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Impact studies on extruded food foams

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A Charpy-type impact test has been performed on a number of foams produced by the extrusion cooking process. The energy to break falls with increasing notch size for values of the notch length greater than the pore size. The critical strain energy release rate has been calculated from linear elastic fracture mechanics for rectangular cross-section foams. This approach has also been applied to foams of circular cross-section using calibration factors obtained from a comparison of rectangular and circular cross-section foamed plastics.

1. Introduction

The extrusion process is extensively used in the production of snack-foods and crispbreads which are brittle foams formed by steam released from the food melt or dough [1]. A considerable range of foam structures may be produced by manipulation of the process variables. The consumer-perceived textural attributes of these products depend on the mechanical properties [2]. The majority of studies on the mechanical properties of extruded materials has been carried out using devices based on tensile testing machines. Multiblade platens have frequently been devised to measure textural properties [3]. In addition simpler tensile, compressive and flexural tests have been carried out [4, 5]. These experimental procedures are performed at low deformation rates and few data exist for mechanical properties at high strain rates. Van Zuilichem *et al.* [6] used an Izod impact test to obtain the mechanical strength of extruded maize as a function of extrusion moisture content. Hayter *et al.* [7] used an instrumented pendulum to compress extruded foams and found an approximately linear relationship between the failure stress and the foam density.

The present work examines the mechanical properties of extruded foams using a Charpy impact geometry. Some rectangular section foams were cut from extrudates produced using a slit die and the critical strain energy release rate calculated from the impact tests. In many cases extruded foams have a circular cross section for which the Charpy test method is inapplicable. Nonetheless these samples were notched and tested as for rectangular cross-section foams. A comparison of circular and rectangular cross-section specimens was made using a foamed plastic to give calibration factors for cylindrical samples. This permitted estimates of the critical strain energy release rate to be made for this geometry.

2. Experimental approach

Maize grits and wheat starch were extruded using a co-rotating, twin-screw extrusion cooker (Baker Perkins MPF 50D). A commercial foamed plastic was also examined.

The density of the food foams was calculated from the displacement of fine sand. The density of the plastic foam was derived from the weight of blocks of known volume.

The impact properties were obtained using a Zwick 5102 testing machine with a 0.5 J hammer. Between four and eight samples of each foam were tested at each notch depth and an average energy loss calculated. The energy to break was corrected for the pendulum air resistance by subtracting the free swing energy loss. A kinetic energy correction was not possible for these low-strength samples [8].

Rectangular cross sections were produced from extrudates obtained using a slit die attachment on the extruder. Samples were cut using a sharp blade a short time after extrusion, before the extrudate had finally cooled and solidified. It was found to be impossible to cut undamaged rectangular specimens from cylindrical extrudates. These samples were tested directly using the same notching procedures as for those of rectangular cross section.

The extrudate test pieces were notched using a low speed diamond-impregnated wafering saw (Buehler Isomet) of sufficiently large radius (127 mm) to minimize notch curvature. This was fitted with a sample holder which could be indexed towards the blade by means of a micrometer in steps of 0.635 mm. Notches of width 0.4 mm and various lengths could then be made. This technique was used in the current studies because the pore size was generally greater than 0.4 mm and less damage was caused to the surrounding foam than by razor notching.

3. Results and discussion

The energy to break selected foams is plotted as a function of notch length in Fig. 1. It is evident that in some cases the energy is approximately constant below a certain notch length. The transition in the energy plot corresponds to the notch length equalling the pore size. When the notch length is less than the cell size the notch is an ineffective flaw, as would be expected. In other respects these data closely follow those obtained for isotropic polymethyl methacrylate samples [9].

McIntyre and Anderton [10] used linear elastic fracture mechanics to obtain the critical strain energy

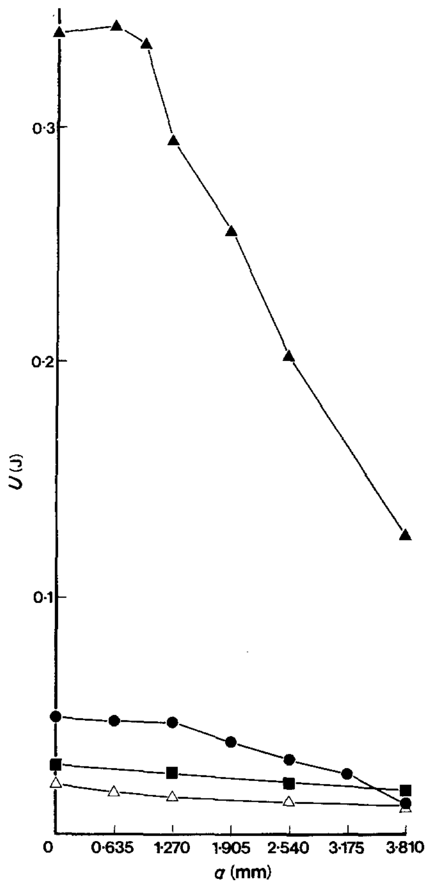

Figure 1 The energy to break cylindrical foam samples, U, as a function of notch length, a. (▲) Wheat starch, (●) maize, (■) wheat starch, (△) foamed plastic.

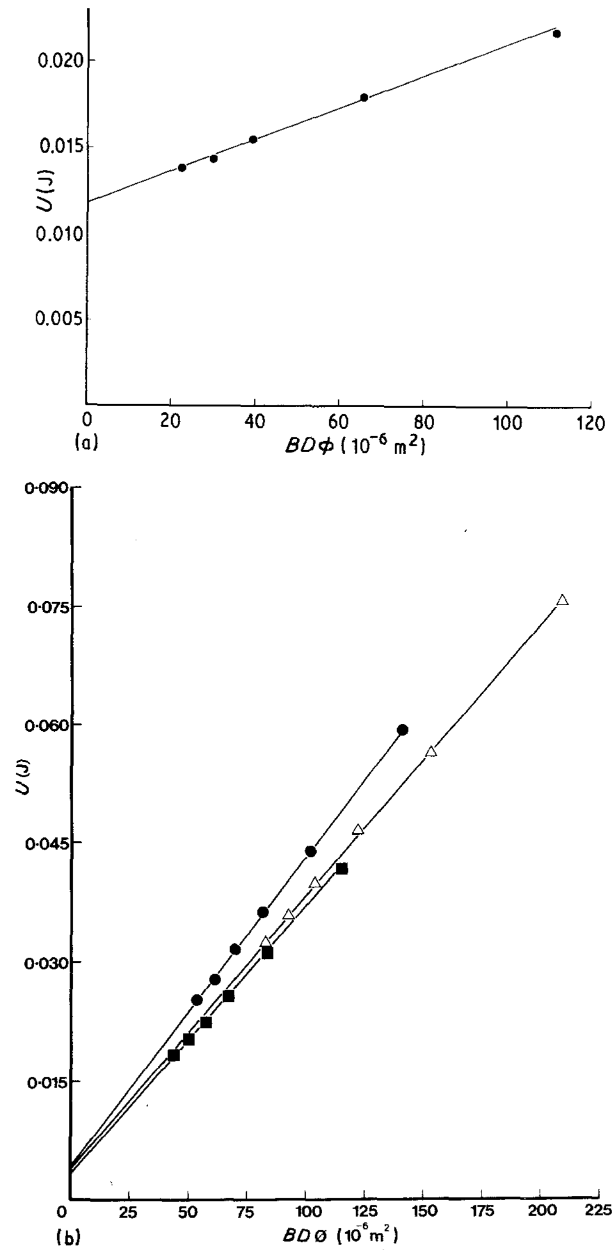

Figure 2 The energy to break rectangular section foams, U, as a function of the term, $BD\phi$. The ϕ calibration factors were taken from [11]. (a) Foamed plastic, bulk density $30\,\mathrm{kg\,m^{-3}}$. (b) Extruded maize, bulk densities: (●) 790, (△) 660, (■) $640\,\mathrm{kg\,m^{-3}}$.

release rate, G_c, for rigid polyurethane foams.

$$U = G_c BD\phi$$

Their procedure was adopted for the foams of rectangular cross-section. The energy U is plotted against the term $BD\phi$ in Fig. 2 where B is the specimen thickness, D is the specimen height and ϕ is the calibration factor for the Charpy geometry [11]. The values of ϕ were taken from the original Plati and Williams data [11] where possible. In the case of the extruded food foams, the specimen length to height ratio depends on processing conditions, and interpolation between their data was necessary. The energy U was varied through the notch length, a, where ϕ is a function of a/D.

The same method was also used for the circular cross-section foams. The values of BD were equated to πR^2 where R is the radius of the cross section. The value of D was obtained by equating $D_{\mathrm{eqv}} = (\pi R^2)^{1/2}$.

The notch depth to sample depth ratio, a/D, was identified with the ratio of the area of the segment comprising the notch to the cross-sectional area. The Charpy ϕ calibration factors were used as before, and this resulted in curved plots of U against $BD\phi$. A geometry correction was then made to the ϕ factors by comparison of rectangular and circular cross-section samples of the foamed plastic. The values of ϕ were adjusted to give linear U against $BD\phi$ plots of the same slope (G_c) as the data for the rectangular cross-section samples. The modified dependence of ϕ on notch size is shown in Fig. 3, together with the data for rectangular section samples from [11]. These modified ϕ factors were then used for the cylindrical food extrudates which resulted in linear U against $BD\phi$ plots (Fig. 4).

The variation of the fracture toughness, K_{IC}, with density has been predicted by Ashby [12]

$$K_{\mathrm{IC}} \propto \sigma_{\mathrm{w}} \, (\varrho/\varrho_{\mathrm{w}})^n \, (\pi l)^{1/2} \tag{1}$$

where σ_{w} is the failure stress of the wall, l is the pore size and ϱ, ϱ_{w} are the densities of the foam and cell wall, respectively.

$$G_c \propto K_{\mathrm{IC}}^2/E \tag{2}$$

where E is Young's modulus.

Ashby [12] also related the elastic properties of foams to their density

$$\frac{E}{E_{\mathrm{w}}} \propto \left(\frac{\varrho}{\varrho_{\mathrm{w}}}\right)^m \tag{3}$$

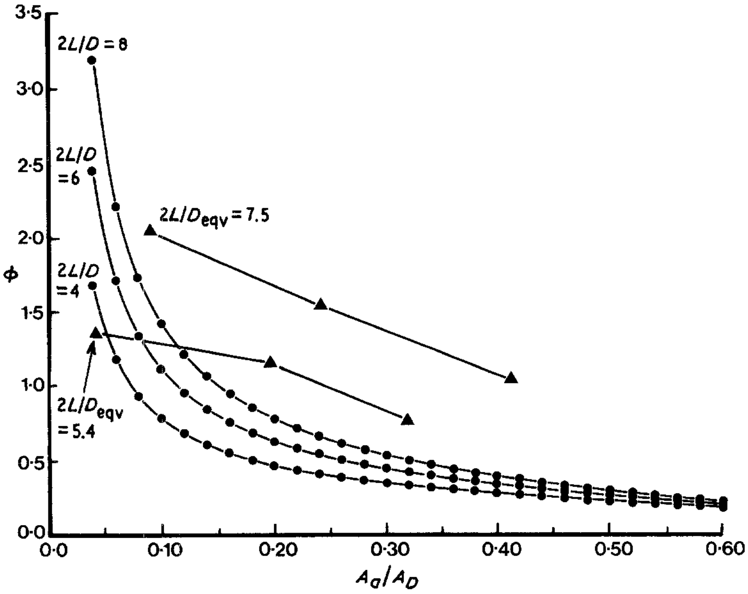

Figure 3 The calibration factors, ϕ, as a function of the ratio of the segment area containing the notch to the cross-sectional area for circular section specimens, A_a/A_p (▲). The standard data for rectangular cross section specimens are taken from [11] (●) for which $A_a/A_D = a/D$. $2L$ is the sample span and $D_{eqv} = (\pi R^2)^{1/2}$.

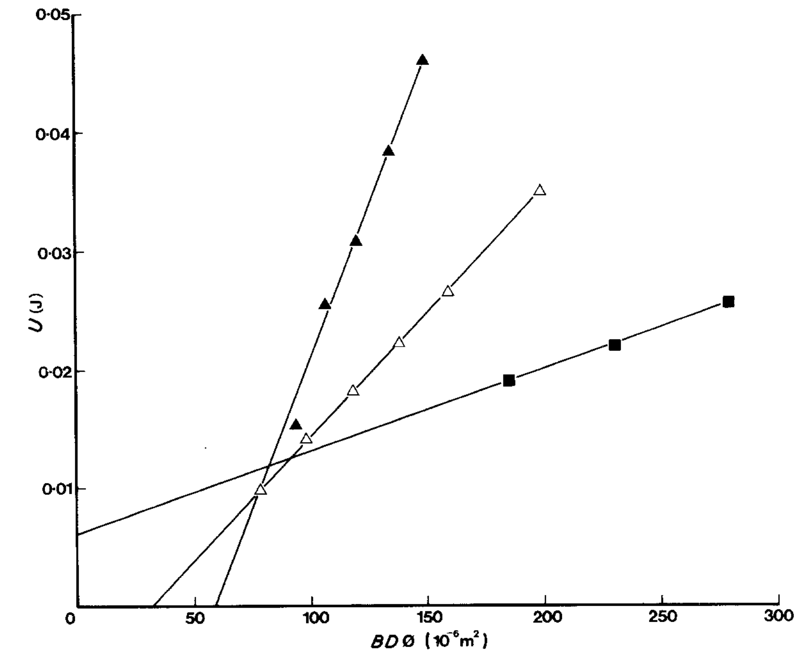

Figure 4 The energy to break circular section foams, U, as a function of the terms $(BD)\phi$. The ϕ calibration factors were taken from Fig. 3, BD was taken as the cross-sectional area of the foam cylinders. Bulk densities (kg m^{-3}): (■) wheat starch, 70; (△) maize, 280; (▲) maize 720.

where E, E_w are the Young's moduli of the foam and wall material, respectively.

Substitution of Equations 1 and 3 into Equation 2 yields

$$G_c \propto \frac{\sigma_w^2}{E_w}\left(\frac{\varrho}{\varrho_w}\right)^{2n-m} l \qquad (4)$$

The wall properties of extruded food foams are difficult to define [5, 7]. Previous work on the mechanical properties of extruded food foams [5] has shown that good agreement with the Ashby equations may be obtained by assuming that the wall properties are constant. Equation 4 then reduces to

$$G_c \propto \varrho^{2n-m}\, l$$

For closed or open cell foams, $2n - m = 1$ [12], hence

$$G_c \propto \varrho\, l \qquad (5)$$

l is not single-valued because of the pore size distribution in extruded food foams [7]. This uncertainty in the value of l precludes verification of Equation 5. The dependence of G_c on the bulk density is plotted in Fig. 5. It may be seen that data obtained for rectangular and circular cross-section foams fall on the same line. The results of McIntyre and Anderton [10] indicate G_c values in the range 295 to 540 J m^{-2}, whereas G_c is of order 10^3 J m^{-2} for isotropic specimens [9]. It is interesting to note that McIntyre

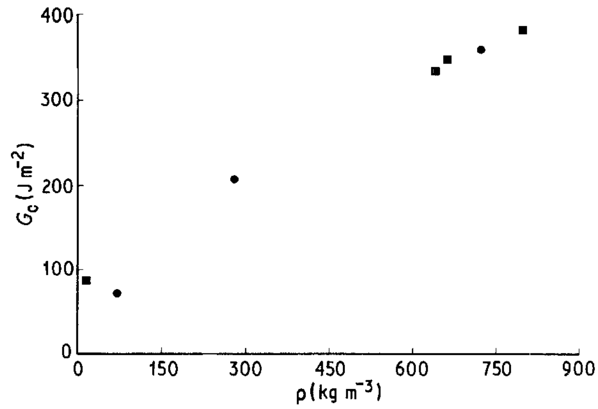

Figure 5 The critical strain energy release rate, G_c as a function of the bulk density. (■) Rectangular section, (●) circular section.

and Anderton also observed an increase in G_c with ϱ for polyurethane foams, although they found a discontinuity in G_c at a density of $130\,kg\,m^{-3}$.

4. Conclusion

A Charpy impact technique has been applied to extrusion cooked foams to obtain the effect of notch size on the energy to break. The notch size only affects the strength when it is greater than a value of the order of the pore size.

The energy to break as a function of notch length has been used to obtain the critical strain energy release rate, G_c, for rectangular section specimens. This approach has been taken over to circular section specimens to obtain G_c values. This was achieved by testing a foamed plastic in both geometries. The dependence of the Charpy calibration factor on notch size for cylindrical samples could then be derived from the basic Plati and Williams data for bars.

The Ashby treatment of foams may be used to predict the dependence of G_c on the product of the density and pore size. This relationship has not been tested due to the pore size distribution in the food foams. The values of G_c do, however, increase with the bulk density in a basically linear relationship.

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