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Bread dough rheology and recoil
I. Rheology

Roger I. Tanner*, Fuzhong Qi, Shao-Cong Dai

School of Aerospace, Mechanical and Mechatronic Engineering, University of Sydney, Sydney NSW 2006, Australia

Dedicated to the memory of Arthur S. Lodge (1922–2005).

Abstract

A new set of experiments on a bread dough includes small-strain oscillatory behaviour, larger-strain oscillatory behaviour, simple shearing beginning from rest, uniaxial elongation beginning from rest, relaxation after sudden shear and recoil from elongation. We believe this is the most complete set of rheological data yet reported for a bread dough. Analysis of these soft-solid experiments proceeds from a Lodge-type rubberlike material with a power-law memory function. The model suggests that the response to steady shear and elongational flows may be described as a product of (strain rate)^{p} times a function of strain; the exponent p is found to be about 0.2–0.3 from small-strain oscillatory measurements. Experiments confirm this finding. The model overestimates stresses, and in order to improve predictions, the use of a KBKZ model and a damage function model are investigated. Due to the eventual fracture of the soft-solid material, the idea of a "damage function" was adopted to produce a simple accurate, integral-type constitutive model for small-strain oscillations, simple shearing and elongation. Further analysis of reversing strains, for example, larger-strain oscillatory flows and recoil, is needed.

Keywords: Bread dough; Soft-solid; Experiments; Recoil; Integral model; Damage function

1. Introduction to bread dough modelling

A mixture of wheat flour and water plus a small amount of salt and possibly other materials such as preservatives or yeast, constitutes bread dough. Dough rheology plays an important role in the quality of baking products [1] and moreover poses many intriguing questions about mechanical behaviour. There is, however, no general consensus as to what set of constitutive equations should be used to describe dough rheology. In particular, there seems to be no basic set of experiments including recoil after stress release, despite the fact that some processes (e.g. sheeting and pressing of dough) could be described by using this information. The present paper therefore describes new experiments, suggests a new approach to constitutive modelling (Part 1) and also applies the model to new experiments on recoil from elongation (Part 2, forthcoming).

The present paper is restricted to unyeasted dough; a recent Ph.D. thesis [2] shows that yeasted dough behaves rheologically in a similar manner to unyeasted dough, so we believe that many of the ideas can be carried over to the yeasted case, at least for processes that are quick compared to the yeast development time.

The rheology of dough is sensitive [3] to changes in water content, starch content, wheat genetics and mixing procedure, as well as temperature. In our experiments, we have used a single flour, mixed to the same degree with the same water content; temperature was always at room temperature (24 °C). This enables us to concentrate on the general mechanical behaviour of the material, leaving the other variables for possible future exploration. The investigation of dough rheology goes back a long way; the early work (1932–1937) of Schofield and Scott Blair [4] established the solid-like behaviour of dough, and since then there have been many investigations [1].

Bread dough is a soft-solid, which may be regarded as a filled elastomeric network. Starch particles of two kinds (lenticular particles of about 14 μm in size and smaller spherical particles of about 4 μm diameter) make up the filler, which comprises about 60% of the volume in natural doughs [1]. Electron microscope pictures of dough show clearly the network and the starch particles. Manipulation of the starch content to change dough properties has also been discussed [3]. In dough, the filler

* Corresponding author. Tel.: +61 2 9351 7153; fax: +61 2 9351 7060.
E-mail address: rit@aeromech.usyd.edu.au (R.I. Tanner).

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particles are not strongly attached to the rubbery gluten network, and the starch can easily be washed out of the dough with water. Nevertheless, an increase of about 20 times the small-strain storage modulus (G') above that for gluten alone ($\sim 10^3$ Pa at 1 Hz) to around 2×10^4 Pa, is observed, and hence starch makes a very important contribution to dough rheology.

Various mechanical analogue models have been suggested; a complex model due to Lerchenthal and Muller [5] is shown in Fig. 1a. Fig. 1b shows a model of Bloksma [6]. While these models can be fitted to uniaxial elongational behaviour they do not describe the small-strain behaviour of dough well, since they contain only one or two relaxation modes. In any case, it is very difficult to generalize these uniaxial models to a complete three-dimensional system. From another viewpoint, attempts have been made to simply use models devised for unfilled non-crosslinked polymers [7,8] but these models do not reflect the solid-like behaviour of dough. Phan-Thien et al. [9] showed that a model of the type shown in Fig. 1(c) could be used for shear behaviour, including large amplitude sinusoidal shearing. However, there are difficulties [2] when one attempts to describe both elongation and shear behaviour with this model; in any case, one can see immediately from Fig. 1(c) that predictions of recoil from elongation will always give perfect (100%) recoil so it cannot be applied to recoil experiments, where recovery is usually less than perfect.

Charalambides et al. [10] used a purely rubber–elastic model of the Mooney-Rivlin type to discuss biaxial stretching with some success, but the model clearly cannot describe partial recoil or small-strain oscillatory behaviour. Leonard et al. [11] have also tried to use a Mooney-Rivlin model, but the results are not completely successful. A review by Dobraszczyk and Morgenstern [12] also discusses the use of several models, but clearly the description of recoil is not satisfactory.

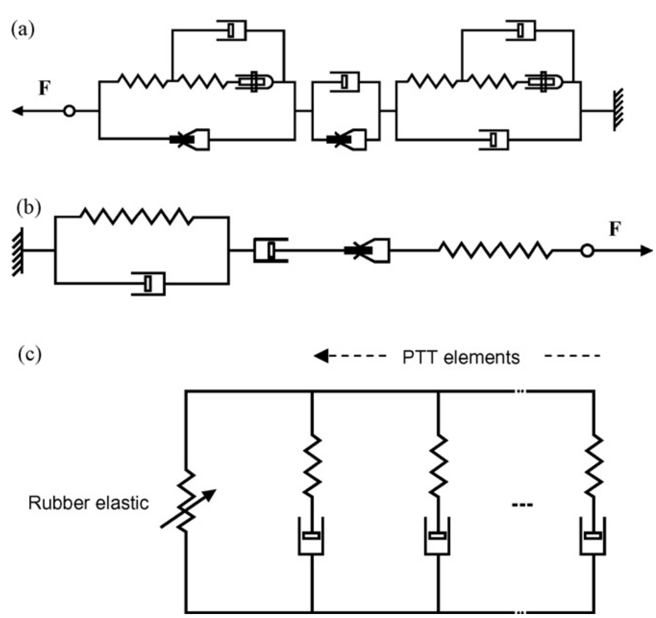

Fig. 1. Bread dough models. (a) 1967 model of Lerchental and Muller [5]. Note the springs, dashpots, shear pins and yield elements. (b) 1960 model of Bloksma [6]. Simpler than (a), it contains one yield element. (c) Phan-Thien model of 2000 [9], successful in unsteady shear, unsatisfactory in elongation and recoil.

Hence, we believe that better models covering a wider range of experimental conditions are needed. In the present paper, we give data for a single dough type in

(1) Small-strain oscillatory shear.
(2) Oscillatory shear for strains up to 10%.
(3) Simple steady shearing beginning from rest.
(4) Constant-rate elongation beginning from rest.

In a subsequent paper, we shall give data for shear relaxation and recoil from constant-rate elongation. There do not seem to be any previously published data covering all of the above tests for the same dough, although there are many reports covering some of the tests. In Part 1, we discuss analysis of small-strain behaviour, shear behaviour and elongation. Part 2 will discuss the analysis of larger amplitude oscillatory flows, relaxation and recoil.

2. The material and experimental methods used

2.1. Dough preparation

The material that was used for this study was a brand of commercial Australian flour. The flour sample was variety JANZ wheat, grown in 2001 at Narrabri, NSW, milled on a Buhler experimental mill. It is a benchmark Australian hard kernel wheat, said to be of medium dough strength. The dough was produced in a 10 g mixograph by mixing 200 mg of salt, 6.0 g of distilled water and 9.5 g of flour, as determined by using a ®Sartorious digital high precision scale. The sample was mixed by four planetary pins on the head revolving round three stationary pins on the bottom of the mixing bowl. The rotation speed was measured to be 71 rpm. The mixing operation was conducted at a temperature of 24 °C and under ambient humidity in an air-conditioned laboratory. The mixing time to peak dough development was determined from the mixing curves [13] and took about 7 min. When the signal peaked, the dough was judged to have been developed [14] and the processing was stopped.

2.2. Elongation measurements

For the elongation measurements, the sample after mixing was first formed in an aluminium cylinder with an inside diameter of 30.6 mm, and stored in a sealed bag to relax for 45 min [14,15]. The sample was then transferred to an Instron 5564 rheometer to perform the elongation tests. The measuring geometries used were two parallel plates: one is a fixed lower plate with a diameter of 31.0 mm, the other is a moving upper plate with a diameter of 30.3 mm. The sensitive load cell used has a measuring range of 10 N. Before testing, the rheometer was calibrated without any loading. The aluminum cylinder containing the dough was fitted on the upper plate, and slowly moved up over the upper plate. Simultaneously, the upper plate was brought down gently until the sample was compressed properly between the plates. However, this compression could not guarantee that the dough would not partially peel from the