Extensional Properties of Dough Sheets

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ABSTRACT

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A device is described for measuring rheological properties of a dough sheet with an Instron universal testing machine. A mathematical analysis of the setup is presented, allowing the stresses, deformation (elongation), deformation rate, and elongational viscosity to be calculated. Measurements on sheeted wheat flour dough at a water level suitable for pastry showed that stress increases with elongation rate. This behavior was linear on a double logarithmic scale, with a slope of 0.2–0.25. Elongational viscosity was of the order 10^5–10^6 Pa·sec when the elongation rate varied from 10^{-3} to 10^{-1} $\sec^{-1}$. Water addition affected the slope and the intercept of the straight lines. With more water added, the slope increased and the intercept decreased. The relaxation of dough sheets took place in about 50 min. The experimental data showed qualitative agreement with data obtained by other researchers using other (compression) methods.

Dough rheology is important in breadmaking, and over the years numerous empirical and fundamental tests have been developed to assess rheological properties of bread dough (Weipert 1992). The rheological behavior of dough is nonlinear, and data obtained at a particular strain or strain rate are only useful for the processing conditions that match that strain or strain rate. Empirically developed instruments such as the farinograph and mixograph simulate the shearing that takes place during mixing. Fundamental rheological properties have been measured with oscillatory methods in shear mode to determine dough properties under baking conditions. However, the analysis is essentially linear and thus restricted to small strains. Other instruments such as the alveograph and extensigraph measure extensional properties of dough. Various attempts have been made to determine fundamental rheological properties from these methods and from biaxial extensional deformations with a universal testing machine (UTM, Instron, Canton, MA) (Muller et al 1961, Rasper 1975, Bagley and Christianson 1986, Launay 1989, Dobraszczyk and Roberts 1994).

Although much work has been done on bread dough rheology, little is published on pastry dough rheology. Methods that are used for determining bread flour quality have been used by some for assessing pastry flour quality (Seibel and Ludewig 1978, Hay 1993), e.g., using the extensigraph method. Yet, pastry dough is quite different, not only in composition, but also in the strains and strain rates that are applied during pastry making. Moreover, pastry dough is produced as a sheet, which makes it impossible to present a sample to an extensigraph. Some attempts have been made to measure properties of a dough sheet (Lagendijk and Van Dalfsen 1965, Miller and Trimbo 1970), but these methods are somewhat tedious, and the results do not translate into fundamental rheological properties.

This article describes a method for measuring extensional properties of sheeted doughs. The method uses a UTM and is quick and easy. Since dough properties change rapidly after sheeting, studying the effect of sheeting on dough properties requires rapid measurement. To understand rheological data, a clear understanding of the effect of method parameters on the data is needed. Therefore, an analysis of elongation and elongation rate as a function of geometry and crosshead speed is given. Experimental data on dough behavior under varying water additions and elongation rates are presented and compared with data obtained by other researchers using different methods.

MATERIALS AND METHODS

Sheet Deformation Setup

The sheet-deforming device consists of two perspex plates with a circular aperture in the middle. A sheet of dough is placed between the plates. The sheet is held by eight sharp pins that are set in a circle 20 mm from the edge of the apertures of both plates. The pins are 1.2 mm in diameter with sharpened ends and protrude about 2 mm into the dough sheet. A flat probe, with rounded edges, is attached to an Instron UTM (model 1011). The dough sheet is deformed by the probe, which moves, with constant speed, vertically down the center of the aperture (Fig. 1). The setup is axially symmetrical, with the axis of symmetry going through the center of the probe. During deformation, the shape of the dough sheet resembles a cone with a flat top. Due to friction between the probe and dough sheet, there is little flow at this interface; hence, the extension takes place in the gap between the probe and the aperture perimeter. This is clearly visible from looking at a sheet after deformation. The deformed dough material

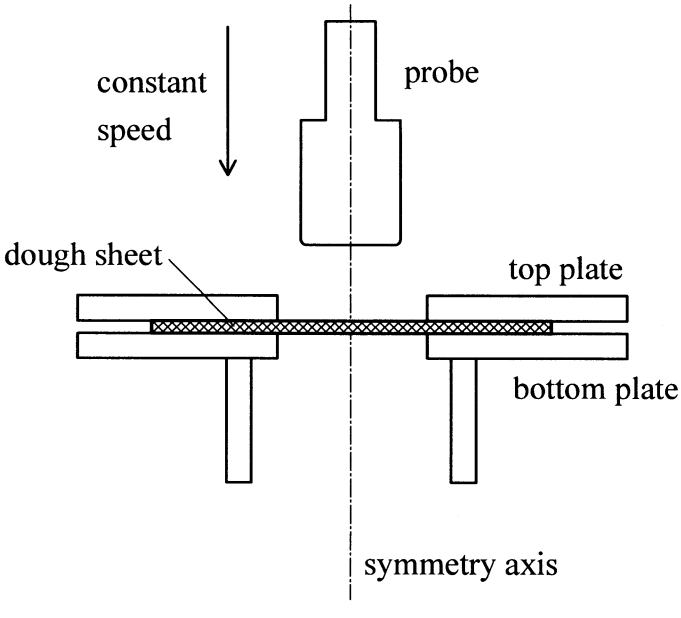

Fig. 1. Cross section of sheet deformation setup (not to scale). Probe diameter is 35 mm; aperture diameter is 55 mm. Typical sheet thickness is 3 mm.

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(the cone) is uniformly thin, whereas the thickness of material that was in contact with the probe or plates shows little change. Shear free flow is assumed. The Reynolds number, Re = $L \cdot v \cdot \rho / \eta$, for the dough extended under these conditions is estimated with a typical length L = 10 mm (gap size), velocity v = 100 mm·min^{-1} (crosshead speed), density $\rho = 1.2 \cdot 10^3$ kg·m^{-3} (typical density of pastry dough), and viscosity $\eta > 10^2$ Pa·sec (Bagley and Christianson 1986, Launay 1989). It follows that Re is $< 2 \cdot 10^{-4} \ll 1$ and a quasisteady-state approximation, neglecting inertial forces, can be applied.

Elongation and elongation rate are calculated as follows: The "length," l, of the sheet (see Fig. 2) is given by:

$$l(t) = \sqrt{l_0^2 + v^2 \bullet t^2} \tag{1}$$

where: l_0 is the distance (gap) between probe and aperture perimeter and v is the (constant) crosshead speed. The elongation rate, $\dot{\varepsilon}$, is:

$$\dot{\varepsilon}(\hat{t}) = \frac{1}{l}\frac{dl}{dt} = \frac{1}{t_c}\frac{\hat{t}}{1+\hat{t}^2} \tag{2}$$

where a characteristic time for the experiment, t_c, is defined and time, t, made dimensionless with this characteristic time:

$$t_c = \frac{l_0}{v} \quad ; \quad \hat{t} = \frac{t}{t_c} \tag{3}$$

Integration of equation 2 yields the elongation, ε, as a function of time:

$$\varepsilon(\hat{t}) = \frac{1}{2}\ln(1+\hat{t}^2) \tag{4}$$

A plot of elongation rate as a function of elongation is always of the same shape, with a scaling factor t_c^{-1} (see Fig. 3). The rate increases from zero value up to a maximum of $1/(2t_c)$ at an elongation of ½ln(2) = 0.35, after which it decreases steadily.

The force on the probe, $F(t)$, is measured as a function of time by the UTM. The force is converted into a voltage, which is recorded by a PC fitted with a data acquisition board (DAS800, Keithley Instruments, Taunton, MA). A program was written with the ASYST command line programming language (ASYST 1992) to record the force as a function of time. The average stress, $\sigma(t)$, in the sheet is calculated by dividing the force component in the direction of the sheet, F_s, by the average cross-sectional area A (see Fig. 2). The stress as a function of time is:

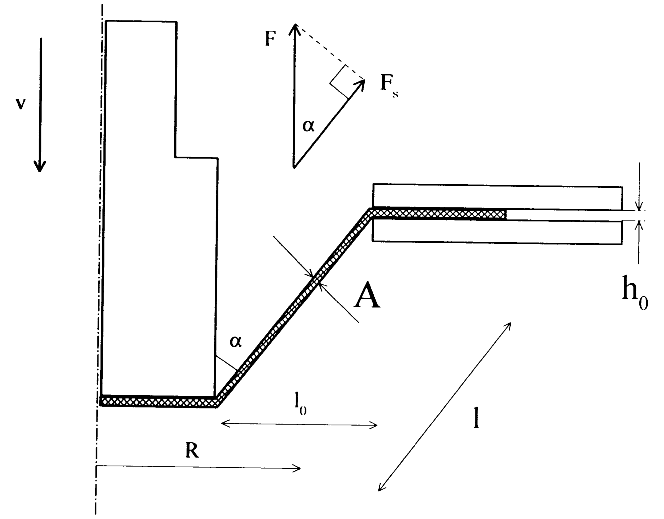

Fig. 2. Diagram of the sheet deformation setup with symbols used in the derivations: v = (constant) crosshead speed, F = force on the probe, F_s = force component in the direction of the sheet, A = average cross-sectional area, h_0 = initial thickness of the dough, l = length of the sheet, l_0 = distance (gap) between probe and aperture perimeter, R = average radius between probe and aperture perimeter.

$$\sigma(t) = \frac{F_s(t)}{A(t)} = \frac{F(t) \bullet \cos(\alpha(t))}{A(t)} \tag{5}$$

and the average cross-sectional area A is:

$$A(\hat{t}) \bullet l(\hat{t}) = 2\pi \bullet l_0 \bullet R \bullet h_0 = \text{constant} \tag{6}$$

and substituting $l(t)$ by (*1*):

$$A(\hat{t}) = 2\pi \bullet R \bullet h_0 \bullet \frac{1}{\sqrt{1+\hat{t}^2}} \tag{7}$$

where R is the average radius between probe and aperture perimeter, and h_0 is the initial thickness of the dough sheet. The average stress is then:

$$\sigma(t) = \frac{F(t)}{2\pi \bullet R \bullet h_0} \bullet \hat{t} \tag{8}$$

The stress values at specific elongations (ε = 0.5, 1.0, 1.5, and 2.0) are recorded by the ASYST program. From equation 2, the elongation rate at these values is calculated, and the ratio of stress and elongation rate gives the elongational viscosity η.

Experimental Design

Measurements were performed on dough sheets, without laminating fat, made from locally obtained pastry flour (protein = 10.9% [N × 5.7]). The dough consisted of 1 kg of flour, 0.49 kg of water, and 18 g of salt. The water addition was determined subjectively to give optimum dough consistency for pastry dough. All ingredients were mixed for 2 min in a twin z-arm mixer (Baker Perkins, Melbourne, Australia, 1-kg variable-speed mixer) at 250 rpm to get a consistent dough mass. This dough mass was then formed into an approximately 20-mm-thick slab and sheeted on a Mini Roll (Sinmag, T'ai-pei, Taiwan) pastry brake (width 520 mm, roller diameter 85 mm, 0.56 kW motor) according to Table I.

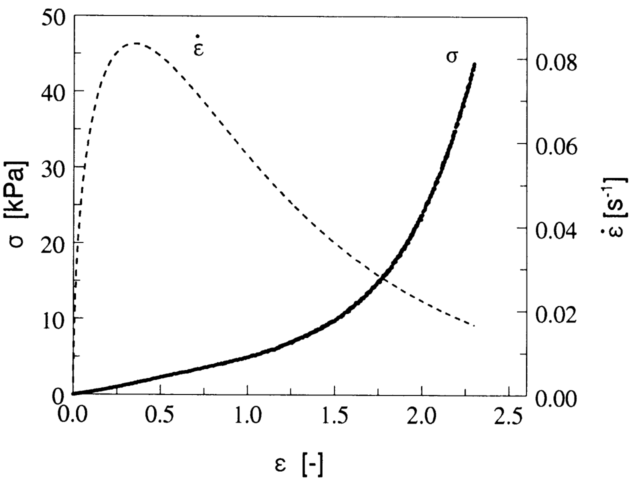

Fig. 3. Typical stress-elongation curve. Probe diameter is 35 mm; aperture diameter is 55 mm; and crosshead speed is 100 mm·min^{-1}. The characteristic experimental time, t_c , is 6 sec. The dotted line is the elongation rate. ε = elongation.

TABLE I
Sheeting Procedure

Original Roller Gap Distance (mm)	Distances (mm) After Passes	Turn
15	⇒[a] 12 ⇒ 10 ⇒ 8 ⇒ 6	90°
6	⇒ 5 ⇒ 4 ⇒ 3 ⇒ 2	90°
2	⇒ 1.5	90°

[a] ⇒ = Reduction pass through rollers.

The final sheet thickness was typically 3 mm. After sheeting, circles (diameter 105 mm) were cut from the sheet with a pastry cutter and rested at high humidity (rh > 85%) and constant temperature (20°C). The high humidity prevented surface drying of the dough sheets. One batch of dough produced about 20 circles.

Dough properties change dramatically after the dough has been subjected to deformations. For this reason, bread dough properties as measured by the extensigraph are measured after a resting period of 45 min following dough mixing (AACC 1983). To determine the relaxation behavior of pastry dough after sheeting, measurements were made at short intervals, starting immediately after sheeting, with a crosshead speed of 100 mm·min^{-1}. A probe diameter of 35 mm and plate aperture diameters of 55 mm were used. Measurements were made over a period of 135 min after sheeting.

Following determination of dough relaxation behavior, a second experiment was performed to investigate the effects of water addition and elongation rate on stress and elongational viscosity. Doughs were prepared with three levels of water addition (0.45, 0.49, and 0.53 kg). The sheets were rested for at least 2 hr, by which time the dough was fully rested, and deformation measurements were made with the same setup. All doughs were measured at five different crosshead speeds (4, 12, 37, 124, and 399 mm·min^{-1}), thus varying the characteristic experimental time, t_c , over two decades (from 1.5 to 150 sec).

RESULTS

A typical stress-elongation curve is presented in Figure 3. The shape of the curve is similar to data obtained by uniaxial compression methods (Van Vliet et al 1992, Dobraszczyk and Roberts 1994). The stress-elongation curve is linear up until an elongation of about 1, which is consistent with results published by Tschoegl et al (1970), who measured bread dough elongational properties in tensile mode. At higher elongation, the stress-elongation curve shows that stress increases rapidly, despite a decreasing elongation rate. This "strain hardening" has been generally observed for polymeric liquids (Bird et al 1987). Repeated measurements on sheets from the same dough agreed generally within 5%.

After sheeting of dough, there is a period of time during which the rheological properties change. Figure 4 shows the apparent elongational viscosity of the dough during resting, at an elongation of 1.5. Initially, a rapid decline in elongational viscosity occurs; this levels off after about 50 min. The viscosity drops to approximately 40% of its value just after sheeting. The 2-hr resting period, used in the second experiment, was sufficient to obtain a fully relaxed dough.

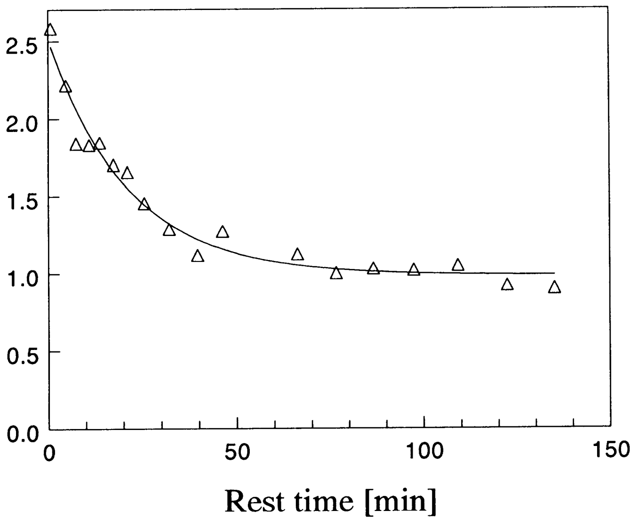

Fig. 4. Apparent elongational viscosity, η, at an elongation ε = 1.5 as a function of resting time after sheeting. Crosshead speed is 100 mm·min^{-1}; t_c = 6 sec; and elongation rate is $\dot{\varepsilon} = 3.6 \cdot 10^{-2}$ sec^{-1}.

In the second experiment, the crosshead speed was varied to obtain measurements at different elongation rates. Figure 5 shows the effect of increasing speed on the stress. The stress at a certain elongation increases with increasing elongation rate. This behavior appears to be linear (in the measured range) when plotted on a log-log scale. This relates well to findings by Van Vliet et al (1992), Dobraszczyk and Roberts (1994), and Kokelaar (1994). Some data points were repeated, and the repeatability stayed within 5%. The slope of the stress-elongation rate lines is about 0.25 for the smaller elongations (0.5 and 1.0) and reduces to about 0.20 for the larger elongations (1.5 and 2.0). Note that the linear region of the stress-elongation curve (Fig. 3) is limited to elongations smaller than about 1.2, which may explain the difference in behavior for small and large deformations. Values for the slope reported for bread dough are slightly higher, between 0.26 and 0.38 (Van Vliet et al 1992, Dobraszczyk and Roberts 1994, Kokelaar 1994), but those results were obtained at higher water addition levels than for the pastry dough used in the work reported here.

The water addition had a large effect on the stresses in the dough. Figure 6 shows the apparent elongational viscosity as a function of elongation rate. Since the apparent viscosity is the stress divided by the elongation rate, the slope of the lines is now negative (pseudoplastic). The behavior can be described with a power law $\eta = K \cdot \dot{\varepsilon}^{m}$. Values for the exponent *m* are given in Figure 6 for the three different water addition levels. The exponent *m* increases with increasing water addition. Thus, the pseudoplastic behavior of the dough becomes less pronounced at higher levels of water addition. At a particular elongation rate, the apparent viscosity is lower for higher levels of water addition. This effect is much stronger than the changes in the slope *m*.

DISCUSSION

The elongation rate was varied by using different crosshead speeds with the geometry held constant. This way, the elongation rate is proportional to speed, irrespective of the way the elongation rate is calculated from the speed. Any approximation errors

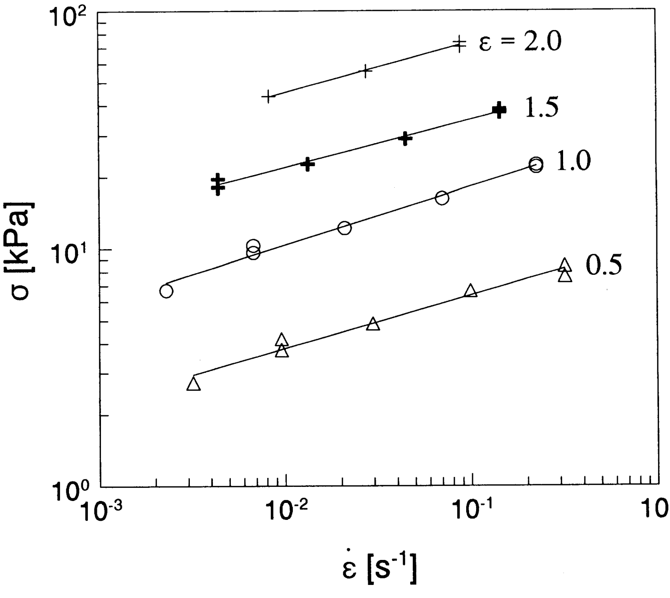

Fig. 5. Stress, σ, as a function of elongation rate, $\dot{\varepsilon}$, at different elongations. Water addition = 49%. For ε = 1.5 and ε = 2, data points at low elongation rate are missing due to rupture of the dough sheet at elongations below 1.5 or 2.

only result in a shift along the logarithmic elongation rate axis. The same holds for the stress at a certain deformation. The actual value of the elongation may have an error, but it will be constant irrespective of the speed. Thus, the slope of the stress-elongation rate is not sensitive to the analysis method. The linear behavior in a double logarithmic plot of stress-elongation rate is also observed for bread dough obtained by compression methods, and the absolute values of stress and elongation rate are of the same order of magnitude (Van Vliet et al 1992, Dobraszczyk and Roberts 1994, Kokelaar 1994).

The characteristic time, $t_c = l_0/v$, depends not only on the crosshead speed (v), but also on the gap (l_0) between probe and plate aperture perimeter. Theoretically, the elongation rates could be varied over a much larger range by using different probe-aperture combinations. However, there will be some flow under the probe and on the edge of the aperture, and this flow will be different for different probe and aperture combinations. This is not taken into account in the model and may therefore introduce an error when making direct comparison of results obtained with different geometries. Further work is needed to assess the extent of this geometry error and, if necessary, to determine a correction term in the model.

For the derivations, a quasisteady-state, shear free flow was assumed, based on a Reynolds number much smaller than 1. The value for the viscosity used in the Reynolds number calculation was based on literature values for doughs with different water contents. The viscosity values we obtained were of order 10^5–10^6 Pa·sec, so that the assumption Re << 1 holds.

The relaxation behavior was studied in this work to obtain the minimum resting time necessary to produce dough pieces with constant properties, which were needed for studying the effect of elongation rate and water addition on the viscosity measurement. The observed relaxation behavior compared well with data obtained for underdeveloped bread dough by Frazier et al (1985), who deformed a dough piece to a certain length on an extensigraph. They measured structural relaxation behavior as a function of dough development and observed a decrease in the relaxation time with increasing level of development until optimum dough development was reached. Dough is developed during sheeting (Kilborn and Tipples 1974), and with increasing number of reduction passes a dough will be better developed. Kilborn and Tipples (1974) needed about 20 folds, producing around 10^6 "dough layers," to fully develop bread dough. The process of sheeting pastry dough usually requires fewer folds than 20, but more than in the described procedure for measuring elongational viscosity of a dough sheet. Therefore, for measuring properties of pastry dough, a shorter relaxation time should be sufficient to obtain a fully relaxed dough.

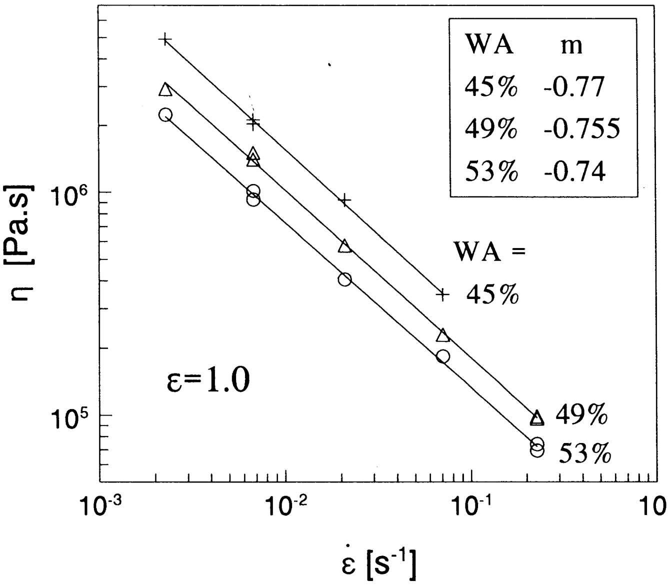

Fig. 6. Apparent elongational viscosity, η, versus elongation rate, $\dot{\varepsilon}$, at an elongation, ε, of 1.0 and at different water addition (WA) levels. The slope *m* (see text) is given for the three WA levels.

The relaxation behavior as shown in Figure 4 was typical of pastry dough when the dough was prepared according to Table I. The data usually fitted well to an exponential decay with a time-axis asymptote larger than zero. A typical decay time was 20 min. This was also observed for both baker's and biscuit flour doughs, suggesting that the relaxation behavior depends more on the dough preparation (Frazier et al 1985) than on flour properties.

CONCLUSION

A method has been presented to measure extensional viscosity of dough sheets. When compared with uniaxial compression methods or tensile methods, the results are in qualitative agreement with those published by other researchers. The method was developed specifically for pastry dough sheets, and the combination of a UTM and a probe was chosen for ease of use. Setting up a measurement takes only a few seconds, and the time needed to do an experiment is mainly determined by the crosshead speed of the UTM. This short preparation time is particularly useful when relaxation behavior of dough is studied. The relaxation behavior of pastry dough is important to manufacturers, since most of the processing time is rest time. When pastry dough is not fully relaxed, undesirable shrinkage occurs. Also, pastry dough has a low water addition level compared to bread, which makes it easy to handle, without problems of the sample dough sheet sagging before the contact between probe and sheet.

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LITERATURE CITED

AMERICAN ASSOCIATION OF CEREAL CHEMISTS. 1983. Approved Methods of the AACC. Method 54-10, approved April 1961, reviewed October 1982. The Association: St. Paul, MN.

ASYST 1992. ASYST 4.0. Keithley Instruments, Inc.: Taunton, MA.

BAGLEY, E. B., and CHRISTIANSON, D. D. 1986. Response of commercially leavened doughs to uniaxial compression. Pages 27-36 in: Fundamentals of Dough Rheology. H. Faridi and J. M. Faubion, eds. Am. Assoc. Cereal Chem.: St. Paul, MN.

BIRD, R. B., ARMSTRONG, R. C., and HASSAGER, O. 1987. Dynamics of Polymeric Liquids. Vol. 1, Fluid Mechanics. John Wiley & Sons: New York.

DOBRASZCZYK, B. J., and ROBERTS, C. A. 1994. Strain hardening and dough gas cell-wall failure in biaxial extension. J. Cereal Sci. 20:265-274.

FRAZIER, P. J., FITCHETT, C. S., and RUSSELL EGGITT, P. W. 1985. Laboratory measurement of dough development. Pages 151-175 in: Rheology of Wheat Products. H. Faridi, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.

HAY, R. L. 1993. Effects of flour quality characteristics on puff pastry baking performance. Cereal Chem. 70:392-396.

KILBORN, R. H., and TIPPLES, K. H. 1974. Implications of the mechanical development of bread dough by means of sheeting rolls. Cereal Chem. 51:648-657.

KOKELAAR, J. J. 1994. Physics of breadmaking. Ph.D. thesis. Wageningen Agricultural University.: Wageningen, The Netherlands.

LAGENDIJK, J., and VAN DALFSEN, J. 1965. Classification of puff-pastry fats and margarines based on dough firmness. Cereal Chem. 42:255-263.

LAUNAY, B. 1989. Biaxial extension of wheat flour doughs: Application to the study of elastic properties. Pages 279-291 in: Wheat End Properties. Proc. ICC Symp. H. Salovaara, ed. University of Helsinki:

Helsinki, Finland.
MILLER, B. S., and TRIMBO, H. B. 1970. Factors affecting the quality of pie dough and pie crust. Baker's Dig. 44:46-55.
MULLER, H. G., WILLIAMS, M. V., RUSSELL EGGITT, P. W., and COPPOCK, J. B. M. 1961. Fundamental studies on dough with the Brabender extensograph. I. Determination of stress-strain curves. J. Sci. Food Agric. 12:513-522.
RASPER, V. F. 1975. Dough rheology at large deformations in simple tensile mode. Cereal Chem. 52:24r-41r.
SEIBEL, W., and LUDEWIG, H. G. 1978. Ohne schrumpfen und schnurren. Technol. Blätterteigherstellung. Backtechnik 26:18-22.
TSCHOEGL, N. W., RINDE, J. A., and SMITH, T. L. 1970. Rheological properties of wheat flour doughs. II. Dependence of large deformation and rupture properties in simple tension on time, temperature, and water absorption. Rheol. Acta 9:223-238.
VAN VLIET, T., JANSSEN, A. M., BLOKSMA, A. H. and WALSTRA, P. 1992. Strain hardening of dough as a requirement for gas retention. J. Texture Stud. 23:439-460.
WEIPERT, D. 1992. Descriptive and fundamental rheometry in a new light. Cereal Foods World 37:15-24.

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