Short survey

Review: rheology and the breadmaking process

B.J. Dobraszczyk[a,*], M.P. Morgenstern[b]

[a]School of Food Biosciences, University of Reading, P.O. Box 226, Whiteknights, Reading RG6 6AP, UK
[b]New Zealand Institute for Crop and Food Research, Private Bag 4704, Christchurch, New Zealand

Abstract

The applications of rheology to the main processes encountered during breadmaking (mixing, sheeting, fermentation and baking) are reviewed. The most commonly used rheological test methods and their relationships to product functionality are reviewed.

It is shown that the most commonly used method for rheological testing of doughs, shear oscillation dynamic rheology, is generally used under deformation conditions inappropriate for breadmaking and shows little relationship with end-use performance. The frequency range used in conventional shear oscillation tests is limited to the plateau region, which is insensitive to changes in the HMW glutenin polymers thought to be responsible for variations in baking quality. The appropriate deformation conditions can be accessed either by long-time creep or relaxation measurements, or by large deformation extensional measurements at low strain rates and elevated temperatures.

Molecular size and structure of the gluten polymers that make up the major structural components of wheat are related to their rheological properties via modern polymer rheology concepts. Interactions between polymer chain entanglements and branching are seen to be the key mechanisms determining the rheology of HMW polymers. Recent work confirms the observation that dynamic shear plateau modulus is essentially independent of variations in MW of glutens amongst wheat varieties of varying baking performance and also that it is not the size of the soluble glutenin polymers, but the secondary structural and rheological properties of the insoluble polymer fraction that are mainly responsible for variations in baking performance. Extensional strain hardening has been shown to be a sensitive indicator of entanglements and long-chain branching in HMW polymers, and is well related to baking performance of bread doughs. The Considere failure criterion for instability in extension of polymers defines a region below which bubble walls become unstable, and predicts that when strain hardening falls below a value of around 1, bubble walls are no longer stable and coalesce rapidly, resulting in loss of gas retention and lower volume and texture. Strain hardening in doughs has been shown to reach this value at increasingly higher temperatures for better breadmaking varieties and is directly related to bubble stability and baking performance.
© 2003 Elsevier Ltd. All rights reserved.

Keywords: Rheology; Mixing; Sheeting; Fermentation; Baking; Strain hardening; Gluten polymers; Entanglements; Long-chain branching

1. Introduction—what is rheology?

Rheology is the study of the flow and deformation of materials. Generally, to measure rheological behaviour, a controlled, well-defined deformation or strain is applied to a material over a given time and the resulting force response is measured (or vice versa) to give an indication of material parameters such as stiffness, modulus, viscosity, hardness, strength or toughness of the material. The general aims of rheological measurements are:

- to obtain a quantitative description of the materials' mechanical properties
- to obtain information related to the molecular structure and composition of the material
- to characterise and simulate the material's performance during processing and for quality control

Rheological principles and theory can be used as an aid in process control and design, and as a tool in the simulation and prediction of the material's response to the complex flows and deformation conditions often found in practical processing situations which can be inaccessible to normal rheological measurement.

* Corresponding author. Tel.: +44-118-931-8714; fax: +44-118-931-0080.
E-mail address: b.dobraszczyk@reading.ac.uk (B.J. Dobraszczyk).

For example, it is difficult to access dough during mixing, sheeting, proving and baking without interrupting the process or disturbing the structure of the material. We therefore have to predict the range of conditions the dough experiences during a given process and then extrapolate from rheological measurements made under simple, well-defined laboratory conditions, e.g. via mathematical modelling using analytical or computational methods (Scott and Richardson, 1997). For example, mixing and sheeting of doughs has been simulated (Love et al., 2002; Binding et al., 2003; Morgenstern et al., 2002) and bubble growth during proof of bread doughs (Shah et al., 1999) and expanded cereal extrudes has been modelled through the simulation and growth of bubbles (Fan et al., 1994).

Rheology can be related to product functionality: many rheological tests have been used to attempt to predict final product quality such as mixing behaviour, sheeting and baking performance. This is based on the structural engineering analysis of materials, where small-scale laboratory measurements of mechanical properties have successfully been extrapolated to the behaviour of large engineered structures such as bridges, buildings, pressure vessels etc. resulting in the idea that controlled tests on well-defined small samples of food in the laboratory can be related to the larger, more complex multi-component situations found in practical processing conditions.

2. Rheological testing

Rheological tests attempt to measure the forces required to produce given controlled deformations, such as squashing (compression), bending or pulling apart (tension), and to present them in such a way as to be independent of sample size, geometry, and mode of testing. They measure a well-defined property, such as stress, strain, stiffness or viscosity. A small test piece of the material is usually deformed in a controlled way, normally on a motor driven machine, and the force is measured as well as the distance moved or displacement of the object. The force is then usually plotted against the displacement to give a force-displacement curve. Normally for stiff materials we would divide the force and displacement by the *original* sample dimensions to obtain stress (force/original cross section area) and Cauchy, or Engineering strain (displacement /original dimension, e.g. dL/L_o, where dL = extension, L_o = original length), because the changes in sample dimensions are small and uniform with displacement; this allows us to remove the sample size as a variable. Many food materials are not stiff and undergo large deformations in practice, where the geometry often changes in a non-uniform and unpredictable manner giving large and non-uniform stresses and strains along the sample. For example, dough thins out non-uniformly when stretched, in common with many polymers, giving rise to large stresses and strains not correctly calculated by the conventional method of dividing by

original sample dimensions. In this case, it is necessary to normalise by *actual* change in dimensions during deformation to obtain true stress (force/instantaneous area) or Hencky strain (displacement/instantaneous length (L), e.g. $dL/L = \ln(L/L_o)$), in which case sample dimensions should be measured locally and independently by using contact extensometers or non-contact techniques such as laser, video or photographic techniques. For materials which flow under normal measurement time scales, stress is normally divided by strain rate (strain/time of strain application) to give viscosity.

Rheological properties should be independent of size, shape and how they are measured; in other words, they are universal, rather like the speed of light or density of water, which do not depend on how much light or water is being measured or how it is being measured. It would be comforting to know that the stiffness of bread or viscosity of dough measured in one laboratory will be the same measured in any laboratory in the world, even if they are measured using different tests, sample sizes or shapes. An objective of rheology is to determine properties reproducibly in a manner that allows comparison between different samples, test sizes and shapes, and test methods.

3. Rheological test methods

There are many test methods used to measure rheological properties. It is not possible to describe all the available testing geometries here, and the reader is referred to general reviews of rheology (Whorlow, 1992; Ferry, 1980; Barnes et al., 1989), rheological testing of foods (Sherman, 1970; Carter, 1990; Rao and Steffe, 1992; Dobraszczyk and Vincent, 1999; van Vliet, 1999) and cereal products (Bloksma and Bushuk, 1988; Faridi and Faubion, 1990; Muller, 1975; Faridi and Faubion, 1986). It is common to categorise rheological techniques according to the type of strain imposed: e.g. compression, extension, shear, torsion etc. and also the relative magnitude of the imposed deformation, e.g. small or large deformation. The main techniques used for measuring cereal properties have traditionally been divided into descriptive empirical techniques and fundamental measurements (Bloksma and Bushuk, 1988).

4. Descriptive rheological measurements

Within the cereals industry there has been a long history of using descriptive empirical measurements of rheological properties, with an impressive array of ingenious devices such as the Penetrometer, Texturometer, Consistometer, Amylograph, Farinograph, Mixograph, Extensigraph, Alveograph, various flow viscometers and fermentation recording devices, reviewed by Muller (1975) and Shuey (1975), (Table 1). Empirical tests are easy to perform and

Table 1
Rheological methods used for cereal products

Method	Products	Property measured
Empirical methods		
Mixers: farinograph, mixograph, reomixer	Dough	Mixing time/torque apparent viscosity
Extensigraph	Dough	Extensibility
Taxt2/Kieffer Rig	Dough, gluten	Extensibility
Alveograph	Dough, gluten	Biaxial extensibility
Amylograph, RVA	Pastes, suspensions	Apparent viscosity, gelatinisation temp
Consistometer	Sauces, fillings	Apparent viscosity
Flow cup	Fluids, sauces, batters	Apparent viscosity
Falling ball	Fluids	Apparent viscosity
Flow viscometers	Fluids, pastes	Apparent viscosity
Fermentometers	Dough	Height, Volume
Penetrometers	Semi-solid foods, gels	Firmness, hardness
Texturometer, TPA	Solid foods	Texture, firmness
Fundamental methods		
Dynamic oscillation, concentric cylinders, parallel plates	Fluids, pastes, batters, doughs	Dynamic shear moduli, dynamic viscosity
Tube viscometers: capillary, pressure, extrusion, pipe flow	Fluids, sauces, pastes, dough	Viscosity, viscosity, in-line viscosity
Transient flow: concentric cylinders, parallel plates	Semi-solid (visco-elastic) materials	Creep, relaxation, moduli and time
Extension: uniaxial, biaxial, dough inflation system, lubricated compression	Solid foods, doughs	Extensional viscosity, strain hardening

are often used in practical factory situations, providing data which is useful in evaluating performance during processing and for quality control. The instruments are often robust and capable of withstanding demanding factory environments, and do not require highly skilled or technically trained personnel. They have provided a great deal of information on the quality and performance of cereal products such as consistency, hardness, texture, viscosity etc. However, these instruments do not fulfil the requirements of a fundamental rheological test, since:

- the sample geometry is variable and not well defined
- the stress and strain states are uncontrolled, complex and non-uniform
- it is therefore impossible to define any rheological parameters such as stress, strain, strain rate, modulus or viscosity.

Therefore, these tests are purely descriptive and dependent on the type of instrument, size and geometry of the test sample and the specific conditions under which the test was performed. For example, empirical tests have been used to characterise the behaviour of bread doughs during processing. Many of these are used as 'single point' tests, where a single parameter is often arbitrarily selected from a whole range of data acquired during the test as, for example, in selecting the peak torque from a mixing trace and then using this to correlate with performance, which neglects a large part of the recorded data (Dobraszczyk and Schofield, 2002; Wikström and Bohlin, 1996), and is appropriate only to the set of conditions under which that test was performed and is generally not applicable to any other deformation conditions. Since dough experiences a wide range of conditions of stress states and strain rates during processing and baking, and the rheological properties of dough are dependent both on time and strain, there is often a discrepancy between such single point type tests and actual performance in the plant, where conditions of strain and strain rate may be poorly defined and very different to those in the laboratory test. Whilst this may give the illusion of a 'scientific' test by being performed on a machine (frequently with a computer attached), and may give satisfactory correlations with a textural or processing parameter, it is impossible to compare results between different testing machines, e.g. between Farinograph, Mixograph or Extensigraph, or to extrapolate the results to other deformation conditions, such as during baking.

Most food materials are viscoelastic and therefore their properties depend on how quickly the test is performed (the strain rate or frequency). This is important in many aspects of dough processing: if the dough is deformed quickly, such as in mixing or sheeting, then the rheological properties of the dough will be very different if measured at the typically slower rates of deformation found in conventional testing machines. Alternatively, during processing dough will experience strains very different in magnitude and nature than those generally available in a rheological test. Many food processes operate under large deformation extensional flow, whilst most rheological tests on foods are performed in small deformation shear oscillation. Measurements under large deformations often show very different rheological response to those in small deformation, especially if the material contains high molecular weight (HMW) polymers. Tests under only one particular set of conditions of rate, temperature and strain will almost certainly not be applicable to another set of deformation conditions. What is necessary is to define the set of deformation conditions which the food sees in practice and perform tests under similar conditions.

5. Fundamental rheological tests

Problems encountered with such fundamental tests are: complex instrumentation which is expensive, time consuming, difficult to maintain in an industrial environment and

337 require high levels of technical skill, often inappropriate
338 deformation conditions, difficulty in interpretation of
339 results, and slip and edge effects during testing.

340 The most common types of fundamental rheological tests
341 used in cereal testing are: (i) small deformation dynamic
342 shear oscillation; (ii) small and large deformation shear
343 creep and stress relaxation; (iii) large deformation exten-
344 sional measurements; and (iv) flow viscometry (Table 1).

6. Dynamic oscillation measurements

349 Adapted from techniques developed for measuring
350 viscoelastic properties of polymer melts and concentrated
351 solutions (Ferry, 1980; Barnes et al., 1989), this is one of the
352 most popular and widely used fundamental rheological
353 techniques for measuring cereal doughs and batters. These
354 tests measure rheological properties (such as elastic and
355 viscous moduli) by the application of sinusoidally oscillat-
356 ing stress or strain with time and measuring the resulting
357 response. They have the advantage of a well developed
358 theoretical background, readily available instrumentation,
359 and simultaneous measurement of elastic and viscous
360 moduli, while the non-destructive nature of the test enables
361 multiple measurements to be performed as temperature,
362 strain or frequency are varied.

363 Disadvantages of the dynamic oscillation method are that
364 the deformation conditions are often inappropriate to
365 practical processing situations, because they are carried
366 out at rates and conditions very different from those
367 experienced by the dough during processing or baking
368 expansion. For example, rates of expansion during proof
369 and oven rise in bread doughs have been calculated between
370 5×10^{-3} and $5 \times 10^{-4} \text{ s}^{-1}$, compared with measuring rates
371 in rheological tests several orders of magnitude greater
372 (Bloksma, 1990).

373 Conventional oscillatory shear rheological tests usually
374 operate in the linear region at small strains in the order of up
375 to 1%, whilst strain in gas cell expansion during proof is
376 known to be in the region of several hundred percent
377 (Amemiya and Menjivar, 1992). Furthermore, most
378 dynamic rheological tests are carried out in shear, whilst
379 most large-strain deformations in dough (i.e. extrusion,
380 sheeting, proof and baking) are extensional in nature. It is
381 not widely recognised within the cereals science community
382 that measurements in large deformation shear show a
383 completely different response to extensional measurements.
384 Polymer melt fluid dynamics show that very different
385 rheology occurs under shear deformation than under
386 extension due to the different physical effects large
387 deformations can have on networks of HMW polymers
388 (Ferry, 1980; Padmanabhan, 1995). From extensional
389 studies on long-chain high molecular weight polymer
390 melts it is known that entirely different rheological proper-
391 ties are obtained in shear than in tension, especially if the
392 polymer chains are branched. For example, the elongational

393 viscosity of low-density (branched-chain) polyethylene
394 melts increases with both strain and strain rate (strain
395 hardening), whilst the shear viscosity decreases with strain
396 and strain rate (shear-thinning), giving widely different
397 values in final viscosities between elongation and shear
398 (Fig. 1a). For dough, shear and elongational viscosities at
399 low strains are similar, with extensional viscosity slightly
400 higher than shear viscosity but at higher strains they diverge
401 and the elongational viscosity rises steeply to give a value 2
402 orders of magnitude higher at failure (Fig. 1b).
403 This increased strain hardening is attributed to entanglement
404 of long-chain molecules during extensional flow, whereas in
405 simple shear they remain coiled and can slip past each other,
406 giving rise to observed shear thinning at higher strains
407 (Cogswell, 1981).

408 Therefore, many of the rheological tests for doughs
409 reported in the literature are inappropriate in predicting end-
410 use quality because they do not measure the system under
411 the appropriate deformation conditions and they are not
412 sensitive to the molecular structures responsible for baking
413 quality. Small deformation dynamic shear rheological tests
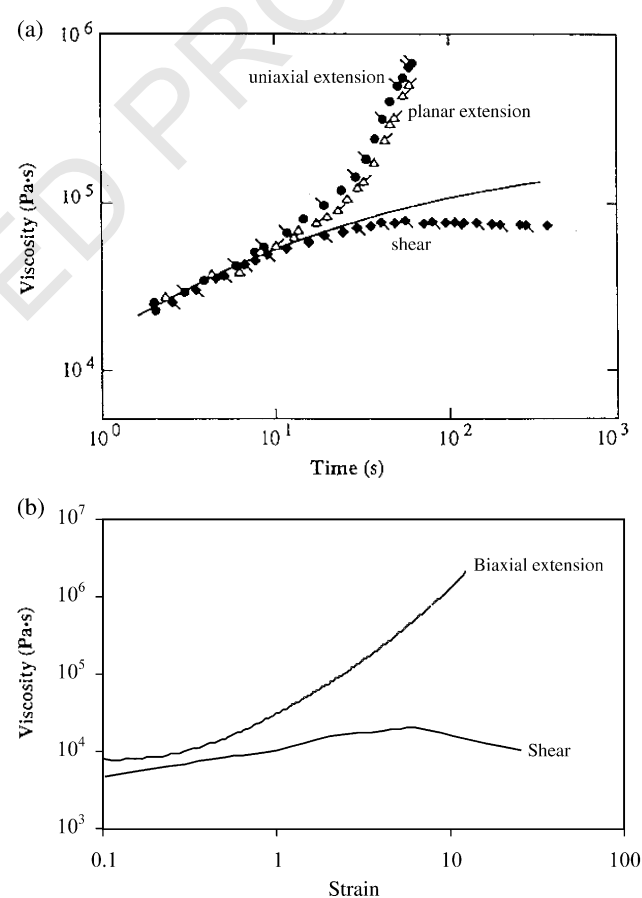414 are frequently performed and applied almost indiscrimi-

Fig. 1. (a) Shear and extensional viscosity of LDPE (low density
polyethylene) at 125 °C at constant strain rate (0.05 s^{-1}). From MacLeish
and Larson (1998). (b) Large deformation shear and biaxial extensional
viscosities vs. Cauchy strain for dough at constant strain rate (0.1 s^{-1}).

7. Creep and relaxation measurements

In stress relaxation measurements, deformation is held constant and the force response is measured, whilst in creep the stress is held constant and the deformation is measured. Schofield and Scott Blair (1937) first measured the creep response of dough and obtained values for elastic moduli and viscosity which are still relevant. Bloksma and Bushuk (1988) surveyed the experimental results from the literature for stress relaxation measurements for a number of doughs. None of the curves showed the exponential decay typical of a single relaxation time, which would indicate a single molecular mechanism responsible for relaxation, but correspond to a decay typical of a broad spectrum of relaxation times. This shows a broad distribution of molecular mechanisms is responsible for the relaxation process within dough, which can be related to the wide molecular weight distribution of gluten.

Many authors have shown that a slower relaxation time is associated with good baking quality (Bloksma, 1990; Launay, 1990; Wang and Sun, 2002), with relaxation time relatively independent of water, mixing time or temperature. Stress relaxation measurements on dough and gluten in shear showed that the relaxation behaviour of dough could be described by two relaxation processes (Bohlin and Carlson, 1980): a rapid relaxation over 0.1–10 s and a slower process occurring over 10–10,000 s. The rapid relaxation process has been associated with small polymer molecules which relax rapidly, and the longer relaxation time has been linked to the HMW polymers found within gluten. Measurements of large-deformation creep and shear stress relaxation properties were found to be useful in discriminating between different wheat varieties of varying quality, and were found to be closely associated with baking volume (Safari-Ardi and Phan-Thien, 1998; Wikström and Eliasson, 1998) and strength of durum wheat varieties (Edwards et al., 1999, 2001). At small strain amplitudes (0.1%), doughs with different baking quality showed no differences in relaxation behaviour, but at a range of large strains (up to 29%) their creep and relaxation behaviour was closely correlated with the baking behaviour of dough (Safari-Ardi and Phan-Thien, 1998).

Doughs exhibited a characteristic bimodal distribution of relaxation times, with the second peak clearly discriminating between cultivars with varying strength and quality, which reflects the differences in the MW distribution of glutenin polymers (Rao et al., 2001; Li et al., 2003). The second relaxation peak is related to the entanglement properties of high molecular weight insoluble glutenin polymers, and has been shown to be directly related to the insoluble fraction of the high MW glutenins (Li et al., 2003). Relaxation properties of doughs relate well to MWD and particularly to entanglements of HMW glutenin polymers and may be used as a rapid method of discriminating variations in MWD between varieties which vary in baking quality.

8. Extensional techniques

There are many types of extensional flow measurements, including: simple uniaxial tension, fibre wind-up or spinning, converging flow, capillary extrusion, opposed jets, lubricated compression and bubble inflation (Whorlow, 1992; Macosko, 1994). There are several methods which have been used to measure the rheological properties of dough in extension: simple uniaxial extension, where dough is stretched in one direction; and biaxial extension, where the dough is stretched in two opposing directions, which can be achieved either by compression between lubricated surfaces or by bubble inflation (Dobraszczyk and Vincent, 1999; Huang and Kokini, 1993; Bagley and Christianson, 1986).

Many food materials undergo large deformations in practice during processing and eating, and many of these have a large extensional component. For example, extensional flows are important in mixing and sheeting of pastry and dough, converging and diverging flow such as in extrusion and pumping, spreading of soft solids such as butter, cheeses and pastes, and expansion of bubbles in foams such as bread dough, cakes and heat extruded snacks. Unfortunately, most tests in flow are carried out in shear under small deformations, mainly because most conventional viscometers operate in shear, because the equipment is readily available and the technique well established. However, measurements carried out in shear and using small deformations do not provide information about material behaviour under large extension. Therefore there is an obvious need to perform measurements under conditions relevant to those experienced by the material in actual practice.

9. Uniaxial extension

One of the oldest and most widely used test methods to measure materials properties is the uniaxial tensile test. A strip of material is clamped at both ends and pulled apart at a fixed rate in a suitable testing machine, and the force measured at the same time as the displacement of the object. The force is generally plotted against the displacement (extension) to give a force–extension curve. Tensile tests may produce an approximately uniform extension of a sample provided necking does not occur. Normally the force and extension are divided by the original sample dimensions to obtain stress and strain, and allows removal of the sample geometry as a variable, but for doughs undergoing large extensional deformation the actual change in dimensions must be measured or calculated. The slope of

the stress–strain curve then gives the elastic modulus or stiffness. Many test methods attempt to measure the uniaxial extensional properties of doughs, such as the Simon Research Extensometer, Brabender Extensigraph, Stable Micro Systems Kieffer dough and gluten extensibility rig, but none of these gives rheological data in fundamental units of stress and strain, because the sample geometry is not defined or measured, dimensions change extensively and non-uniformly during testing, and it is therefore impossible to define any rheological parameters such as stress, strain, strain rate, modulus or viscosity.

Studies on the fundamental uniaxial extensional rheological properties of doughs have been carried out by many workers (Schofield and Scott Blair, 1932; Tschoegl et al., 1970; Tschoegl et al., 1970; Rasper, 1975; Uthayakumaran et al., 2000). Some of the earliest attempts to characterise the fundamental rheological properties of dough were in a series of uniaxial extensional measurements by Schofield and Scott Blair (1932) who stretched a cylinder of dough floated on a mercury bath and measured the elongation and force. Plastic and elastic components of deformation were resolved and viscosity and elastic modulus were calculated. They showed that the rheological behaviour of dough is non-linear with strain and strain rate, i.e. elastic modulus and viscosity vary with both rate and strain. Tschoegl et al., 1970a,b) measured the large extension properties of doughs by extending a ring of dough suspended in a liquid of density equivalent to that of the dough between two hooks at constant deformation rates until rupture. The stress-strain curves showed considerable strain hardening, and strain and stress at rupture was considerably less for poor quality flours than good quality flours.

10. Biaxial extension

In biaxial extension a sample is stretched at equal rates in two perpendicular directions in one plane, as in an expanding spherical balloon. The most widely used methods for measuring biaxial extension properties of food materials are inflation techniques and compression between flat plates using lubricated surfaces, which produce purely extensional flow provided no friction occurs (Dobraszczyk and Vincent, 1999; Chatraei et al., 1981).

Inflation was first used as an empirical technique to measure wheat gluten and bread dough extensibility in 1920s (Hankoczy, 1920; Chopin, 1921). This method was later developed to assess rheological parameters (Launay et al., 1977) and further developed to measure the fracture and biaxial extensional rheological properties of wheat doughs and glutens, and to assess the quality of wheat flour doughs and glutens (Dobraszczyk and Roberts, 1994; Dobraszczyk, 1997). The major advantage of this test is that the deformation closely resembles practical conditions experienced by the cell walls around the expanding gas cells within the dough during proof and oven rise, i.e. large

deformation biaxial extension. Extensional rheological properties can be measured at large strains up to failure and low strain rates, and the gripping problems normally associated with uniaxial tests can be minimised. Extensional rheological properties of wheat doughs have been measured using lubricated compression and bubble inflation (Huang and Kokini, 1993; Bagley and Christianson, 1986; Uthayakumaran et al., 2000; Chatraei et al., 1981; Hankoczy, 1920; Chopin, 1921; Launay et al., 1977; Dobraszczyk and Roberts, 1994; Dobraszczyk, 1997; van Vliet et al., 1992; Wikström and Bohlin, 1999a,b). Differences in extensional strain hardening between varieties of different baking quality were found to relate to baking quality, with good breadmaking varieties showing greater strain hardening and extensional viscosity (Dobraszczyk and Roberts, 1994; Dobraszczyk, 1997; van Vliet et al., 1992; Wikström and Bohlin, 1999a,b).

11. Applications of rheology to cereal products

11.1. Mixing

Mixing is a critical operation in food processing where, apart from the obvious function of mixing ingredients, the structure of the food is often formed. For example, in the production of batters, pastes and doughs, the nature of the mixing action develops the viscoelastic properties of gluten and also incorporates air, which has a major effect on their rheology and texture. There is an intimate relationship between mixing, aeration and rheology: the design and operation of the mixer will develop texture, aeration and rheology to different extents (Campbell and Shah, 1999), and conversely the rheology of the food will affect the time and energy input required to achieve optimal development. This is seen in the great variety of mixers used in the food industry and the fact that certain mixers are required to produce a desired texture or rheology in a food (Campbell, 1995).

Studies on the rheology of mixing have focused on a number of areas: (i) the effects of mixer design and operation on the development of rheology and texture; (ii) empirical measurement of rheology during mixing from mixer torque or power consumption; (iii) effect of rheology on mixing patterns and performance; and (iv) simulation and prediction of mixing flow deformation patterns as functions of mixer geometry and rheology.

Most of the studies on doughs have been on the relationships between mixing, rheology and baking performance, because of the rheological changes that occur in the gluten viscoelastic network during mixing and their importance for product quality. Despite the obvious importance of mixing in the development of rheology and texture in doughs, there is very little information in the literature on these changes during the different stages in the mixing process. Most work has either concentrated on

7

empirical measurement of mixer motor torque, voltage or power consumption during mixing as a qualitative indication of changing rheology, or measurement of rheological changes at some time after mixing. Problems associated with these approaches are: failure to take into account motor and drive losses, frictional and surface effects between the dough and the mixer, varying signal damping and data acquisition rates, effects of aeration on rheology, and rheological relaxation effects. Since dough is a viscoelastic material which shows rapid relaxation after deformation, which varies between different flours, such measurements are not ideal and run the risk of giving misleading information. Nevertheless, much useful information has been obtained about the effect of mixing on gluten structure (Weegels et al., 1996; Skerrit et al., 1999), rheology and baking performance. Extensive work on dough mixing has shown that mixing speed and energy (work input) must be above a certain value to develop the gluten network and to produce satisfactory breadmaking (Kilborn and Tipples, 1972), and an optimum in work input or mixing time has been related to optimum breadmaking performance (Skeggs, 1985), which varies depending on mixer type, flour composition and ingredients (Mani et al., 1992). For example, mixing doughs by elongational flow in sheeting to achieve optimum development required only 10–15% of the energy normally used in conventional high speed shear mixers (Kilborn and Tipples, 1974), suggesting that much higher rates of work input can be achieved due to the enhanced strain hardening of doughs under extension. Numerous studies have shown that rheological measurements after mixing parallel changes in mixer torque and power consumption (Mani et al., 1992; Zheng et al., 2000; Anderssen et al., 1998), especially if rheological measurements are made under large, non-linear deformation conditions closer to those experienced in the mixer (Mani et al., 1992; Hwang and Gunasekaran, 2001). Recent studies have suggested that qualitative elongational rheological information during mixing can be derived directly from the torque/power consumption of a dough mixer (Gras et al., 2000).

Another approach is the experimental measurement, simulation and modelling of deformation patterns within a mixer using high speed imaging techniques and 3D numerical computational fluid dynamics (CFD). Here the objective is to predict the effect of changing mixer geometry and rheological properties on deformation during mixing to produce mixers better designed to achieve optimum dough processing. Close correspondence between actual and predicted flow patterns indicates the validity of such models, and can be used to obtain indirect information on rheological behaviour during mixing. Model 3D simulation and experimental studies have been carried out for complex rotating flows associated with dough mixing (Binding et al., 2003). Laser Doppler Anemometry was used to obtain the actual flow profiles and velocities during mixing and compared with the numerical modeling simulation to validate the predicted flow. The problem with such approaches is that many models contain highly simplistic rheological relationships (such as a Newtonian power law shear flow for dough (Levine and Drew, 1990)) which do not take into account the viscoelastic shear and extensional properties of doughs at large deformations, and render such models inaccurate.

11.2. Sheeting

Sheeting of dough with rolls is a common operation in the manufacturing of products from cereals. There is a range of different products and raw materials that are sheeted. The purpose of sheeting is different for each product. Bread dough is sheeted in a moulder to shape a dough and to control the bubble size distribution. Repeated sheeting can be used to develop the gluten network in bread dough. Biscuit dough is sheeted both to form the dough and to develop the gluten. Corn masa is sheeted to produce a coherent dough sheet and pastry dough is sheeted and folded to produce a layered structure. There are several different sheeter arrangements, ranging from a single rolling pin to multi-rollers. Generally, the shape of the dough changes during sheeting and the rheological properties of the dough determine the stresses and strains during sheeting. Care must be taken to use rheological properties relevant to the particular application, taking the magnitude of the strain and the rate of strain into account.

Few studies have been done to find the relationship between fundamental rheological properties and sheeting. Most studies are empirical in nature and relate flour properties to end product quality. Bread dough has been studied most extensively. When bread dough is sheeted repeatedly the gluten forms a network, which increases the elasticity in the dough. This gluten network is an essential structure for bread making. Its development is usually measured by the amount of energy that is used to form the dough. Kilborn and Tipples (1974) measured the energy requirement and found that sheeting uses 10–15% of the energy required for dough mixing. It is obvious that the energy requirement is not an inherent flour or dough property as it depends on the mixer or sheeter it has been produced on. To measure rheological properties during sheeting the force or torque on the rolls can be measured. The force and torque depend on the flour strength: a stronger flour produces higher forces. But the roll diameter and roll gap also affect the force and torque (Kilborn and Preston, 1982; Raghavan et al., 1996). Rheological properties can be measured immediately after sheeting. Extensigraph resistance and extensional viscosity increase with repeated sheeting and then decrease again (Moss, 1980; Morgenstern et al., 1999). The maximum viscosity coincides with highest bread volume, showing that the repeated sheeting affects the dough in a similar way to mixing.

Puff pastry is made by enveloping a sheet of butter or fat in dough, sheeting it, folding it to increase the numbers of

layers and sheeting it again to reduce the thickness. This process is repeated a number of times to obtain a layered structure with thin fat/dough layers. The rheological properties of the pastry dough are quite different from a bread dough. The dough is less elastic and ruptures at smaller deformations. Dough with high extensibility and resistance (measured by Extensigraph) produces best lift (rise) during baking (Hay, 1993). When pastry dough is sheeted the stresses relax over a period of up to 1 h. This stress relaxation is related to shrinkage of baked puff pastry and therefore a resting time is usually observed between sheeting and baking (Newberry et al., 1996).

There is no standardised test for measuring rheological properties of a dough sheet. Many studies use the Extensigraph. However, the Extensigraph was developed for bread dough and the standard test uses rested (relaxed) dough with a water level related to bread dough. Clearly, applications with different water levels will have very different rheological properties than measured with the Extensigraph test. An adapted extensional test was proposed by Morgenstern et al. (1996) to measure extensional viscosity on a dough sheet. Measurements on bread dough demonstrated power law behaviour and strain hardening for large deformations.

For a fundamental understanding of the sheeting operation Levine (1985) used a mathematical model, borrowed from polymer calendaring, to predict sheet thickness, roll separation force and energy consumption of sheeting. Dough rheology was described with a power law relationship between stress and strain rate. This model has been extended to include finite width sheets, to include air bubbles, to describe flaking, and to include the effect of ingredient levels (Levine and Levine, 1997; Raghavan et al., 1995; Levine, 1998; Levine et al., 2002; Morgenstern et al., 2002). The power law, however, does not incorporate viscoelasticity, and predictions of sheeting behaviour have been only satisfactory in a qualitative sense. A recent study has incorporated elasticity in the models (Morgenstern et al., 2002; Love, 2002).

11.3. Fermentation and baking

Fermentation is an important step in the breadmaking process, where the expansion of air bubbles previously incorporated during mixing provides the characteristic aerated structure of bread, which is central to its appeal (Dobraszczyk et al., 2000). Although fermentation is clearly important in breadmaking, most rheological tests are performed on doughs without yeast and at room temperature. Few studies have been made on the changing rheological properties during fermentation and baking. Direct rheological measurements have been made on yeasted bread doughs (Kilborn and Preston, 1981), cake batters (Massey, 2002; Sahi, 1999), sour doughs (Wehrle and Arendt, 1998), and cracker sponge and dough (Oliver and Brock, 1997). Such measurements suffer from the problem of the evolving gas volume and metabolites from fermentation confounding the rheological data. The decrease in density as a result of increasing gas volume would be expected to have the effect of decreasing modulus and viscosity, but the compressibility of air may counteract this effect, especially at higher gas volumes and low densities where the moduli of the solid and gas phases converge, such as in cake batters, where shear modulus is directly related to the air content (Massey, 2002). Fermentation metabolites such as lactic and acetic acid, may also exert rheological effects through changes in pH (Wehrle et al., 1997).

Other approaches have been to measure the increase in height or volume of the fermenting product using devices such as the rheofermentometer or risograph, but these provide no direct information about the rheology of the material, since they do not measure force or deformation per change in unit dimensions. Changes in aeration have been predicted from modelling the increase in dough height (Shah et al., 1999), or by directly measuring internal gas pressure during fermentation (Matsumoto et al., 1975). Another approach has been to prevent fermentation by inactivating the yeast by freezing and thawing (Newberry et al., 2002), or by mixing under oxygen to rapidly saturate the yeast activity (Chamberlain and Collins, 1979).

Rheological studies on doughs related to baking have normally been performed in small deformation shear oscillation at room temperature. Such dynamic rheological measurements on doughs have been investigated in many studies (Hibberd and Wallace, 1966; Hibberd and Parker, 1975a,b; Abdelrahman and Spies, 1986; Smith et al., 1970; Dreese et al., 1988). Viscous (G'') and elastic (G') moduli for dough are measured over a range of frequencies. Elastic properties predominate over viscous properties, and the moduli are slightly frequency dependent, which is typical of a cross-linked polymer network (Rao and Steffe, 1992).

No convincing relationship has been established between dynamic rheological properties and baking performance (Khatkar et al., 1995; Kokelaar et al., 1996; Hayman et al., 1998; Autio et al., 2001). Abdelrahman and Spies (1986) compared two flours of different baking quality and measured lower values of elastic (storage) modulus (G') for the higher baking quality flour. Similarly, many reports have found lower values of G' corresponded with better baking quality (Faridi and Faubion, 1986; Weipert, 1988; Weipert, 1992; Schober et al., 2002). Others, however, have found that a higher value of G' for glutens and doughs relates to better baking performance (Amemiya and Menjivar, 1992; Mani et al., 1992; Attenburrow et al., 1990; Janssen et al., 1996), see Table 2. Small deformation dynamic rheological measurements have provided useful information about the properties of isolated glutens and their sub-fractions in relation to baking quality, but similar measurements on whole dough systems have not shown any significant differences (Khatkar et al., 1995). It is thought that these conflicting results are obtained because most of

these tests are carried out at rates and deformation conditions very different from those experienced by the dough during baking expansion, and also because dynamic rheological parameters in the plateau region are generally insensitive to differences in molecular weight (MW) of polymers. However, these parameters are highly sensitive to changes in polymer concentration and diluents such as water, which are almost never kept constant in these experiments on doughs. Most dynamic rheological tests on doughs and glutens have been carried out over a relatively narrow frequency range in the plateau zone, which is known to be insensitive to changes in molecular weight (Ferry, 1980; Macosko, 1994). If, as is generally accepted, large MW glutenin polymers are responsible for the variations in breadmaking performance between different wheat varieties, then it is to be expected that measurements of the plateau modulus will not be good indicators of baking performance and are therefore not appropriate to baking.

During proof and baking the growth of gas bubbles determines the expansion of the dough and therefore the ultimate volume and texture of the baked product (He and Hoseney, 1991). The limit of expansion of these bubbles is related directly to their stability, due to coalescence and the eventual loss of gas when the bubbles fail. The rheological properties of the bubble walls will therefore be important in maintaining stability against premature failure during baking, and also in relation to gas cell stabilization and gas retention during proof, and thus to the final structure and volume of the baked product (Dobraszczyk et al., 2000). The relevant rheological conditions around an expanding gas cell during proof and baking are biaxial extension, large strain and low strain rate. Any rheological tests which seek to relate to baking performance should therefore be performed under conditions similar to those of baking expansion, such as large strain biaxial extension and low strain rates. Methods such as bubble inflation and lubricated compression potentially offer the most appropriate method for measuring rheological properties of doughs. The major advantage of these tests is that the deformation closely resembles practical conditions experienced by the cell walls around the expanding gas cells within the dough during proof and oven rise, i.e. large deformation biaxial extension, and can be carried out at the low strain rates and elevated temperatures relevant to baking (Dobraszczyk et al., 2003).

Extensional rheology is sensitive to polymer chain branching and entanglement interactions between high MW polymers at large deformations (MacLeish and Larson, 1998; Wagner et al., 2000; Münstedt et al., 1998), the theory is simple and relatively well developed, and it generally provides good correlations with the relevant large deformation processing quality parameters (Table 2). Biaxial extensional rheological properties can be measured at large strains up to failure, and the gripping problems normally associated with uniaxial tests can be minimised. Disadvantages are that there is no single well-defined and accepted method for extensional measurement, with many different

Table 2
Correlations between rheological properties and baking performance

Rheological parameter	Baking parameter	Correlation	References
(i) Small deformation shear oscillation			
G' 1 Hz (dough)	Volume	0.15 ($n = 48$)	Autio et al. (2001)
G'SLOPE		0.72	
G' 10 Hz (wet gluten)	Volume	−0.85 ($n = 27$)	Schober et al., 2002
	Form ratio (W/H)	0.65	
G' 1 Hz (gluten)	Volume	N.S ($n = 20$)	Tronsmo et al. (2003)
TAN DELTA	Form ratio (H/W)	0.69	
	(H/W)	−0.71	
G' 1 Hz	Loaf height	−0.64 ($n = 8$)	Uthayakumaran et al. (2000)
TAN DELTA		N.S.	
G'	Volume	N.S. ($n = 4$)	Safari-Ardi and Phan-Thien (1998)
(ii) Large deformation			
Biaxial extensional	Volume	0.89 ($n = 20$)	Tronsmo et al. (2002)
Strain hardening	Form ratio	0.80	
Max. Uuniaxial, extensional viscosity	Loaf height	0.81	Uthayakumaran et al. (2002)
Biaxial strain hardening	Volume	0.92–0.97 ($n = 6$)	Dobraszczyk and Roberts (1994), Dobraszczyk (1997), and Dobraszczyk et al., 2003
Biaxial strain, hardening	Volume	Good	Wikström and Bohlin (1999a,b)
Biaxial strain hardening	Volume	Good	Kokelaar et al. (1996)
Relaxation	Volume	Good	Wikström and Eliasson (1998)
Creep		0.94 ($n = 23$)	Wang and Sun (2002)
Relaxation	Quality	Good	Safari-Ardi and Phan-Thien (1998)
Shear relaxation, shear viscosity	Quality	Good	Amemiya and Menjivar (1992)

methods being used depending on the type and viscosity of the material being studied; the tests often use large amounts of material and the tests are destructive. The measurement of extensional flow is often difficult, because the deformation is large and non-uniform and it is therefore impossible to calculate strain directly from the machine displacement, requiring the direct measurement or calculation of changes in sample dimensions, often at high speeds. In biaxial extension, for example, inaccuracies in the calculation of rheological properties can be introduced due to deviations of the bubble shape from assumed ideal sphericity (Charalambides et al., 2002a,b).

The failure of gas cell walls in doughs has been shown to be directly related to the elongational strain hardening properties of the dough measured under large deformation biaxial extension (Dobraszczyk and Roberts, 1994; Dobraszczyk, 1997; Dobraszczyk et al., 2003). Strain hardening is shown as an increase in the slope of the true stress-strain curve with increasing extension, giving rise to the typical J-shaped stress–strain curve observed for highly extensible materials (Fig. 2) and has been shown to be necessary for stability in any operations which require large extensions, such as cold-drawing of polymer fibres, inflation of polymer films and blow moulding of plastic bottles, and the expansion of gas cells within expanding bread doughs (Dobraszczyk and Roberts, 1994; Kokelaar et al., 1996). Strain hardening in doughs is thought to arise mainly from entanglement coupling of the larger glutenin molecules which gives rise to the high viscosities observed at large strains (Singh and MacRitchie, 2001). Under extensional flow, entangled polymers exhibit strain hardening which is enhanced for polymers with a broad MW distribution, particularly a bimodal distribution (Watanabe, 1999) and branching (Wagner et al., 2000; Münstedt et al., 1998). It is therefore expected that the broad bimodal MW distribution and branched structure of gluten will result in enhanced strain hardening and a bimodal distribution of relaxation times (Bohlin and Carlson, 1980; Li et al., 2003).
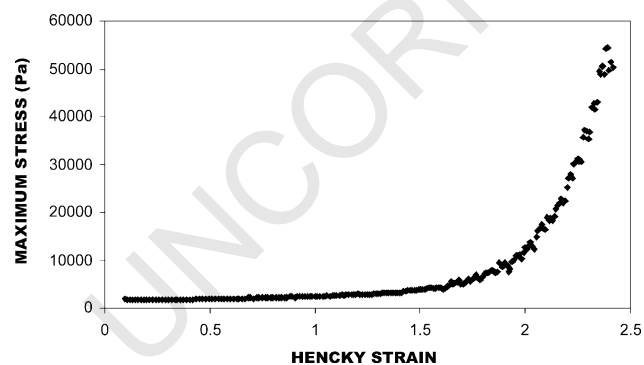

Fig. 2. Typical J-shaped stress-Hencky strain curve in biaxial extension for a dough bubble inflated at 50 °C and constant strain rate (0.1 s^{-1}). Bubble inflation using SMS Dough Inflation System, maximum stress and Hencky strain calculated for bubble wall polar region.

Gas cell wall failure in expanding dough bubbles can be predicted using the Considere criterion for instability in extension for polymers (Dobraszczyk and Roberts, 1994; Wikström and Bohlin, 1999). This criterion states that the stability in extension of a viscoelastic material is guaranteed provided the strain is less than that at which a maximum occurs in the force–extension plot and defines a critical strain beyond which failure is inevitable on further extension. Uniform extension of a viscoelastic membrane during inflation is guaranteed provided the strain does not reach this maximum. Beyond this critical value of strain the criterion states that the material cannot be extended homogeneously and instead undergoes a dynamic failure event (MacKinley and Hassager, 1999). During large extension of materials, plastic strain is uniform throughout the sample up to the point of maximum force. Beyond this point, force begins to decrease and it is at this point that localised and non-uniform plastic deformation begins to occur. The cross-sectional area begins to change in a non-uniform way, and a neck or localised constriction forms, which can either stabilise or propagate in an unstable manner to failure. If the cross section at any point is slightly less than elsewhere or there are any irregularities in the sample when the force is increasing in plastic flow, the stress will increase locally. Whilst the force is increasing the deformation will be stable, i.e. any local constrictions are self-arresting. In contrast, under a decreasing force the deformation is no longer stable, leading to the formation and cumulative increase of necking and eventual failure. Hence the force maximum defines a point of instability in tension, beyond which fracture is inevitable. The occurrence of strain hardening (sometimes called work hardening) in a material stabilises any regions of incipient localised thinning that could lead to unstable necking and eventual fracture during high extensions, and can allow much larger extensions before rupture than would otherwise be possible.

Recent work has shown that bread doughs exhibit strain hardening in large deformations such as bubble expansion, and that these extensional rheological properties are important in baking performance (Dobraszczyk and Roberts, 1994; Dobraszczyk, 1997; van Vliet et al., 1992; Wikström and Bohlin, 1999a; Janssen et al., 1996; Dobraszczyk et al., 2003). Strain hardening allows the expanding gas cell walls to resist failure by locally increasing resistance to extension as the bubble walls become thinner, and appears to provide the bubbles with greater stability against early coalescence and better gas retention. It is expected therefore that doughs with good strain hardening characteristics should result in a finer crumb texture (e.g. smaller gas cells, thinner cell walls and an even distribution of bubble sizes) and larger baked volume than doughs with poor strain hardening properties. It has been shown that good bread-making doughs have good strain hardening properties and inflate to larger single bubble volume before rupture, whilst poor bread-making doughs inflate to lower volumes and

have much lower strain hardening (Dobraszczyk and Roberts, 1994; Dobraszczyk, 1997). Loaf volume for a number of commercial white flour doughs has been related directly to the failure strain and strain hardening properties of single dough bubbles measured at elevated temperatures in biaxial extension (Dobraszczyk et al., 2003). Strain hardening and failure strain of cell walls were both seen to decrease with temperature, with cell walls in good breadmaking doughs remaining stable and retaining their strain hardening properties to higher temperatures (60 °C), whilst the cell walls of poor breadmaking doughs became unstable at lower temperatures (45–50 °C) and had lower strain hardening (Fig. 3). Strain hardening measured at 50 °C gave good correlations with baking volume, with the best correlations achieved between those rheological measurements and baking tests which used similar mixing conditions. As predicted by the Considere failure criterion, a strain hardening value of around 1 defines a region below which gas cell walls become unstable, and discriminates well between the baking quality of a range of commercial flour blends of varying quality (Fig. 4). It is suggested that changes in strain hardening and bubble stability in this temperature region are important in relation to bubble coalescence. When strain hardening falls below a value of 1, bubble walls are no longer stable and coalesce rapidly, resulting in loss of gas retention and lower volume and texture. Bubble walls with good strain hardening properties remain stable for longer during baking, allowing the bubbles to resist coalescence and retain gas for much longer. Strain hardening in poorer breadmaking varieties starts to decrease at much lower temperatures, giving earlier bubble coalescence and release of gas, resulting in lower loaf volumes and poorer texture (Dobraszczyk et al., 2003).
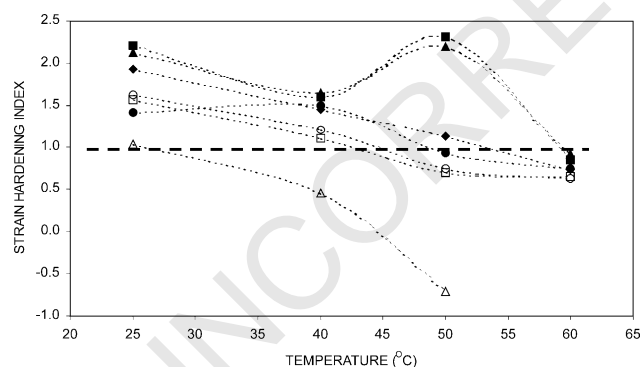
Fig. 3. Mean bubble cell wall strain hardening values ($n = 6$) for a number of wheat varieties inflated at constant strain rate (0.1 s^{-1}) at various temperatures on the SMS Dough Inflation System. The dashed line at strain hardening index = 1.0 defines the region below which expanding bubble walls become unstable. ■ = Pillsbury, ▲ = Soissons, ● = Rialto 1999, ◆ = Hereward, ○ = Rialto 1998, □ = Charger, △ = band (From Dobraszczyk et al. (2003)).
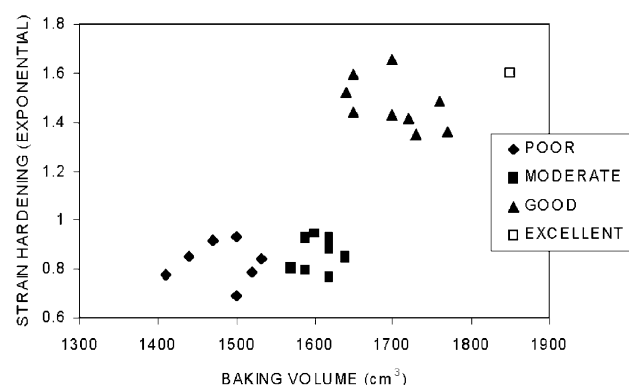
Fig. 4. Discrimination of CBP baking performance for a range of commercial flour blends of varying baking quality using mean bubble cell wall strain hardening properties obtained at 50 °C and constant strain rate (0.1 s^{-1}). (From Dobraszczyk et al. (2003)).

12. Rheological and polymer molecular structure–function relationships in breadmaking

Gluten is the major protein in wheat flour doughs, responsible for their unique viscoelastic behaviour. It is now widely accepted that gluten proteins are responsible for variations in baking quality, and in particular it is the insoluble fraction of the HMW glutenin polymer, which is best related to differences in dough strength and baking quality amongst different wheat varieties (MacRitchie and Lafiandra, 1997; Weegels et al., 1996). However, the exact molecular mechanisms responsible for this variation still remain unclear, largely because information about the molecular size and structure of this fraction is inaccessible by conventional polymer size characterization techniques such as GPC and SE-HPLC due to its insolubility. Therefore other techniques sensitive to changes in polymer MWD and structure are necessary.

One such technique is rheology, which is increasingly being used as a sensitive indicator of changes in the structure of HMW polymers. It has long been recognized that the key mechanisms determining the rheology of HMW polymer melts and concentrated solutions arise from physical structural interactions between polymer molecules (Doi and Edwards, 1986), and that much of the rheological behaviour of these polymers is independent of their chemistry. Recent work has shown that the elongational rheology of HMW polymer melts and concentrated solutions is a sensitive indicator of changes in secondary molecular structure such as small increases in the size of the highest end of the MW distribution, or the presence of long chain branching (LCB) (Wagner et al., 2000; Münstedt et al., 1998). The most significant property is elongational strain hardening (the non-linear rapid increase in viscosity with increasing strain) which is highly sensitive to the degree of entanglement and LCB of the polymer. For example, LCB has been shown to explain the radically different behaviour of branched and linear polymers. Polymer melts which show

no LCB, such as High Density Polyethylene (HDPE) show no extensional strain hardening, whilst branched polymers such as LDPE (Low Density Polyethylene), exhibit pronounced strain hardening (Kurzbeck et al., 1999). The presence of chain branches is important in giving rise to strain hardening, which is a necessary property for stability of polymers undergoing large deformation. Since HMW subunits of gluten have been shown to have a branched structure (Humphris et al., 2000) with branches occurring every 40–50 nm, it is expected that this structure will result in strain hardening in doughs, and will contribute strongly to its resistance to extension and bubble wall stability under large deformation.

Modern polymer physical models relate the molecular size and structure of polymers to their rheological properties and end-use performance. The pom-pom model, recently proposed by MacLeish and Larson (1998) describes the rheological behaviour of HMW branched polymer melts. This class of polymers is envisaged as a relatively flexible HMW backbone to which are attached a number of branches (pom-poms) radiating out from either end of the backbone. This model accurately predicts, for the first time, the well-known phenomenon of strain hardening under uniaxial and planar extensional flow and strain softening (shear thinning) in shear seen in branched HMW polymer melts (Fig. 1a) and in gluten (Fig. 1b). The branches entangle with the surrounding polymers and stretching of the flexible back-bone between entanglements produces strain hardening. Predictions of this model have shown that the number of branches and the distance between entanglements have the most effect on strain hardening (Fig. 9).

Beyond a critical molecular weight (MW$_c$), characteristic for each polymer, zero-shear viscosity (η_0) starts to increase rapidly with increasing MW, following a relationship $\eta_0 = \text{MW}^{3.4}$ for linear polymer melts, independent of polymer chemistry. Above this critical MW, the polymers start to entangle, giving rise to the observed rapid increase in viscosity with MW (Fig. 5). Branching has the effect of increasing viscosity and strain hardening still further, although the rapid increase in viscosity is shifted to higher MW with increasing branching, giving an effective decrease in viscosity at a constant MW. Entanglements also give rise to the steep increase in stiffness and viscosity with strain known as strain hardening. Entanglements can be viewed as physical constraints between segments of the polymer chain, rather like knots, where the polymer chains are stuck and are not free to move past each other (Fig. 6). As can be seen in Fig. 5, a relatively small variation in the highest end of the MWD or branching can give rise to a large increase in viscosity and strain hardening, and is likely to have a large effect on baking performance. Molecular entanglements of HMW polymers under large deformation are related to changes in their relaxation spectrum and extensional strain hardening, which reflect
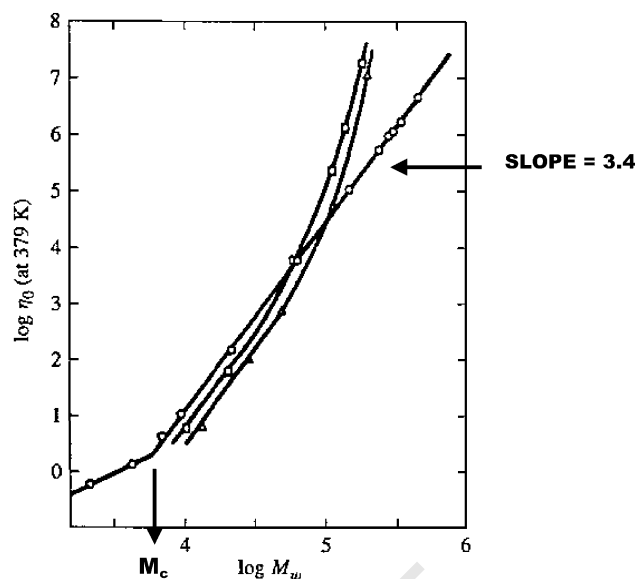

Fig. 5. Effect of MW and branching on zero-shear viscosity for polymer melts. Beyond a critical molecular weight for entanglements (M_c) zero-shear viscosity (η_0) increases rapidly for linear polymer (○) as MW$^{3.4}$. (□) = 3 armed branched polymer (linear with one long side chain), (△) = 4-armed branched polymer. Source: rheological properties of multichain polybutadienes, Kraus and Gruver (1965) Journal of Polymer Science, John Wiley & Sons.

the expected qualitative differences in the underlying MWD of glutenin polymers.

Dynamic shear properties such as G' and relaxation time are sensitive to MW and entanglements. Lefebvre et al. (2000) have shown that the height of the plateau modulus increased with the proportion of the highest MW fractions extracted from heated gluten. Dynamic oscillation measurements are usually made over a relatively narrow window of frequencies, which are not relevant to the strain rates observed during fermentation and baking, and which do not reflect the intermolecular interactions of the HMW glutenin polymers known to be responsible for baking performance. The frequency range of most conventional oscillatory shear rheological tests on doughs is limited to a part of the plateau range, at which the HMW polymers are entangled and are
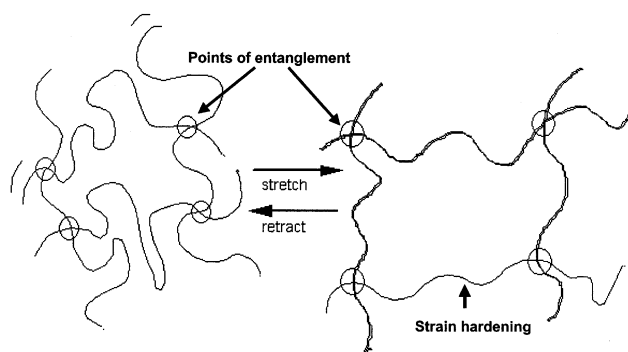

Fig. 6. Model of entanglement network in a high MW polymer during stretching.

insensitive to changes in the MWD (Graessley, 1974, 1982). Therefore, it is necessary to extend these measurements into the low frequency range or the terminal zone, which is known to reflect the disentanglement of the HMW polymers. Because of the extreme polydispersity in MW of the gluten, it is thought necessary to separate out fractions of varying solubility and MW from the gluten (gliadins, soluble glutenins and insoluble glutenins) and then to seek to use additive laws in a recombination of their properties (Tsiami et al., 1997). Fig. 7 shows the effect of increasing MW on the dynamic shear modulus for a narrow MW linear polystyrene polymer melt. As the MW increases, a plateau in modulus begins to appear, which increases in width as the MW increases further. The plateau represents the effect of entanglements, which at a certain polymer size effectively lock the polymer structure into a temporary 3D network with a fixed modulus, the height of which is independent of MW. At some frequency the polymer network begins to disentangle, and the modulus starts to decrease rapidly into the terminal zone, where the polymer chains are free to move about and act as a viscous liquid. The larger the polymer, the longer it stays entangled, and therefore the wider the frequency range over which the plateau remains. Thus it is the width of the plateau, or the point at which it descends into the terminal zone, which is defined by the MW of the polymer. Unfortunately, most rheological measurements on dough and gluten have been performed in the plateau region, which is the region most insensitive to differences in MW. For example, Fig. 8a shows the relationship between the wt% fraction of the various polymer MW size fractions calculated from the total MWD of gluten up to values $>10^8$ (measured by flow-field flow fractionation and light scattering (Stathopoulos, 2003)),
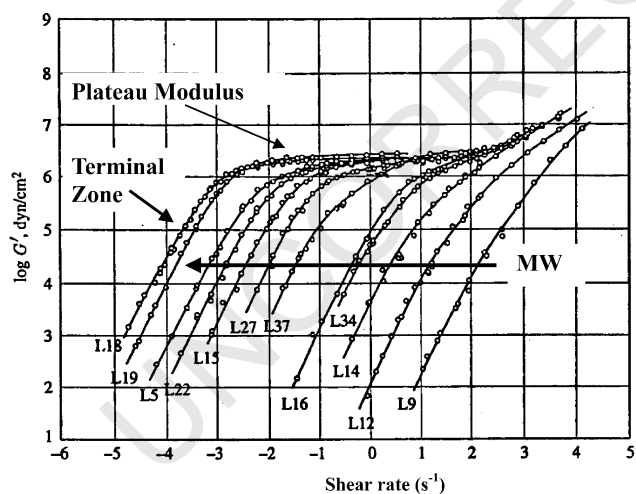
Fig. 7. Effect of increasing MW on dynamic shear modulus for a series narrow MW linear polystyrene polymer melts. (From: Onogi, Masuda, and Kitagawa (1970) Macromolecules 3: 109–116.)
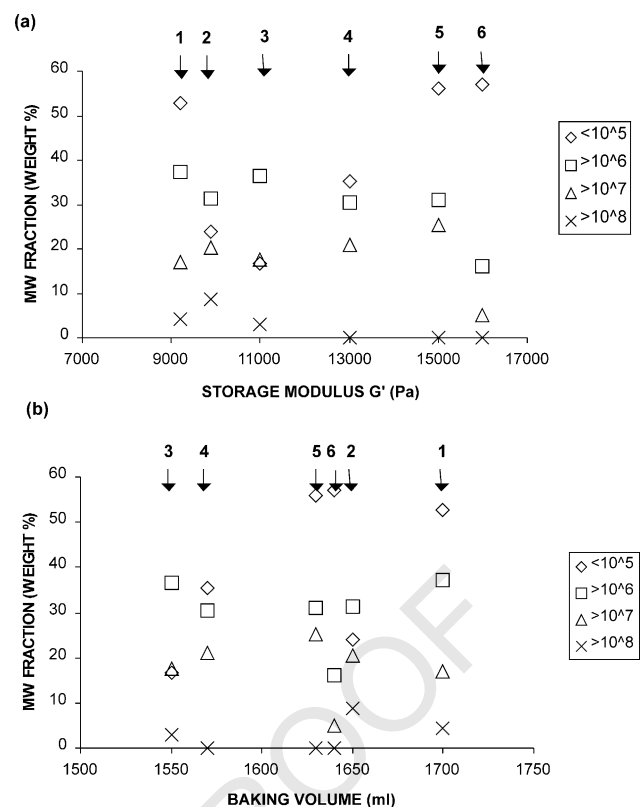
Fig. 8. (a) Relationship between molecular weight fractions and plateau storage modulus (G') measured at 1 Hz. Molecular weight expressed as wt% of fractions greater than certain molecular sizes calculated from the total molecular weight distributions for glutens obtained from five UK wheat varieties and one US commercial flour: 1 = Hereward 2 = Pillsbury 3 = Riband 4 = Soissons 5 = Charger 6 = Rialto. MW data obtained by light scattering from Stathopoulos (2003)). (b) Relationship between molecular weight fractions from (a) and CBP baking volume for a number of UK wheat varieties and one US commercial flour: 1 = Hereward 2 = Pillsbury 3 = Riband 4 = Soissons 5 = Charger 6 = Rialto.

plateau storage modulus (G' at 1 Hz) of gluten and baking quality (Fig. 8b) from a number of wheat varieties of varying baking performance. These show that neither plateau modulus nor baking volume is related to MW up to a size of about 5×10^8. This confirms the observation that plateau modulus is essentially independent of MW and also that it is not the size of the soluble glutenin polymers, but the insoluble polymer fraction that is mainly responsible for baking performance. This does not support the commonly held view that the MW of the glutenin polymers is related to their small deformation shear rheology and to baking quality, but that that is more likely to be the secondary molecular structure of the insoluble glutenin that is responsible for baking performance. Recent evidence suggests that these insoluble HMW polymers are entangled with a corresponding long relaxation time (Fig. 9) (Li et al., 2003), they are branched, and form extensive intermolecular secondary structures held together by covalent and hydrogen bonding (Belton, 1999; Popineau et al., 1994; Feeney et al., 2003).
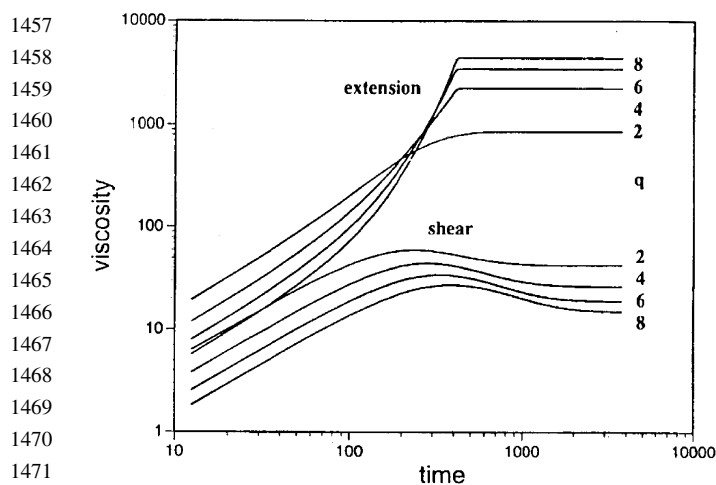
Fig. 9. Modelling the effect of polymer chain branching on shear and extensional rheology. (q = no. of branch points). From: MacLeish and Larson (1998).

13. Conclusions

It would appear that for HMW polymers such as gluten, large deformation extensional rheological properties are more sensitive to changes in MWD, polymer entanglements and branching than small deformation dynamic shear properties, based on sound polymer physics principles and experimental data. Insoluble HMW glutenins have been shown to be best related to variations in baking quality, and to the presence of long relaxation times, indicating entanglements of the HMW polymers. Strain hardening, which has been shown to be a sensitive indicator of entanglements and long-chain branching in HMW polymers, is seen in large extensional deformation of doughs and glutens, and is well related to bubble wall stability, long relaxation times and to variations in baking performance amongst different wheat varieties.

15. Uncited References

Faubion and Faridi (1985).

References

Abdelrahman, A., Spies, R., 1986. Dynamic rheological studies of dough systems. In: Faridi, H., Faubion, J.M. (Eds.), Fundamentals of Dough Rheology, American Association of Cereal Chemists, St Paul, Minnesota, USA, pp. 87–103.

Amemiya, J.I., Menjivar, J.A., 1992. Comparison of small and large deformation measurements to characterise the rheology of wheat flour doughs. Journal of Food Engineering 16, 91–108.

Anderssen, R.S., Gras, P.W., MacRitchie, F., 1998. The rate-independence of the mixing of wheat flour dough to peak dough development. Journal of Cereal Science 27, 167–177.

Attenburrow, G.E., Barnes, D.J., Davies, A.P., Ingman, S.J., 1990. Rheological properties of wheat gluten. Journal of Cereal Science 12, 1–14.

Autio, K., Flander, L., Kinnunen, A., Heinonen, R., 2001. Bread quality relationship with rheological measurements of wheat flour dough. Cereal Chemistry 78, 654–657.

Bagley, E.B., Christianson, D.D., 1986. Response of commercial chemically leavened doughs to uniaxial compression. In: Faridi, H., Faubion, J.M. (Eds.), Fundamentals of Dough Rheology, American Association of Cereal Chemists, St Paul, Minnesota, USA, pp. 27–36.

Barnes, H.A., Hutton, J.F., Walters, K., 1989. An Introduction to Rheology, Elsevier, Amsterdam.

Belton, P.S., 1999. On the elasticity of wheat gluten. Journal of Cereal Science 29, 103–107.

Binding, D.M., Couch, M.A., Suyatha, K.S., Webster, J.F.E., 2003. Experimental and numerical simulation of dough kneading in filled geometries. Journal of Food Engineering in press.

Bloksma, A.H., 1990. Rheology of the breadmaking process. Cereal Foods World 35, 228–236.

Bloksma, A.H., Bushuk, W., 1988. Rheology and chemistry of dough. In: Pomeranz, Y., (Ed.), Wheat Chemistry and Technology II, AACC, St Paul, Minnesota, USA.

Bohlin, L., Carlson, T.L.G., 1980. Dynamic viscoelastic properties of wheat flour doughs: dependence on mixing time. Cereal Chemistry 57, 175–181.

Campbell, G.M., 1995. New mixing technology for the food industry. Food Technology International Europe, 119–122.

Campbell, G.M., Shah, P., 1999. Entrainment and disentrainment of air during bread dough mixing, and their effect on scale-up of dough mixers. In: Campbell, G.M., Webb, C., Pandiella, S.S., Niranjan, K. (Eds.), Bubbles in Food, American Association of Cereal Chemists, St Paul, Minnesota, USA.

Carter, R.E., 1990. Rheology of Food, Pharmaceutical and Biological Materials with General Rheology, Elsevier Applied Science, London.

Chamberlain, N., Collins, T.H., 1979. The Chorleywood bread process: the role of oxygen and nitrogen. Bakers' Digest 53, 18–24.

Charalambides, M.N., Wanigasooriya, L., Williams, J.G., Chakrabarti, S., 2002a. Biaxial deformation of dough using the bubble inflation technique. I. Experimental. Rheologica Acta 41, 532–540.

Charalambides, M.N., Wanigasooriya, L., Williams, J.G., 2002b. Biaxial deformation of dough using the bubble inflation technique. II. Numerical modeling. Rheologica Acta 41, 541–548.

Chatraei, S.H., Macosko, C.W., Winter, H.H., 1981. Lubricated squeezing flow: a new biaxial extensional rheometer. Journal of Rheology 25, 433–443.

Chopin, M., 1921. Relations entre les proprietes mecaniques des pates de farines et la panification. Bull. Soc. Encour. Ind. Nal. 133, 261.

Cogswell, F.N., 1981. Polymer Melt Rheology, George Godwin Ltd, London.

Dobraszczyk, B.J., 1997. Development of a new dough inflation system to evaluate doughs. Cereal Foods World 42, 516–519.

Dobraszczyk, B.J., Roberts, C.A., 1994. Strain hardening and dough gas cell-wall failure in biaxial extension. Journal of Cereal Science 20, 265–274.

Dobraszczyk, B.J., Vincent, J.F.V., 1999. Measurement of mechanical properties of food materials in relation to texture: the materials approach. In: Rosenthal, A.J., (Ed.), Food Texture: Measurement and Perception, Aspen Publishers, Maryland.

Dobraszczyk, B.J., Schofield, J.D., 2002. Rapid assessment and prediction of wheat and gluten baking quality with the 2-g direct drive mixograph using multivariate statistical analysis. Cereal Chemistry 79, 607–612.

Dobraszczyk, B.J., Campbell, G.M., Gan, Z., 2000. Bread—a unique food. In: Dobraszczyk, B.J., Dendy, D.A.V. (Eds.), Cereals and Cereal Products: Technology and Chemistry, Aspen Publishers, USA.

Dobraszczyk, B.J., Smewing, J., Albertini, M., Maesmans, G., Schofield, J.D., 2003. Extensional rheology and stability of gas cell walls in bread doughs at elevated temperatures in relation to breadmaking performance. Cereal Chemistry 80, 218–224.

Doi, M., Edwards, S.F., 1986. The Theory of Polymer Dynamics, Oxford University Press, Oxford.

Dreese, P.C., Faubion, J.M., Hoseney, R.C., 1988. Dynamic rheological properties of flour, gluten and gluten–starch systems. I. Temperature-dependent changes during heating. Cereal Chemistry 65, 348–353.

Edwards, N.M., Dexter, J.E., Scanlon, M.G., Cenkowski, S., 1999. Relationship of creep-recovery and dynamic oscillatory measurements to durum wheat physical dough properties. Cereal Chemistry 76, 638–645.

Edwards, N.M., Peressini, D., Dexter, J.E., Mulvaney, S.T., 2001. Viscoelastic properties of durum wheat and common wheat dough of different strengths. Rheologica Acta 40, 142–153.

Fan, J., Mitchell, J.R., Blanshard, J.M.V., 1994. A computer simulation of the dynamics of bubble growth and shrinkage during extrudate expansion. Journal of Food Engineering 23, 337–356.

Faridi, H., Faubion, J.M., 1986. Fundamentals of Dough Rheology, American Association of Cereal Chemists, St Paul, Minnesota, USA.

Faridi, H., Faubion, J.M., 1990. Dough Rheology and Baked Product Texture, AVI Van Nostrand Reinhold, New York.

Faubion, J.M., Faridi, H., 1985. Dough rheology: its benefits to cereal chemists. In: Faridi, H., (Ed.), Rheology of Wheat Products, American Association of Cereal Chemists, St Paul, Minnesota, USA, pp. 1–9.

Feeney, K.A., Wellner, N., Gilbert, S.M., Halford, N.G., Tatham, A.S., Shewry, P.R., 2003. Molecular structures and interactions of repetitive peptides based on wheat glutenin subunits depend on chain length. Biopolymers (Biospectroscopy) 72, 123–131.

Ferry, J.D., 1980. Viscoelastic Properties of Polymers, Wiley, New York.

Graessley, W.W., 1974. The entanglement concept in polymer rheology. Advances in Polymer Science 16, 1–179.

Graessley, W.W., 1982. Entangled linear, branched and network polymer systems—molecular theories. Advances in Polymer Science 47, 67–117.

Gras, P.W., Carpenter, H.C., Anderssen, R.S., 2000. Modelling the developmental rheology of wheat flour dough using extension tests. Journal of Cereal Science 31, 1–13.

Hankoczy, J., 1920. Apparat fur kleberverwertung. Z.Gesamte Getreide-wiss. 12, 57.

Hay, R.L., 1993. Effect of flour quality characteristics on puff pastry baking performance. Cereal Chemistry 70, 392–396.

Hayman, D., Sipes, K., Hoseney, R.C., Faubion, J.M., 1998. Factors controlling gas cell failure in bread dough. Cereal Chemistry 75, 585–589.

He, H., Hoseney, R.C., 1991. Gas retention of different cereal flours. Cereal Chemistry 68, 334–336.

Hibberd, G.E., Parker, N.S., 1975a. Dynamic viscoelastic behaviour of wheat flour doughs, part IV. Non-linear behaviour. Rheologica Acta 14, 151–157.

Hibberd, G.E., Parker, N.S., 1975b. Measurement of the fundamental rheological properties if wheat flour doughs. Cereal Chemistry 52, 1–23.

Hibberd, G.E., Wallace, W.J., 1966. Dynamic viscoelastic behaviour of wheat flour doughs, part 1. Linear aspects. Rheologica Acta 5, 193–198.

Huang, H., Kokini, J.L., 1993. Measurement of biaxial extensional viscosity of wheat flour doughs. Journal of Rheology 37, 879–891.

Humphris, A.D.L., McMaster, T.J., Miles, M.J., Gilbert, S.M., Shewry, P.R., Tatham, A.S., 2000. Atomic force microscopy (AFM) study of interactions of HMW subunits of wheat glutenin. Cereal Chemistry 77, 107–110.

Hwang, C.H., Gunasekaran, S., 2001. Determining wheat dough mixing characteristics from power consumption profile of a conventional mixer. Cereal Chemistry 78, 88–92.

Janssen, A.M., van Vliet, T., Vereijken, J.M., 1996. Rheological behaviour of wheat glutens at small and large deformations. Comparisons of two glutens differing in breadmaking potential. Journal of Cereal Science 23, 19–31.

Khatkar, B.S., Bell, A.E., Schofield, J.D., 1995. The dynamic rheological properties of glutens and gluten sub-fractions from wheats of good and poor bread making quality. Journal of Cereal Science 22, 29–44.

Kilborn, R.H., Preston, K.R., 1981. A dough height tracker and its potential application to the study of dough characteristics. Cereal Chemistry 58, 198–201.

Kilborn, R.H., Preston, K.R., 1982. A dough sheeting and molding property indicator. Cereal Chemistry 59, 171–174.

Kilborn, R.H., Tipples, K.H., 1972. Factors affecting mechanical dough development I. Effect of mixing intensity and work input. Cereal Chemistry 49, 4–47.

Kilborn, R.H., Tipples, K.H., 1974. Implications of the mechanical development of bread dough by means of sheeting rolls. Cereal Chemistry 51, 648–657.

Kokelaar, J.J., van Vliet, T., Prins, A., 1996. Strain hardening and extensibility of flour and gluten doughs in relation to breadmaking performance. Journal of Cereal Science 24, 199–214.

Kurzbeck, S., Oster, F., Münstedt, H., Nguyen, T.Q., Gensler, R., 1999. Rheological properties of two polypropylenes with different molecular structure. Journal of Rheology 43, 359–374.

Launay, B., 1990. A simplified non-linear model for describing the viscoelastic proerties of wheat flour doughs at high shear strains. Cereal Chemistry 67, 25–31.

Launay, B., Bure, J., Praden, J., 1977. Use of the Chopin Alveograph as a rheological tool. I. Dough deformation measurements. Cereal Chemistry 54, 1042–1048.

Lefebvre, J., Popineau, Y., Deshayes, G., Lavenant, L., 2000. Temperature induced changes in the dynamic rheological behaviour and size distribution of polymeric proteins for glutens from wheat near-isogenic lines differing in HMW glutenin subunit composition. Cereal Chemistry 77, 193–201.

Levine, L., 1985. Throughput and power consumption of dough sheeting rolls. Journal of Food Process Engineering 7, 223–238.

Levine, L., 1998. Models for dough compressibility in sheeting. Cereal Foods World 43, 629–634.

Levine, L., Drew, B.A., 1990. Rheological and engineering aspects of the sheeting and laminating of doughs. In: Faridi, H., Faubion, J.M. (Eds.), Dough Rheology and Baked Product Texture, Van Nostrand Reinhold, New York, pp. 513–556.

Levine, L., Levine, S., 1997. A preliminary investigation of the deformation of cereal pellets by flaking rolls. Cereal Foods World 42, 444–451.

Levine, L., Corvalan, C.M., Campanella, O.H., Okos, M.R.A., 2002. model describing the two-dimensional calendering of finite width sheets. Chemical Engineering Science 57, 643–650.

Li, W., Dobraszczyk, B.J., Schofield, J.D., 2003. Stress relaxation behaviour of wheat dough and gluten protein fractions. Cereal Chemistry 80, 333–338.

Love, R.J., 2002. Mathematical modelling of bread dough sheeting. PhD thesis, Massey University, New Zealand.

Love, R.J., Hemar, Y., Morgenstern, M., McKibbin, R., 2002. Modelling the sheeting of wheat flour dough. Ninth Asian Pacific Confederation of Chemical Engineering Congress APCChE 2002 and 30th Annual Australasian Chemical Engineering Conference CHEMECA 2002, Christchurch, New Zealand.

MacKinley, G.H., Hassager, O., 1999. The Considere condition and rapid stretching of linear and branched polymer melts. Journal of Rheology 43, 1195–1212.

MacLeish, T.C.B., Larson, R.G., 1998. Molecular constitutive equations for a class of branched polymers. Journal of Rheology 42, 81–110.

MacRitchie, F., Lafiandra, D., 1997. Structure–function relationships of wheat proteins. In: Damodaran, S., Paraf, A. (Eds.), Food Proteins and their Applications, Marcel Dekker, New York, pp. 293–323.

Macosko, C.W., 1994. Rheology: Principles, Measurements and Applications, VCH, New York.

Mani, K., Eliasson, A.-C., Lindahl, L., Trägårdh, C., 1992. Rheological properties and bread making quality of wheat flour doughs made with different dough mixers. Cereal Chemistry 69, 222–225.

Massey, A.H., 2002. Air inclusion mechanisms and bubble dynamics in intermediate viscosity food systems. PhD thesis, The University of Reading, UK.

Matsumoto, H., Nishiyama, J., Mita, T., Kuninori, T., 1975. Rheology of fermenting dough. Cereal Chemistry 52, 82r.

Morgenstern, M.P., Newberry, M.P., Holst, S.E., 1996. Extensional properties of dough sheets. Cereal Chemistry 73, 478–482.

Morgenstern, M.P., Zheng, H., Ross, M., Campanella, O.H., 1999. Rheological properties of sheeted wheat flour dough measured with large deformations. International Journal of Food Properties 2, 265–275.

Morgenstern, M.P., Wilson, A.J., Ross, M., Al-Hakkak, F., 2002. The importance of visco-elasticity in sheeting of wheat flour dough. In: Welti-Chanes, J., Barbosa-Canovas, G.V., Aguilera, J.M., Lopez-Leal, L.C., Wesche-Ebeling, P., Lopez-Malo, A., Palou-Garcia, E. (Eds.), Proceedings of the Eighth International Congress on Engineering and Food, Technomic, Puebla, Mexico, pp. 519–521.

Moss, H.J., 1980. Strength requirements of doughs destined for repeated sheeting compared with those of normal doughs. Cereal Chemistry 57, 195–197.

Münstedt, H., Kurzbeck, S., Egersdörfer, L., 1998. Influence of molecular structure on rheological properties of polyethylenes. Part II. Elongational behaviour. Rheologica Acta 37, 21–29.

Muller, H.G., 1975. Rheology and the conventional bread and biscuit making process. Cereal Chemistry 52, 89r–105r.

Newberry, M.P., Morgenstern, M.P., Ross, M., 1996. Dough relaxation during and after puff pastry processing. Cereal'96 Proceedings of the 46th Australian Cereal Chemistry Conference, RACI, Melbourne, Australia, pp. 311–314.

Newberry, M.P., Phan-Thien, N., Larroque, O.R., Tanner, R.I., Larsen, N.G., 2002. Dynamic and elongation rheology of yeasted bread doughs. Cereal Chemistry 79, 874–879.

Oliver, G., Brock, C.J., 1997. A rheological study of mechanical dough development and long fermentation processes for cream cracker dough production. Journal of the Science of Food and Agriculture 74, 294–300.

Padmanabhan, M., 1995. Measurement of extensional viscosity of viscoelastic liquid foods. Journal of Food Engineering 25, 311–327.

Popineau, Y., Bonenfant, S., Cornec, M., Pezolet, M.A., 1994. study by infrared spectroscopy of the conformations of gluten proteins differing in their gliadin and glutenin compositions. Journal of Cereal Science 20, 15–22.

Raghavan, C.V., Nagin, C., Srichandan Babu, R., Srinivasa Rao, P.N., 1995. Modelling the power consumption during sheeting of doughs for traditional Indian foods. Journal of Food Process Engineering 18, 397–415.

Raghavan, C.V., Babu, R.S., Chand, N., Rao, P.N.S., 1996. Response surface analysis of power consumption of dough sheeting as a function of gap, reduction ratio, water, salt and fat. Journal of Food Science and Technology-Mysore 33, 313–321.

Rao, M.A., Steffe, J.F., 1992. Viscoelastic Properties of Foods, Elsevier Applied Science, New York.

Rao, V.K., Mulvaney, S.J., Dexter, J.E., Edwards, N.M., Peressini, D., 2001. Stress-relaxation properties of mixograph semolina-water doughs from durum wheat cultivars of variable strength in relation to mixing characteristics, bread- and pasta-making performance. Journal of Cereal Science 34, 215–232.

Rasper, V.F., 1975. Dough rheology at large deformations in simple tensile mode. Cereal Chemistry 52, 24r–41r.

Safari-Ardi, M., Phan-Thien, N., 1998. Stress relaxation and oscillatory tests to distinguish between doughs prepared from wheat flours of different varietal origin. Cereal Chemistry 75, 80–84.

Sahi, S.S., 1999. Influence of aeration and emulsifiers on cake batter rheology and textural properties of cakes. In: Campbell, G.M., Webb, C., Pandiella, S.S., Niranjan, K. (Eds.), Bubbles in Food, American Association of Cereal Chemists, St Paul, Minnesota, USA.

Schofield, R.K., Scott Blair, G.W., 1932. The relationship between viscosity, elasticity and plastic strength of soft materials as illustrated by some mechanical properties of flour doughs, I. Proceedings of the Royal Society of London A 138, 707–718.

Schofield, R.K., Scott Blair, G.W., 1937. The relationship between viscosity, elasticity and plastic strength of a soft material as illustrated by some mechanical properties of flour dough, IV. The separate contributions of gluten and starch. Proceedings of the Royal Society of London A 160, 87–94.

Scott, G., Richardson, P., 1997. The application of computational fluid dynamics in the food industry. Trends in Food Science and Technology 8, 119–124.

Schober, T.J., Clarke, C.I., Kuhn, M., 2002. Characterization of functional properties of gluten proteins in spelt cultivars using rheological and quality factor measurements. Cereal Chemistry 79, 408–417.

Shah, P., Campbell, G.M., Dale, C., Rudder, A., 1999. Modelling bubble growth during proving of bread dough. In: Campbell, G.M., Webb, C., Pandiella, S.S., Niranjan, K. (Eds.), Bubbles in Food, American Association of Cereal Chemists, St Paul, Minnesota, USA.

Sherman, P., 1970. Industrial Rheology, with Particular Reference to Foods, Pharmaceuticals, and Cosmetics, Academic Press, London.

Shuey, W.C., 1975. Practical instruments for rheological measurements on wheat products. Cereal Chemistry 52, 42r–81r.

Singh, H., MacRitchie, F., 2001. Application of polymer science to properties of gluten. Journal of Cereal Science 33, 231–243.

Skeggs, P.K., 1985. Mechanical dough development—dough water level and flour protein quality. Cereal Chemistry 62, 458–462.

Skerrit, J.H., Hac, L., Bekes, F., 1999. Depolymerization of the glutenin macropolymer during dough mixing: I. Changes in levels, molecular weight distribution and overall composition. Cereal Chemistry 76, 395–401.

Smith, J.R., Smith, T.L., Tschoegl, N.W., 1970. Rheological properties of wheat flour doughs III. Dynamic shear modulus and its dependence on amplitude, frequency, and dough compositionI. Rheologica Acta 9, 239–252.

Stathopoulos, C., 2003. The role of gluten proteins in gas cell stabilisation in dough during baking, PhD thesis, University of Reading, UK.

Tronsmo, K.M., Faergestad, E.M., Schofield, J.D., Magnus, E.M., 2002. Wheat protein quality in relation to baking performance evaluated by the Chorleywood bread process and a hearth bread baking test. In: Wheat gluten proteins: analysis of properties and relation to baking performance. PhD thesis, Department of Chemistry and Biotechnology, Agricultural University of Norway, Ås, Norway, submitted for publication.

Tronsmo, K.M., Magnus, E.M., Faergestad, E.M., Schofield, J.D., 2003. Relationships between gluten rheological properties and hearth loaf characteristics. Cereal Chemistry in press.

Tschoegl, N.W., Rinde, J.A., Smith, T.L., 1970a. Rheological properties of wheat flour doughs I. Method for determining the large deformation and rupture properties in simple tension. Journal of the Science of Food and Agriculture 21, 65–70.

Tschoegl, N.W., Rinde, J.A., Smith, T.L., 1970b. Rheological properties of wheat flour doughs II. Dependence of large deformation and rupture properties in simple tension on time, temperature and water absorption. Rheologica Acta 9, 223–238.

Tsiami, A.A., Bot, A., Agterof, W.G.M., Groot, R.D., 1997. Rheological properties of glutenin subfractions in relation to their molecular weight. Journal of Cereal Science 26, 15–27.

Uthayakumaran, S., Newberry, M., Keentock, M., Stoddard, F.L., Bekes, F., 2000. Basic rheology of bread dough with modified protein content and glutenin to gliadin ratios. Cereal Chemistry 77, 744–749.

Uthayakumaran, S., Newberry, M.P., Phan-Thien, N., Tanner, R., 2002. Small and large strain rheology of wheat gluten. Rheologica Acta 41, 162–172.

Wagner, M.H., Bastian, H., Hachmann, P., Meissner, J., Kurzbeck, S., Münstedt, H., Langouche, F., 2000. The strain hardening behaviour of linear and long-chain-branched polyolefin melts in extensional flows. Rheologica Acta 39, 97–109.

Wang, F.C., Sun, X.S., 2002. Creep recovery of wheat flour doughs and relationship to other physical dough tests and breadmaking performance. Cereal Chemistry 79, 567–571.

Watanabe, H., 1999. Viscoelasticity and dynamics of entangled polymers. Progress in Polymer Science 24, 1253–1403.

Weegels, P.L., van der Pijpekamp, A.M., Graveland, A., Hamer, R.J., Schofield, J.D., 1996. Depolymerisation and re-polymerisation of wheat glutenin during dough processing. I. Relationships between glutenin macropolymer content and quality parameters. Journal of Cereal Science 23, 103–111.

Weegels, P.L., Hamer, R.J., Schofield, J.D., 1996. Critical review: functional properties of wheat glutenin. Journal of Cereal Science 23, 1–18.

Wehrle, K., Arendt, E.K., 1998. Rheological changes in wheat sourdough during controlled and spontaneous fermentation. Cereal Chemistry 75, 882–886.

Wehrle, K., Grau, H., Arendt, E.K., 1997. Effects of lactic acid, acetic acid and table salt on fundamental rheological properties of wheat dough. Cereal Chemistry 74, 739–744.

Weipert, D., 1988. The benefits of basic rheometry in studying dough rheology. Cereal Chemistry 67, 311–317.

Weipert, D., 1992. Descriptive and fundamental rheology in a new light. Cereal Foods World 37, 15–24.

Whorlow, R.W., 1992. Rheological Techniques, 2nd ed., Rheological Techniques 2nd., Ellis Horwood, Chichester, UK.

Wikström, K., Bohlin, L., 1996. Multivariate analysis as a tool to predict bread volume from mixogram parameters. Cereal Chemistry 73, 686–690.

Wikström, K., Bohlin, L., 1999a. Extensional flow studies of wheat flour dough. I. Experimental method for measurements in contraction flow geometry and application to flours varying in breadmaking performance. Journal of Cereal Science 29, 217–226.

Wikström, K., Bohlin, L., 1999b. Extensional flow studies of wheat flour Dough. II. Experimental method for measurements in constant extension rate squeezing flow and application to flours varying in breadmaking performance. Journal of Cereal Science 29, 227–234.

Wikström, K., Eliasson, A.-C., 1998. Effect of enzymes and oxidizing agents on shear stress relaxation of wheat flour dough. Cereal Chemistry 75, 331–337.

Zheng, H., Morgenstern, M.P., Campanella, O.H., Larsen, N.G., 2000. Rheological properties of dough during mechanical dough development. Journal of Cereal Science 32, 293–306.

van Vliet, T., 1999. Rheological classification of foods and instrumental techniques for their study. In: Rosenthal, A.J., (Ed.), Food Texture: Measurement and Perception, Aspen Publishers, Maryland, USA.

van Vliet, T., Janssen, A.M., Bloksma, A.H., Walstra, P., 1992. Strain hardening of dough as a requirement for gas retention. Journal of Texture Studies 23, 439–460.