

COMMUNICATION TO THE EDITOR

Free Surface Energy in the Elasticity of Wheat Flour Dough

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To understand the importance of changes in free surface energy of dough gas cells in the deformation of wheat flour dough, the following quantities are useful: 1) gas volume of the dough, 2) distribution of dough gas cell radii, 3) distribution of deformation between gas cells and gas-free dough, 4) surface tension between gas cells and gas-free dough, and 5) change in surface area of the gas cells when deformed. Knowing these, one can judge the importance of free surface energy by comparing it in deformation with the energy needed to deform dough elastically.

Baker and Mize (1) and Bloksma (2) demonstrated that up to 20% (v/v) of gas was occluded into wheat flour dough during its mixing. The gas volume in dough used in our study was determined to be 10%. The density value for gas-free dough was 1.24 g/cm^3 (1).

We found no data in the literature on the distribution of gas cell radii in dough. The following method was adopted for determining this distribution: slices of dough obtained by microtomy were photographed in a transmission light microscope, enabling us to measure cross sections of gas cells. These cross sections were converted to diameters.¹ Figure 1 shows the observed distribution function of gas cell radii, together with an analytic function fitted to the data. Appendix I gives details of the fitted analytic function and derivation of the ratio of surface area to volume of gas cells. Measuring gas cell cross sections corresponding to a radius of less than $\sim 45 \mu\text{m}$ with any certainty was impossible, although the theoretical resolution of cell radius should be $\sim 30 \mu\text{m}$ (dough slices $30 \mu\text{m}$ thick). From the fitted distribution function, the average surface area per cubic centimeter (A) was calculated to be 41 cm^2 .

Calculation of the change in gas cell surface area resulting from a uniaxial tensile deformation of dough requires an equation relating the strain of the dough to the strain of the gas cells in the dough. Given a homogeneous distribution of identical gas cells of volume fraction v_g , and further that no shear stresses are set up internally during the deformation, the behavior under tensile deformation can be approximated to the schematic drawing shown in Fig. 2.

Since equilibrium requires stresses to balance out internally, two equations follow from Hooke's law:

$$\sigma = E_d \epsilon_d = E_g \epsilon_g \quad (1)$$

where σ is the tensile stress; E and ϵ are Young's modulus and tensile strain, respectively; d is gas-free dough phase; and g is gas phase.

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The total strain of the dough is observable. We wish to derive an equation relating the individual strains of the two phases to the observable total strain. This is done as follows, by the definition of strain:

$$\epsilon_{\text{tot}} = \frac{\Delta l_g + \Delta l_d}{l_0} \quad (2)$$

Since the individual strains are given by:

$$\epsilon_g = \frac{\Delta l_g}{v_g l_0}; \quad \epsilon_d = \frac{\Delta l_d}{v_d l_0} \quad (3)$$

it follows by insertion of equation 3 into equation 2 that

$$\epsilon_{\text{tot}} = v_g \epsilon_g + v_d \epsilon_d \quad (4)$$

Unfortunately, information on the relative elastic strength of the gas and gas-free dough is lacking. Sixty percent (v/v) of a dough is made up of starch granules (3,4). This in turn means that in a dough with 10% gas cells, gluten material makes up nearly all the remaining 30%. Starch granules are rigid particles compared to gluten and gas cells. Hence, the gas cells make up 25% (v/v) of the *deformable* material in the dough. Using a value of 1.5 g/cm³ (5) for starch granule density and a specific area of 10,000 cm²/g for starch granules (5), we find a thickness of roughly 0.5 μm of the protein film covering the starch granule and gas cell area. What we term gas-free dough contains starch granules covered with a protein film, and is most likely much more solid-like than the gas phase. If the two phases deform independently as assumed above, the gas cell should show a

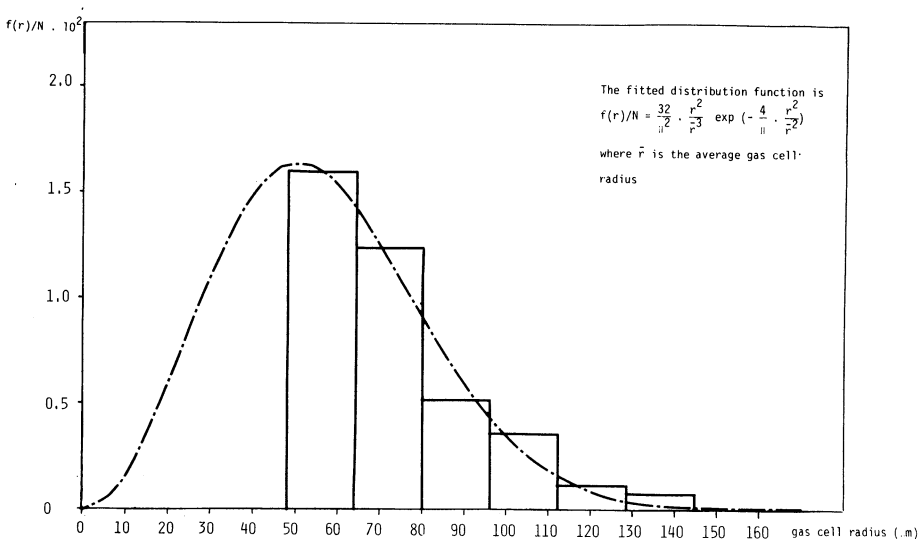
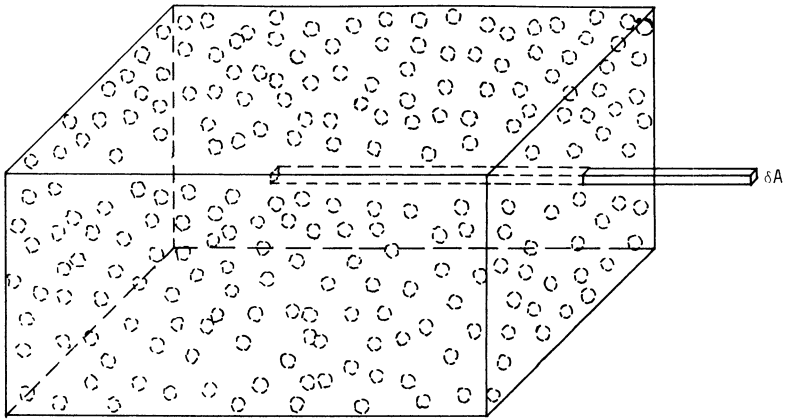


Fig. 1. Distribution of gas cell radii. Columns are measured radius. Curve is fitted distribution function.

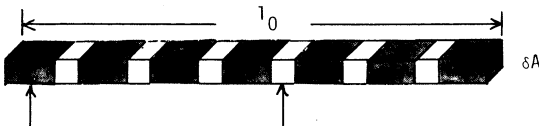
much lower resistance to deformation than the gas-free dough. In other words, Young's modulus of the gas cell is likely to be so much smaller than that of gas-free dough that ϵ_d can be neglected compared with ϵ_g (see equation 1). If the volume fraction gas v_g is not too low, equation 4 turns into the useful relationship of:

$$\epsilon_{tot} \approx v_g \epsilon_g \tag{5}$$

A SCHEMATIC PIECE OF DOUGH INCLUDING GAS CELLS

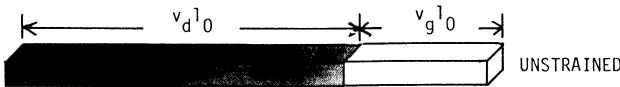


SMALL RECTANGULAR SECTION OF SAMPLE

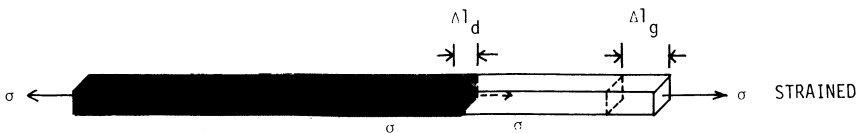


GAS FREE DOUGH GAS PHASE (including surrounding protein membrane)

EQUIVALENT CONSTRUCTION FOR TENSILE STRAIN CONSIDERATIONS



UNSTRAINED



STRAINED

Fig. 2. Schematic picture of uniaxial tensile deformation of dough. v_d and v_g are volume fractions of gas-free dough and gas cells, respectively.

The energy change involved in the deformation of the gas cells is the change in free surface energy, i.e., the product of surface tension and the change in surface area. The surface tension in the membranes surrounding the gas cells is not known. The most correct value to use is the equilibrium surface tension. Tschoegl and Alexander (6) give surface tension area data of gluten, and here we have used the surface pressure value of gluten at the air-water interface at "close-packing," ~ 10 dyn/cm, as an approximate value for the surface pressure of the interface between gas and gas-free dough. This surface pressure corresponds to a surface tension (γ) of ~ 60 dyn/cm at room temperature.

The amount of elastic energy density (energy per unit volume) w , involved in a uniaxial tensile extension of dough is

$$w = 1/2 \sigma \cdot \epsilon \quad (6)$$

where σ is the tensile stress and ϵ is the tensile strain. Data on the tensile deformation of dough (7) reveal that a tensile stress of $6 \cdot 10^3$ dyn/cm² results in a tensile strain of 0.04. The elastic energy density w from equation 6 is 120 erg/cm³.

To calculate the change in surface area of spherical gas cells when subjected to strain, we believe the following is a reasonable assumption: the spherical gas cell deforms into an ellipsoid at constant gas volume where the long axis is equal to $r(1 + \epsilon_g)$ (r is the sphere radius). This model does not overestimate the increase in surface area of the gas cell. The strain of 0.04 of dough with 10% (v/v) gas volume as discussed in the above results in a strain of 0.4 of the gas cells (equation 2). The surface area/gas volume ratio in this case is 4% larger in the ellipsoid compared with the sphere (see Appendix II). This means that the elastic strain in dough gas cells as described corresponds to an energy density of $0.04 \cdot \gamma \cdot A$ equal to 99 erg/cm³. Comparing this with the value 120 erg/cm³ for the total elastic energy density, we conclude that the change in free surface energy accounts for $\sim 80\%$ of the elastic energy involved in deformation of dough.

The temperature dependence of the free surface energy is dependent on how surface tension and surface area vary with temperature. The surface area is insensitive to changes in temperature, whereas the surface tension normally decreases with increasing temperature (8). This means that the deformation increases with increasing temperature at constant stress. This is opposite to the temperature dependence of rubber elasticity. Bloksma and Nieman (9) have found the former temperature dependence for wheat flour dough.

The proposed mechanism is attractive in several respects; it connects rheology with functionality for wheat flour dough, e.g., its gas holding capacity; it makes possible an understanding of how surface active material such as polar lipids improve dough and bread properties of wheat flour. A more rigorous theoretical and experimental study of this subject is currently under way at our laboratory.

Acknowledgments

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