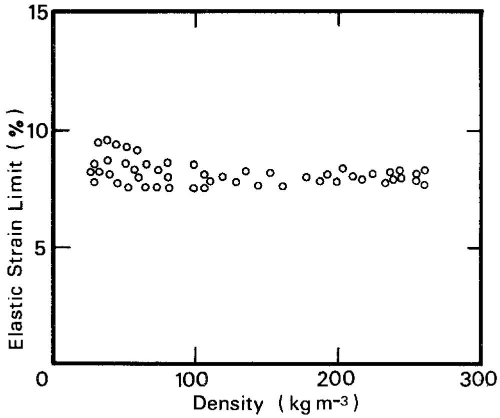

Figure 3 Influence of density on elastic strain limit ϵ_p for foamed polyurethane.

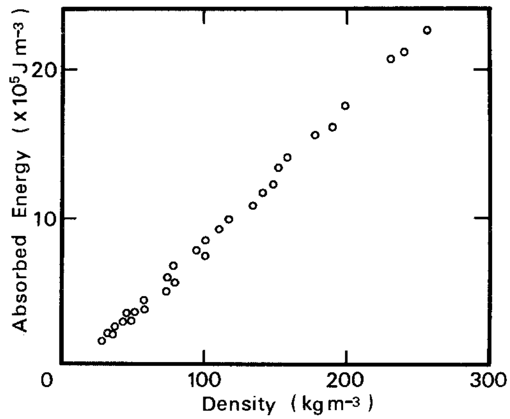

Figure 4 Influence of density on absorbed energy up to the end of the plateau region for foamed polyurethane.

that foamed polyurethane has an unexpectedly high energy absorbability.

The structure of the cells is shown in Fig. 5. As shown in the figure, the cell is of a kind of polyhedron, the wall is very thin and the ridge is thick and rather straight. The photograph of the fragments is shown in Fig. 6. The size of the fragments is about half of the cell size. The fragments have sharp edges, and appear to have resulted from brittle fracture. The fracture mode may well be predicted, because polyurethane is a brittle material.

In the brittle fracture, the energy is absorbed through strain and a creation of surface. The strain energy of the foamed polyurethane is considered to be less than the maximum strain energy, E_e, allowable for the solid polyurethane which has the same volume as the sum of those of walls and ridges of the foamed polyurethane. Since, as mentioned above, the structure of the cell is complex and the thickness is not uniform, and the actual strain of the polyurethane in the substantial part of the cell will be much less than the maximum fracture strain of the uniform solid material. The calculated value of E_e is given in Table I.

The energy absorbed by the fracture surface is given by the size and the thickness of fragments. The sum of the new surface, S, is estimated as follows:

$$S \sim \frac{1}{3}\frac{\rho}{\rho_0}\frac{1}{d} \qquad (1)$$

where ρ, ρ_0 and d stand respectively for the density of the foamed polyurethane, that of solid polyurethane and the cell size. Equation 1 can be derived on the assumption that the cell is a cubic balloon with a constant thickness. Also, it can be deduced from the assumption that the cell is a cubic balloon having infinitely thin walls and consisting of twelve ridges of constant section.

Anderton has reported 91.4 J m^{-2} as the fracture surface energy for foamed rigid polyurethane [11]. The values of estimated surface energy calculated by using this value and the sum of the surface energy and the strain energy are given in Table I. The sum is much less than the actual absorbed energy. Therefore, the energy absorption mechanism may be considered to be different from the mechanism conventionally proposed and so far described in this report.

The stress–strain curves for Celoam and Foam Glass are given in Figs. 7 and 8 respectively. The curves are very similar to that of the foamed polyurethane. The absorbed energy is given in Table II. As shown in the table, also, foamed glass

TABLE I Estimated strain energy and surface energy of foamed polyurethane

Specimen number	Density (kg m^{-3})	Observed energy ($\times 10^5$ J m^{-3})	Estimated strain energy, E_e ($\times 10^5$ J m^{-3})	Estimated surface energy, E_s ($\times 10^5$ J m^{-3})	$E_e + E_s$ ($\times 10^5$ J m^{-3})
1	50	3	0.09	0.05	0.14
2	100	9	0.17	0.09	0.26
3	200	17	0.34	0.19	0.53

TABLE II Comparison of observed energy with calculated energy based on the proposed mechanism

Specimen	Density ($kg\,m^{-3}$)	Cell size (cm)	σ_p ($\times 10^5\,N\,m^{-2}$)	ϵ_p	Observed energy ($\times 10^5\,J\,m^{-3}$)	Calculated energy ($\times 10^5\,J\,m^{-3}$) Cubic cell			Spherical cell		
						$m = 1$	$m = 50$	$m = 100$	$m = 1$	$m = 50$	$m = 100$
Polyurethane	50	0.03	5	0.08	3	2.8			2.7		
	100	0.03	15	0.08	9	8.2			7.8		
	200	0.03	33	0.08	17	17.2			16.5		
Celoam	190	0.1	35	0.01	25	1.1	21.0	25.6	1.1	19.7	23.8
Foam Glass	130	0.1	10	0.01	6	0.3	6.0	7.3	0.3	5.6	6.8

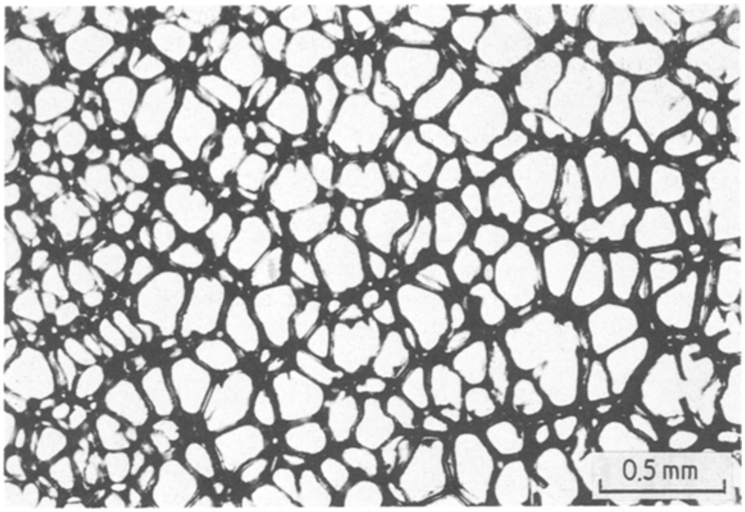

Figure 5 Typical cell structure of foamed polyurethane.

absorbs much energy in a similar way to the foamed polyurethane. The photographs of the fragments of Celoam and Foam Glass are shown in Figs. 9 and 10. The fragments are very small as compared with cell size, which is a significant difference from polyurethane. From this observation, the fracture of a cell is thought to occur step by step.

The observation of the crushing way of the foamed polyurethane reveals that crushing occurs in a layer of cells perpendicular to the pressing direction (Fig. 11). From these, crushing of the polyurethane is thought to occur in the following way (Fig. 12). The first breaking occurs at the weakest cell. This results in stress concentration on the cells located round the broken cell in the layer which contains the broken one and is perpendicular to the pressing direction, and the cells in the layer break successively. As a result of the break, the strain in the cells lying above and below the crushed cells is released tentatively, since the stress in the crushed cells become free. After a substantial breaking of the layer, the strain increases again, because the unbroken layers just above and below the crushed layer come into contact with each other due to the load application. Thus, crushing of cells will propagate to the whole, by repetition of strain storage and release.

The maximum stress during the propagation may be almost the same as that at the initiation of breaking, because the cell dimensions are nearly the same throughout the specimen. Therefore, the stress–strain curve is expected to be nearly constant after a linear increase in the curve. This mechanism is a good explanation of the observed stress–strain curve.

The final stress increase is attributed to the

Figure 6 Crushed cells of foamed polyurethane.

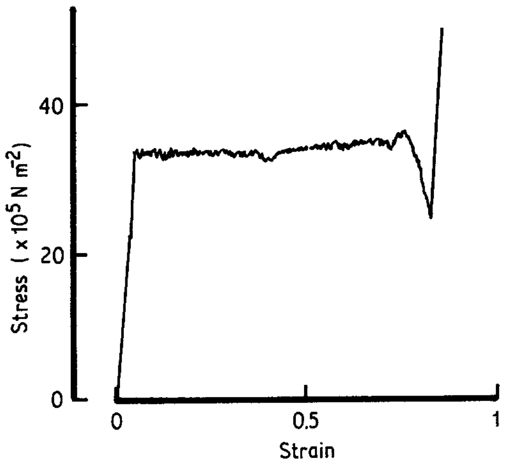

Figure 7 Stress–strain curve of Celoam.

compression of the inflexible fragments, resulting from a complete breaking of cells.

The absorbing energy of the foamed polyurethane can be estimated by consideration of the following steps, based on the above proposed mechanism. First, energy is absorbed by elastic deformation before occurrence of crushing. Second, crushing of a layer releases part of the stored energy, and energy absorption is made again by deformation of uncrushed layers to the ultimate strain. On the assumption that one cell breaks at a time (single process), the strain released in each layer that survives in one layer-crushing period is given by averaging the effective height of the vacant space of one cell through which the top wall of the cell can traverse in one layer-crushing period. This partial strain-release occurs so long as the size or height of monolayer of cells is less than the ultimate strain of all survived

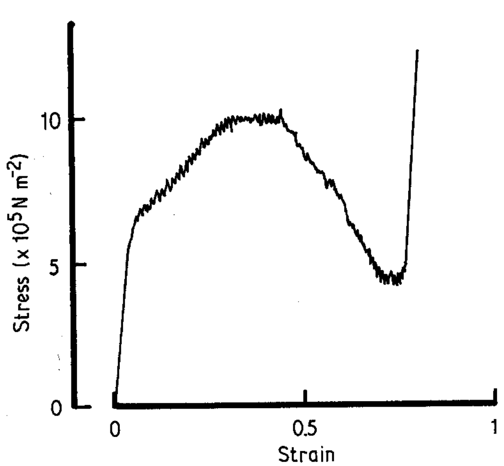

Figure 8 Stress–strain curve of Foam Glass.

layers. In the third stage, when the sum of the strain is less than the cell size, the strain of the specimen is released completely. The energy stored by survived layers in the period between one crushing and the succeeding one is given by the ultimate strain energy of one layer multiplied by the number of the survived layers.

It is assumed that the load–deflection curve of one cell is linear as shown in Fig. 13. The fracture load is f_0 and the ultimate strain is z_0. The energy absorbed by one column of n_z cells which are arranged in the direction of the compressing force is given for each stage as follows. In the first stage, the energy is evidently given by the following,

$$E_1 = \tfrac{1}{2} f_0 z_0 n_z. \tag{2}$$

In the second stage, it is given by the following,

$$E_2 = f_0(d-rt^s)(n_z-n_c) - \frac{1}{2}\frac{f_0}{z_0}(d-rt^s)^2 \sum_{n=n_c}^{n_z} \frac{1}{n} \tag{3}$$

where the term, $d-rt^s$, stands for the effective height of the vacant space of the cell in which the top wall of the cell can traverse in one layer-crushing period under the influence of the compressive stress, and s as well as r is a geometrical factor depending on the shape of the cell, d and t stand respectively for the size of a cell and a half of wall thickness of a cell. The effective height is less than the cell size, because the vacant space in the cell is partially occupied by the crushed cell walls piled on the bottom of the cell in the crushing. On the assumption that the crushed cell walls are packed densely on the bottom of the vacant space, s and r can be calculated, and $s = 1$, $r = 6$ for a cubic cell, $s = 1/2$, $r = (2d)^{1/2}$ for a spherical cell.

In the third stage, it is given by the following,

$$E_3 = \tfrac{1}{2} f_0 z_0 \sum_{n=1}^{n_c} n \tag{4}$$

where n_c is the critical number of survived cells in the column, for which the sum of the ultimate strain of survived cells is equal to the cell size, d, or

$$n_c z_0 = d \tag{5}$$

The total energy of the unit volume, which is assumed to consist of $n_z \times n_z \times n_z$ cells is given by summing E_1, E_2, and E_3, as follows,

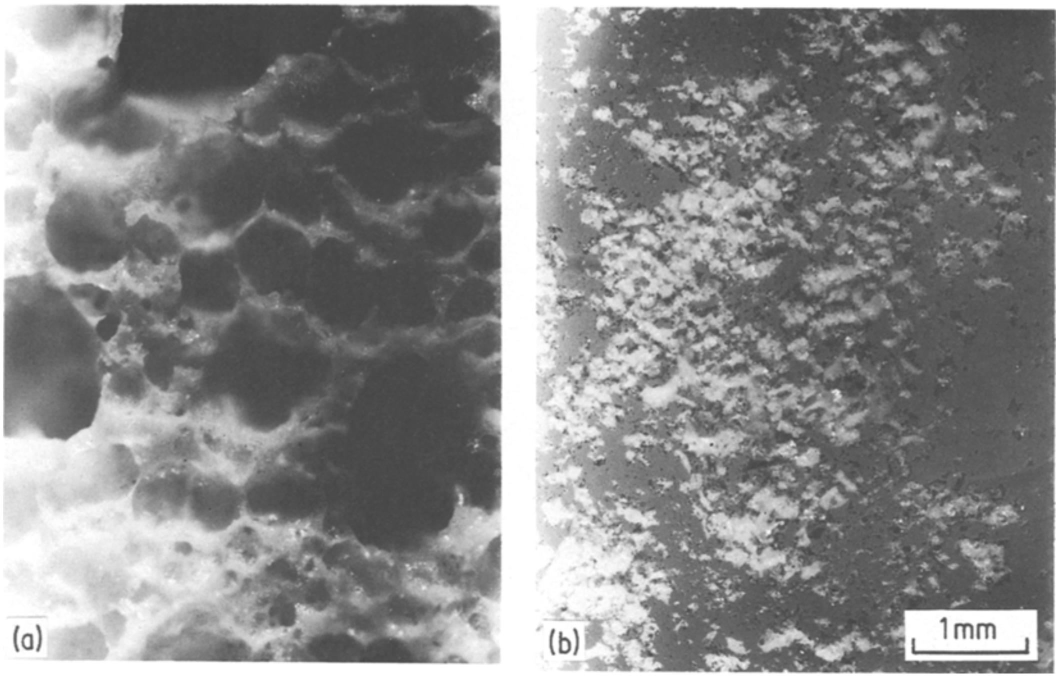

Figure 9 Cell structure and fragments of Celoam.

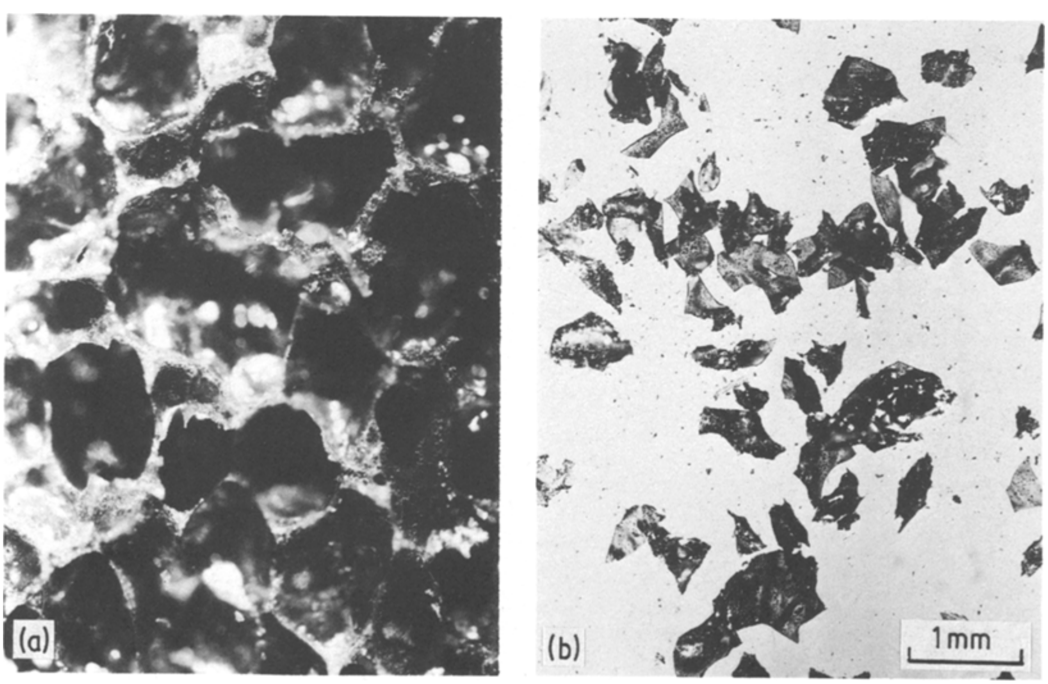

Figure 10 Cell structure and fragments of Foam Glass.

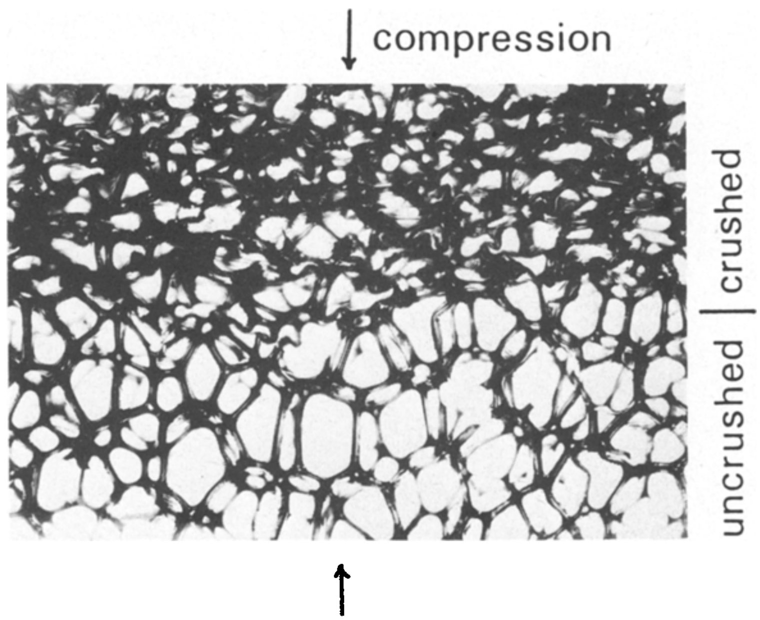

Figure 11 Photograph of partially crushed polyurethane.

$$E_c = \tfrac{1}{2}\sigma_p\epsilon_p + \sigma_p\left[1 - k\left(\frac{\rho}{\rho_0}\right)^s\right]\frac{n_z - n_c}{n_z} - \frac{1}{2}\frac{\sigma_p}{\epsilon_p}\left[1 - k\left(\frac{\rho}{\rho_0}\right)^s\right]^2 \frac{1}{n_z}\sum_{n=n_c}^{n_z}\left(\frac{1}{n}\right) + \tfrac{1}{2}\sigma_p\epsilon_p\frac{1}{n_z}\frac{n_c(n_c+1)}{2} \tag{6}$$

where k is a geometrical factor depending on the shape of the cell, and $s = 1, k = 1$ for a cubic cell, $s = 1/2$, $k = 1/3^{1/2}$ for a spherical cell, on the assumption of the dense piling of the crushed cell walls.

Equations 2 to 6 are derived on the assumption of the single process in that one cell is crushed completely at a time. In a material of large foams, crushing of a cell is expected to be completed after multiple partial breaking (multiple process). And in the period between one partial breaking and the succeeding one, the strain energy is assumed to be stored and released in the same way as in the single process.

In the multiple process, on the assumption that the cell is crushed after m times partial breaking, that the stress–strain curve is common also to the partially broken cell and that the released strain is the same for each partial breaking or equals the averaged height over m-times breaking, $(d - rt^s)/m$, the absorbed energy is given in correspondence to Equations 2 to 4 as follows.

The absorbed energy in the first stage is the same as that in the single process,

$$E_1' = \tfrac{1}{2}f_0 z_0 n_z \tag{7}$$

In the second stage, the energy is stored and released by survived cells as well as partially broken cell. The energy absorbed by survived cells is given by the following,

$$E_{2,ub}' = f_0\left\{\sum_{q=1}^{n_z - n_c'} \times \sum_{p=1}^{m}\frac{(d - rt^s)}{m(n_z - q) - (p-1)}(n_z - q)\right\} - \frac{f_0}{2z_0}\left\{\sum_{q=1}^{n_z - n_c'} \times \sum_{p=1}^{m}\left[\frac{(d - rt^s)}{m(n_z - q) - (p-1)}\right]^2 (n_z - q)\right\} \tag{8}$$

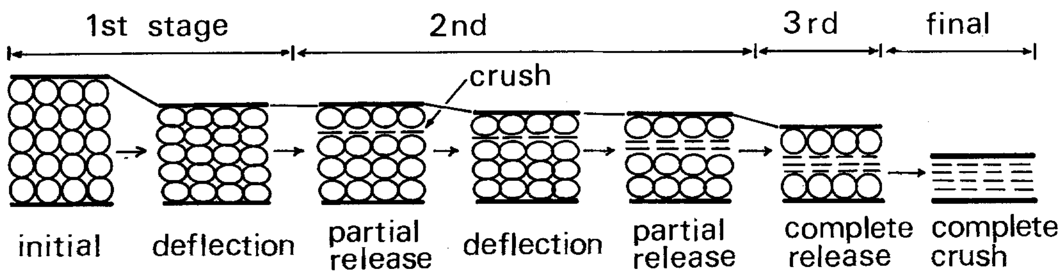

Figure 12 Cell crushing model.

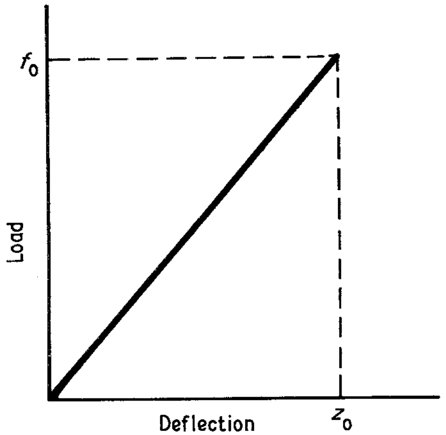

Figure 13 Assumed load–deflection curve of one cell.

The energy absorbed by the partially broken cell is given by the following,

$$E'_{2,pb} = f_0\left\{\sum_{q=1}^{n_z-n'_c}\sum_{p=1}^{m}\frac{(1-p/m)(d-rt^s)}{m(n_z-q)-(p-1)}\right\}$$
$$-\frac{f_0}{2z_0}\left\{\sum_{q=1}^{n_z-n'_c}\right.$$
$$\left.\times\sum_{p=1}^{m}\left[\frac{(1-p/m)(d-rt^s)}{m(n_z-q)-(p-1)}\right]^2\right\} \quad (9)$$

And the energy absorbed in the second stage is given by summing up $E'_{2,ub}$ and $E'_{2,pb}$,

$$E'_2 = E'_{2,ub} + E'_{2,pb} \quad (10)$$

where n'_c is given by the following, in correspondence to Equation 5

$$mn'_c z_0 = d \quad (11)$$

Combination of Equations 5 and 11 gives the following,

$$n'_c = n_c/m \quad (12)$$

when $m = 1$ in Equation 10, E'_2 tends evidently to E_2 (Equation 3). In Equations 8 to 10, as $n_z - q \geqslant n'_c > 1$ and $p - 1 < m$, the following is assumed to hold,

$$m(n_z-q) \gg p-1. \quad (13)$$

On this assumption, the term $(p-1)$ in the equations are neglected, and E'_2 is approximated as follows,

$$E'_2 = f_0(d-rt^s)\left\{\left(n_z-\frac{n_c}{m}\right)+\sum_{n=n'_c}^{n_z}\left(\frac{1}{n}\right)\right.$$
$$\left.-\frac{1}{2}\frac{f_0}{z_0}\frac{(d-rt^s)^2}{m}\left\{\sum_{n=n'_c}^{n_z}\left(\frac{1}{n}+\frac{1}{n^2}\right)\right)\right\} \quad (14)$$

Furthermore, in Equation 14, as $\Sigma\, 1/n \ll n_z$ and $1/n^2 \ll 1/n$, E'_2 can be well approximated as follows,

$$E'_2 = f_0(d-rt^s)\left(n_z-\frac{n_c}{m}\right)$$
$$-\frac{1}{2}\frac{f_0}{z_0}\frac{(d-rt^s)^2}{m}\sum_{n=n'_c}^{n_z}\left(\frac{1}{n}\right) \quad (15)$$

In the final stage, the absorbed energy is given as follows,

$$E'_3 = \tfrac{1}{2}f_0 z_0\sum_{n=1}^{n'_c} n \quad (16)$$

Then, the absorbed energy in the multiple process is given by summing up E'_1, E'_2 and E'_3 as follows,

$$E'_c = \tfrac{1}{2}\sigma_p\epsilon_p + \sigma_p\left[1-k\left(\frac{\rho}{\rho_0}\right)^s\right]\left(\frac{mn_z-n_c}{mn_z}\right)$$
$$-\frac{1}{2}\frac{\sigma_p}{\epsilon_p}\left[1-k\left(\frac{\rho}{\rho_0}\right)^s\right]^2\frac{1}{mn_z}\sum_{n=n_c/m}^{n_z}\left(\frac{1}{n}\right)$$
$$+\tfrac{1}{2}\sigma_p\epsilon_p\frac{1}{mn_z}\frac{n_c(n_c/m+1)}{2} \quad (17)$$

where $s = 1$, $k = 1$ for a cubic cell and $s = 1/2$, $k = 1/3^{1/2}$ for a spherical cell, as discussed before. When $m = 1$, E'_c tends to E_c in the single process, as seen from Equation 17.

The calculated values of E_c for various foamed materials of two kinds of cell, cubic and spherical, are given in Table II. The values of σ_p and ϵ_p in Equations 6 and 17 cannot be theoretically estimated, because the structure of cells is very complex [4]. Therefore, their observed values were used in calculation of E_c. The values based on the single process agree well with the observed ones for the foamed polyurethane. This proves the validity of the postulated mechanism. However, the values based on the process do not agree with the observed ones for foamed glasses. Yet, for foamed glass, the value based on the multiple process of $m = 50$ or $m = 100$ agrees rather well with the observed one. In this glass, the fragments are much smaller than the cell size in contrast with the case of the foamed polyurethane, as mentioned before. This observation seems to support the interpretation of the process as the multiple one. And these agreements appear to prove the validity of the mechanism, again.

The equations will apply to every brittle material. Therefore, for any brittle material, a high energy absorbability can be given by making products of finely foamed cells. A phenomenological criterion to obtain high energy absorbability from brittle materials will be occurrence of the layer by layer crushing.

4. Conclusions

Foamed rigid polyurethane has an unexpectedly high energy absorbability due to the existence of a large plateau stress region in the stress–strain curve under a compressive load. Crushing of cells occurs in a weakest layer perpendicular to a compressive load and then propagates to another layer. The layer by layer crushing continues up to a complete breaking of cells, during which a large plateau stress region is observed in the stress–strain curve. The strain energy is stored and released by the layers which survive in every layer-crushing, and the cell in the layer of the pth crushing absorbs about p times the energy of one cell crushed by a single loading. According to this mechanism, a brittle foamed material absorbs much more energy than a solid material of the same substance. A cell in foamed polyurethane is crushed completely by a single loading (single process) and a cell in foamed glass with a larger cell size is crushed through multiple partial breaking (multiple process). The calculated energy based on the mechanism agrees well with the observed one. This agreement proves the validity of the postulated mechanism. For any brittle material, a high energy absorbability can be given by making products of finely foamed cells.

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