Sheeting Characteristics of Salted and Alkaline Asian Noodle Doughs: Comparison with Lubricated Squeezing Flow Attributes

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ABSTRACT

Changes in low-water, wheat-flour noodle dough sheets passing through counter-rotating rollers were observed by measuring changes in thickness and springback (thickness of the machined dough sheet relative to the roll gap) during sheeting. Doughs were also subjected to lubricated squeezing flow (LSF) at 50 and 90% compression (strain). The LSF parameters reported were maximum stress to compress to the prescribed strain, time for stress to decay to 1/*e* (36.8%) of the maximum at constant strain (relaxation time), and apparent biaxial extensional viscosity. Using these techniques and two flours with contrasting dough properties, it was observed that the responses of doughs changed depending on whether they were rested before or between compound and reduction sheeting, whether they were salted or alkaline, and whether these treatments were applied to flours producing doughs, which by conventional assessment were either weak or strong. Being salted or alkaline in turn dictated whether resting and subsequent working through the reduction-sheeting process made the doughs become either relatively more (alkaline doughs from 'Paul' rested for 45 min) or relatively less (salted doughs from 'Paul' processed immediately) elastic throughout the sheeting process, as described by parameters such as springback measured in the rollers or relaxation time measured in LSF.

Dough mixing during Asian noodle processing is performed primarily to hydrate the flour solids. The result of mixing is a crumbly, somewhat friable dough. In the majority of conventional, machine-based noodle-making processes, the crumbly dough is compounded between counter-rotating rollers to form a dough sheet. Further processing occurs through a series of sheeting operations that develop the gluten network and reduce the dough sheet to the desired thickness in a stepwise fashion. Characteristics of noodle doughs differ markedly from those of breadmaking doughs, primarily because noodle doughs are made with a relatively low amount of liquid (saline or an alkaline "kansui" solution), often ranging from 28 to 35% (flour basis) (6).

A number of methods have been used successfully to investigate the effects of changes in water content, formulation, and flour composition on noodle dough properties. These methods include dynamic oscillating rheometry (8,21), probe tests (3,12), measurement of changes in length of doughs (11), and measurement of the force exerted on the rollers during sheeting (work input) (10,11). These techniques are useful but have constraints. The techniques used by Jin and Quail (12) and Beasley and coworkers (3) produced empirical results from which fundamental rheological parameters could not be derived. The apparent constraint in the Edwards and coworkers (8) study was that rheological testing was delayed for 2.5 hr after sheeting. This was done to test fully relaxed doughs, as is customary and recommended for fundamental dough rheology studies. However, the delay precluded observation of the properties of unrelaxed doughs. Understanding the properties of unrelaxed doughs may be essential to understanding the phenomena occurring during reduction sheeting, in which each successive deformation occurs in rapid succession and there is little time for doughs to relax.

In the sheeting process, noodle doughs are normally constrained to a constant width, so the deformation geometry is planar extension. This is characterized by reduced height (i.e., dough thickness or y-coordinate axis), increased length (x-coordinate axis), and fixed width (z-coordinate axis) (22). As a result, during rheological testing of noodle doughs it seems reasonable to use some type of extension technique. Choices in types of deformation geometry include planar, uniaxial, and biaxial extensions. Of these, noodle rollers generate planar extension, and direct data can be extracted. However, one limitation faced by many researchers is the inability to measure the stresses on the doughs with existing laboratory-scale noodle-processing equipment. Nonetheless, it is possible to observe absolute or relative deformations in the absence of force measurements (9). Alternatively, uniaxial extension, characterized by increased length and reductions in both thickness and width, may be applied. Uniaxial extension may be the least like the deformation of noodle sheets during conventional reduction sheeting, although this deformation geometry is used in the manufacture of traditional hand-stretched noodles and conventional dough extensibility tests.

The third geometry, biaxial extension using a squeezing flow technique, is an attractive option for testing noodle doughs; one can derive some fundamental information, sample presentation is relatively easy, and compression strains of the same order applied in sheeting can be achieved easily. Biaxial extension is characterized by increased length and width accompanied by reduced thickness. Biaxial extension or flow can be generated by expanding a bubble or balloon of dough with gas pressure (7), using other geometries such as the probe method described by Morgenstern and coworkers (16), or by applying uniaxial compression to a sample between two lubricated plates (lubricated squeezing flow [LSF]). LSF is the method of interest here. It has been applied to bread (1,14,18,23) and gluten doughs (14,24), but only limited research on LSF has been applied to noodle doughs (15). Liao (15) used LSF to test noodle doughs made from different flours and suggested its usefulness as a tool for noodle processors. LSF has also been applied to fat-shortened (2) and biscuit (cookie) doughs (19,20).

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The specific objective of this study is to advance understanding of Asian noodle dough behavior during processing through the measurement of deformations occurring during sheeting and determinations of stress responses during LSF rheometry. Because LSF applied to noodle doughs has not been previously reported in the primary literature, there is a parallel objective to develop LSF as a tool for examining the stress responses of noodle doughs. The final objective is to use these techniques to observe the effects on noodle doughs of flour composition, formulation (NaCl or Na_2CO_3), and dough rest periods.

MATERIALS AND METHODS

Two straight-grade flour samples were sourced from the 2006 Pacific Northwest Wheat Quality Council testing program. Flours were milled from grain of the soft white wheat variety Nick and the hard red variety Paul, which produced weak and strong doughs, respectively. Flour milled from ‘Nick’ had a protein content of 9.7% and farinograph absorption, mix time, and stability of 54.1%, 2.5 min, and 2.6 min, respectively. Flour milled from ‘Paul’ had a protein content of 12.1% and farinograph absorption, mix time, and stability of 56.9%, 6.0 min, and 48 min, respectively. Nick was slightly more extensible than was Paul (alveograph *L* values = 120 and 81, respectively) (data were provided by the USDA ARS Western Wheat Quality Laboratory and collaborators of the Pacific Northwest Wheat Quality Council [25]).

Noodle doughs were prepared by dissolving salt (2% flour basis, as is moisture [fb]) or anhydrous sodium carbonate (1% fb) in a fixed amount of water (34% fb) for dough makeup. As judged by an experienced noodle maker, water addition was close to optimum for Nick flour and slightly over optimum for Paul flour. Flour (300 g) was placed in the bowl of a planetary vertical mixer (KitchenAid KP26M) and mixed with a flat beater at a speed 2 for 1 min. The saline or alkaline solution was added to the flour within 30 sec, with the mixer still running, and allowed to mix another minute at speed 2. The mixer was stopped, the dough adhering to the beater was scraped off with a rubber spatula, and the mixture was mixed for another minute at speed 6. The mixing speed was reduced to speed 2, and the dough mixed for another 3 min. Total mixing time was 5 min.

For noodle sheeting, a laboratory-scale noodle machine was used (Ohtake Mfg., Tokyo, Japan). The rollers were 150 mm wide by 175 mm in diameter and were run at 7.5 rpm. The machine had been equilibrated to room temperature (24.0 ± 1.0°C) over a period of weeks. Roll gaps were calibrated at the beginning of each day with stainless-steel feeler gauges. Mixed doughs were compounded into the initial dough sheet with the roll gap set at 5.0 mm. The dough sheet was then folded once, lengthwise, and compressed again through the 5-mm gap with the fold as the leading edge. This was done three times. The dough was then passed once again through the 5-mm gap without folding (five compounding roll passes total). The compound sheet was processed immediately (zero-rest) or rested for 45 min (45’-rested). During resting, all dough sheets were held at room temperature in plastic bags closed with zip-type closures. Dough thickness was reduced by sheeting through successively narrower roll gaps (3.5, 2.45, 1.7, and 1.2 mm), each approximately 30% smaller than the previous. The five sheeting passes (5.0, 3.5, 2.45, 1.7, and 1.2 mm) are designated C, R1, R2, R3, and R4, respectively. The thicknesses of the final doughs were not adjusted to a specific value because the objective was to see how each dough responded to the same sheeting treatment.

Dough lengthening was measured immediately after each reduction pass with an adaptation of the method of Kempf and coworkers (13), but the results are not reported because the measure was relatively insensitive to the treatments applied. After each sheeting pass, dough thickness was measured in four places with a Peacock thickness gauge, and the four results were averaged to give a representative value. A 2-min period was allowed between sheetings during which all measurements were made. Doughs and dough pieces were held in closed plastic bags to prevent surface-drying. Proportional springback of the doughs after each roll pass was calculated as the percent ratio of the dough thickness/roll gap – 100. For example, after rolling through a 1-mm roll gap, dough with a 1.5-mm final thickness has 50% springback.

LSF

Constant area and velocity LSF (2,4,5) was conducted on noodle doughs with a texture meter (TATXplus, Texture Technologies, Scarsdale, NY) fitted with a 25.4-mm-diameter cylindrical probe and matching 25.4-mm-diameter base plate. Separate doughs were used for the 50 and 90% strain experiments. Although Bagley and Christianson (1) indicated that results depended strongly on the rate of compression, we chose to compress at a single constant rate of 1 mm s^{-1} in line with the lower crosshead speed used by Baltsavias and coworkers (2).

Circular dough pieces were cut from the sheet immediately after compounding and after each reduction pass with a 25.4-mm-inside-diameter punch (No. 149, C.S. Osborne and Co., Harrison, NJ). The probe surfaces in contact with the test specimens were lubricated with a smear of Teflon-based grease (Finish Line Technologies, Bay Shore, NY) applied by hand ≈0.5 mm thick. Dough specimens were subjected to a uniaxial compression of 50 or 90% strain. After reaching maximum strain, the doughs were held at that strain for another 30 sec. Parameters measured were maximum stress to compress to 50 or 90% strain and relaxation time (time at maximum strain for stress to decline to 1/*e* of the maximum value). Raw force and distance data were converted to stress, strain, strain rate, and apparent biaxial extension viscosity (ABEV) using equations described by Baltsavias and coworkers (2).

Stress

$$\sigma = F_t/2\pi R^2 \qquad (\mathrm{N{\cdot}m^{-2}}) \qquad (1)$$

Biaxial strain

$$\varepsilon_b = 1/2 \ln(H_t / H_0) \qquad (\text{dimensionless}) \qquad (2)$$

Biaxial strain rate

$$\dot{\varepsilon}_b = d\varepsilon_b/dt \qquad (\mathrm{sec^{-1}}) \qquad (3)$$

ABEV

$$\eta_b = \sigma/\dot{\varepsilon}_b \qquad (\mathrm{Pa{\cdot}sec}) \qquad (4)$$

F_t = Force (N) at time *t*; *R* = probe radius; H_0 = initial specimen height (mm); H_t = specimen height (mm) at time *t*.

Experimental Design and Statistical Analysis

Individual doughs were made in duplicate for each combination of flour source, salt type, and zero-rest or 45’-rested. For individual experiments, all combinations of treatments for each flour were tested in random order during a single day. Analysis of variance (ANOVA) was used to determine random error. Each combination of flour source, salt type, and zero-rest or 45’-rested was considered an individual treatment. Least significance difference (LSD) values were calculated with the residual error term from the ANOVA. Statistical analyses were performed with SAS statistical software (SAS Institute, Cary, NC) and the analysis tools of Microsoft Excel. For clarity throughout the article, all indications of significance are at $P \leq 0.01$.

RESULTS AND DISCUSSION

Sheeting

Reproducibility of sheeting was very good. Coefficients of variation were 0.8% (dough thickness) and 5.9% (springback). ANOVA for both parameters had significant interaction terms, highlighting changes in rank order of the four treatments for both varieties across sheeting passes C to R4. Dough thickness (Table I) decreased significantly at each successively narrower roll gap. Overall, doughs from Paul were thicker than doughs from Nick, which is consistent with the differences observed in conventional dough properties. All 45’-rested doughs thickened slightly during the rest period. However, 45’-rested doughs became significantly thinner than zero-rest doughs after the R1 sheeting pass, suggesting they had become more compliant. The difference in thickness between zero-rest and

45'-rested doughs was progressively lost at subsequent reductions.

Another way of observing the sheeting characteristics of noodle doughs is to measure the relative increase in thickness as a proportion of the roll gap or springback (Table I). Overall, the springback of doughs from Paul was double that of doughs from Nick, which is consistent with their rankings in conventional dough tests. Other than this overall trend, the responses of the doughs were contingent on flour source, formulation, and stage of processing. Springback of zero-rest salted doughs declined from R1 to R4. Springback of 45'-rested salted doughs remained effectively constant over the same process stages. Springback of the zero-rest alkaline dough from Paul also declined from R1 to R4, whereas that of the zero-rest alkaline dough from Nick remained relatively constant. Conversely, 45'-rested alkaline doughs from both varieties had increased springback from R1 to R4, with the consequence that their springback changed from being significantly lower than the zero-rest alkaline doughs at R1, as would be expected of rested doughs, to equal to (Nick) or greater than (Paul) those of the zero-rest alkaline doughs by R4.

Because springback measures an element of the elastic response of doughs, it could be considered a proxy for dough strength. Accordingly, the observation that alkaline doughs have lower springback early in the process is of interest because it suggests that contrary to the literature (17) the rested alkaline doughs were weaker at the start of reduction sheeting and consistent with the same literature were stronger (Paul) or equal in strength (Nick) by the end of the reduction-sheeting process. Extensograph measurements showing higher resistance to extension in alkaline doughs were done on doughs that were molded (deformed) and then rested for 45 min (17), as in this process. However, the extensograph measurements were done at water additions more suitable for bread doughs than for noodle doughs. This suggests that the process that makes alkaline doughs eventually stronger is retarded at the low water levels typical of noodle doughs.

Overall, for salted doughs the 45'-rested doughs were more compliant (thinner with less springback) early in the process. Depending on which parameter and variety was observed, the benefit of resting salted doughs was evident up to R3. The benefit of resting salted doughs was more evident for doughs from the stronger variety, Paul.

For alkaline doughs, the effect of resting was not the same. Overall, in the early stages of sheeting, alkaline doughs, like their salted counterparts, were more compliant. However, as was again more evident in doughs from Paul, alkaline doughs developed a higher elastic response during the process than their salted counterparts, suggesting, not surprisingly, that different physicochemical mechanisms occur in high-pH doughs during processing.

LSF Rheometry

Typical force time curves for a dough compressed to 90% strain and held at that strain for 30 sec are shown in Fig. 1. The overall shape of the curve conformed to curves reported by others for bread doughs (1). The reproducibility of the parameters measured during LSF rheometry was also very good. Coefficients of variation ranged from 3.0% (relaxation time after 50% compression) to 7.6% (relaxation time after 90% compression). In the latter case, macroscopic rupture of the doughs was observed occasionally, particularly for alkaline doughs from Nick, and this contributed to higher variability. ANOVA for the three LSF parameters reported had significant interaction terms, highlighting changes in the rank order of the four treatments for both varieties across the five sheeting passes (C to R4).

Calculation of biaxial strain, biaxial strain rate, and the derivation of ABEV assumes that the flow is radially biaxially symmetrical. All zero-rest doughs showed a marked asymmetry in the horizontal (x,z) plane during compression, with the longer axis corresponding to the width and the shorter axis to the length of the sheeted dough. Asymmetry in wheat flour doughs, i.e., shorter extension along the previously stressed direction (in this case the length of the dough) in a subsequent deformation, has been observed previously (9). Doughs rested for 45 min flowed symmetrically when tested after the rest period but became progressively more asymmetric as sheeting progressed and the dough became progressively more stressed. It was considered practicable to continue with these limitations in mind. Another potential limitation of LSF that has been identified is friction between the plates and samples at large strains (2). The noodle doughs flowed quite markedly ("like toothpaste squeezed from a tube") at uniaxial strains ≥60% without any "barreling," suggesting good lubrication from the Teflon grease. Additionally, when plotting ABEV against strain rate (Fig. 2), all curves showed strain rate thinning behavior beyond uniaxial strains of ≈60%. There was no increase in ABEV at the highest strains or strain rates that could have been attributed to friction between the test piece and the plates.

At 50% strain (Fig. 3), maximum stress (MS50) for doughs from Nick was higher

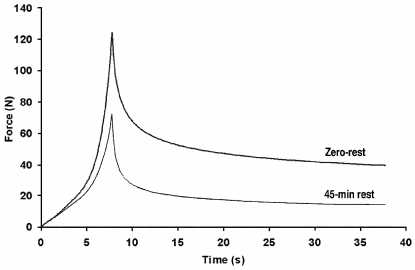

Fig. 1. Typical force time curves up to maximum strain of 90% for salted, compounded noodle doughs derived from the wheat variety Paul.

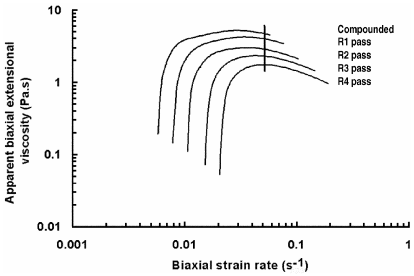

Fig. 2. Typical family of curves for apparent biaxial extensional viscosity plotted as a function of biaxial strain rate for zero-rest salted doughs derived from the wheat variety Paul. The vertical line highlights apparent biaxial extensional viscosity at a biaxial strain rate of 0.05 sec^{-1}.

Table I. Measurement of sheeted dough thickness (mm) and relative springback as a function of roll gap (%) after each sheeting pass

	'Paul'				'Nick'			
	Salt		Alkaline		Salt		Alkaline	
Sheeting Pass	**Zero-Rest**	**45'-Rest[a]**	**Zero-Rest**	**45'-Rest**	**Zero-Rest**	**45'-Rest**	**Zero-Rest**	**45'-Rest**
Thickness[b]								
C[c]	7.4	7.5	7.3	7.4	6.3	6.5	6.4	6.5
R1	5.0	4.4	4.8	4.4	4.2	4.0	4.3	4.1
R2	3.4	3.2	3.3	3.2	2.9	2.9	3.0	2.9
R3	2.3	2.2	2.2	2.3	2.0	2.0	2.1	2.1
R4	1.6	1.6	1.6	1.7	1.4	1.4	1.5	1.5
Springback[d]								
R1	42.9	25.7	36.4	26.4	20.0	13.6	21.4	17.1
R2	37.8	28.6	32.7	29.6	17.4	16.3	20.4	18.4
R3	33.8	26.5	30.9	32.4	14.7	14.7	20.6	20.6
R4	31.3	29.2	30.0	37.5	12.5	14.6	20.8	22.5

[a] 45-min rest.

[b] LSD ($P \leq 0.01$) between treatments = 0.08 and between sheeting passes = 0.14.

[c] Compound dough thickness.

[d] LSD ($P \leq 0.01$) between treatments = 2.6 and between sheeting passes = 4.3.

than that for doughs from Paul, suggesting that doughs from Paul were softer, which is consistent with the initial assessment that the doughs from Paul had slightly more than optimum water addition. MS50 increased from C to R3 for doughs from Paul (Fig. 3A) and from C to R2 for doughs from Nick (Fig. 3B) and then leveled off. Alkaline doughs from Paul tended to have higher MS50 than their salted dough counterparts at all process stages, except C, at which the zero-rest alkaline dough had equal MS50 to its salted dough counterpart. Alkaline doughs from Nick had significantly higher MS50 than their salted dough counterparts at all stages of processing. Additionally, 45'-rested alkaline doughs from Nick had higher MS50 at the later stages of processing than the zero-rest alkaline doughs.

Overall, maximum stress at 90% strain (MS90) (Fig. 4) was higher than at MS50 (Fig. 3), as expected, although the differences between doughs from Paul and Nick were not so clear cut. With one exception, MS90 for doughs from Paul (Fig. 4A) rose slightly but significantly from C to R2 and then remained relatively constant, so the pattern across the sheeting passes was similar to that observed for MS50 (Fig. 3A). In contrast, the zero-rest salted dough from Paul had much higher MS90 values at C and R1 than any other dough from Paul, and from R1 to R4, the stress required to compress this dough decreased until it was equivalent to all three other doughs from Paul by R4. This result can be confirmed by observing the relative differences between the salted zero-rest and 45'-rested doughs from Paul in Fig. 1. After approximately 5 sec of compression, the force response of the zero-rest dough increased much faster than the 45'-rested dough and accounts for the much greater MS90 compared with MS50 values observed for the zero-rest dough. A similar, but not as striking, difference between the zero- and 45'-rested salted doughs from Nick was observed for MS90 (Fig. 4B) compared with MS50 (Fig. 3B). MS90 for all doughs from Nick also decreased significantly as sheeting progressed from C to R4, again in contrast to the MS50 results.

Resting affected salted doughs from Paul and Nick similarly: 45'-rested doughs had lower MS90 values than the zero-rest doughs early in the sheeting process (C, R1, and R2 for Paul and C for Nick), with the differences reduced or not significant by R4. Resting also affected alkaline doughs from Paul and Nick similarly: 45'-rested doughs had lower MS90 values than the zero-rest doughs at C, and the 45'-rested doughs either had significantly higher MS90 values (Paul) or tended to have higher values (Nick) by R4. This was largely consistent with the pattern seen across the process at 50% strain (Fig. 3) and for springback (Table I).

There were two options for measuring the elastic characteristics of the doughs in LSF, residual stress measured after holding at maximum strain for 25 sec, reported as a proportion of maximum stress, or relaxation time. These two measures generally differentiated the doughs in the same manner, and consequently, only the relaxation time results are presented here. Overall, relaxation times at each process stage (Table II) were generally higher for doughs from Paul than for doughs from Nick, in accordance with the conventional assessment of Paul flour as producing stronger doughs. This result also concurs with the understanding that stronger doughs are more elastic and that longer relaxation times are associated with more elastic behavior (i.e., a ideally elastic material would have a theoretical relaxation time of ∞ since there would be no dissipation of stress while the deformation [strain] remained at the prescribed level).

Relaxation times at 50% compression (RT50) (Table II) declined steadily from C to R4 for all doughs. The zero-rest salted and alkaline doughs from Paul had the longest RT50 values at C, but the 45'-rested alkaline dough from Paul had the longest RT50 value at R4 among the doughs from Paul. This result concurs with the higher springback seen for this dough at R4 compared with all other doughs (Table I). RT50 values for the alkaline Nick doughs were significantly longer than their salted counterparts, again indicating both more elastic behavior in the alkaline doughs and a strong

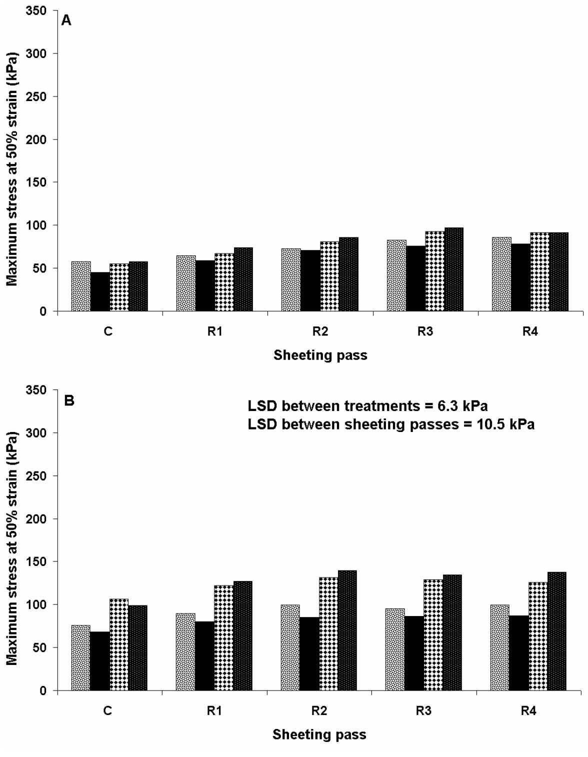

Fig. 3. Maximum stress in lubricated squeezing flow at 50% strain for doughs derived from wheat varieties Paul (**A**) and Nick (**B**). Within the cluster of bars for each sheeting pass, doughs from left to right are zero-rest salted, 45-min rested (45'-rested) salted, zero-rest alkaline, and 45'-rested alkaline.

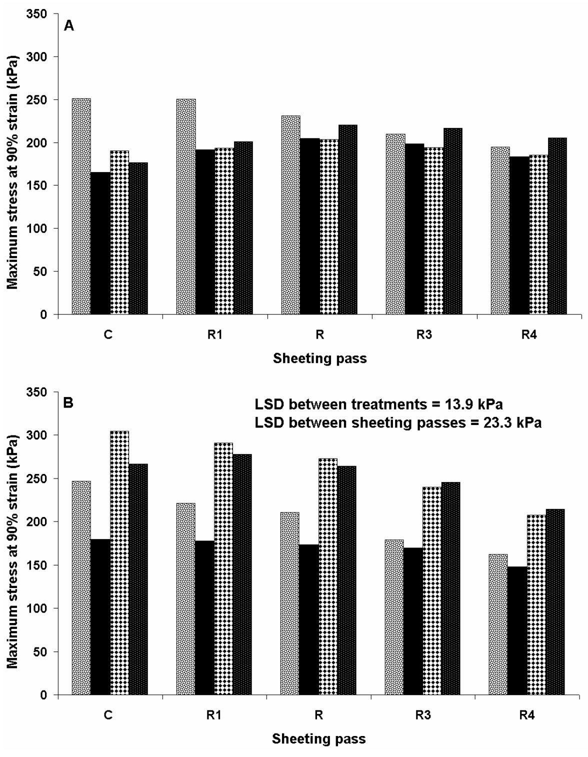

Fig. 4. Maximum stress in lubricated squeezing flow at 90% strain for doughs derived from wheat varieties Paul (**A**) and Nick (**B**). Within the cluster of bars for each sheeting pass, doughs from left to right are zero-rest salted, 45-min rested (45'-rested) salted, zero-rest alkaline, and 45'-rested alkaline.

response to the addition of alkali in flours from the "weaker" variety Nick.

As with the contrasts between MS50 and MS90, the pattern of response across the process varied between RT50 and relaxation times at 90% compression (RT90) (Table II). The zero-rest salted dough from Paul had much higher RT90 values across the process than its 45'-rested counterpart. This was somewhat different in the pattern seen at 50% strain, in which the zero-rest salted dough from Paul had a moderately higher relaxation time at C than its 45'-rested counterpart but equivalent relaxation time by R4 (Table II). Additionally, instead of declining steadily as for RT50, RT90 for the zero-rest salted dough from Paul remained constant until R2 before decreasing thereafter. Unlike the pattern seen for RT50, the 45'-rested salted dough and zero-rest alkaline dough had relatively constant RT90 values from C to R4. In further contrast, RT90 for the 45'-rested alkaline dough from Paul increased from C to R4, again in agreement with the springback results (Table I). For doughs from Nick, RT90 (Table II) also declined across the process as was observed for RT50, and similarly, the decline was greater for the salted doughs than for the alkaline doughs. As observed with other techniques in this study, the elasticities of the alkaline doughs from Nick, in this case viewed as RT90, were generally higher than the elasticities of salted doughs from Nick. This trend was more evident when comparing the 45'-rested salted and alkaline doughs.

ABEV

There were considerable challenges in determining the changes in ABEV in these doughs. First was the discovery that at 50% strain in LSF noodle doughs did not flow, and the response was primarily elastic. ABEV initially rose sharply with increasing strain rate for each dough (Fig. 2); however, as is seen with the curve for the compounded dough (Fig. 2), at 50% strain (biaxial strain rate ≈0.013) the doughs had not begun to show the strain rate thinning behavior typically seen in biaxial flow of wheat flour doughs (2). Indeed, the failure to observe flow under these conditions is why the 90% strain experiment was done. When the uniaxial engineering strain applied to doughs during sheeting was determined, it was in the order of 50%, and this was one reason for choosing 50% strain as a starting point to begin examination of LSF for noodle doughs. The answer as to why the dough did not flow at the same strain normal to the flow direction(s) appears to be simple arithmetic. In planar extension, doughs are constrained along the z-axis (width), so the dough has only one dimension (x-axis or length) in which to extend, and thus flows at y-axis (normal) strains of ≈50% in the rollers, as we can easily observe when making noodles. In biaxial flow, doughs can extend in two dimensions, so it appeared in these experiments that approximately double the y-axis (normal) strain needed to be applied to see similar amounts of flow in the x,z plane.

The second challenge was related to the choice to test the doughs at a constant crosshead velocity. This meant that strain rates increased as the doughs got thinner during LSF testing and at each successively narrower roll gap (Fig. 2). As the dough showed strain rate thinning behavior, each successive dough showed lower ABEV values at all strain rates than the previous dough. When ABEV at a strain rate of 0.05 sec^{-1} was observed across the process from C to R4 (Table II and Fig. 2), the reduction in overall ABEV seen for all treatments might be considered an artifact of the constant velocity technique applied. Additionally, as can be seen in Fig. 2, where the 0.05 sec^{-1} strain rate is highlighted, ABEV was measured at a different point on the curve, and therefore, at a different point in the development of flow in each dough. Clearly, there is a need to reappraise this approach using a constant strain rate approach. However, that may introduce its own artifacts, because the compression velocities would then be quite different for the different sheeting passes and LSF results are reported to be strongly dependent on the rate of compression (1). However, within sheeting passes, some meaningful comparisons can be made.

Zero-rest salted doughs from Paul had strikingly higher ABEV values at C compared with the other doughs from Paul, and differences between this and the other doughs diminished from R1 to R4, which is entirely consistent with the springback MS90 and RT90 results. Alkaline doughs from Nick had much higher ABEV values than the salted doughs from Nick, in contrast to the less obvious response of the alkaline doughs from Paul. Finally, alkaline doughs from Nick had the highest ABEV values (were most resistant to flow) of all doughs at each sheeting step, which is consistent with the observation that these doughs were the most likely to exhibit macroscopic failure and with the observations that the effect of alkali was stronger in doughs made from Nick-derived flour. Overall, LSF agreed with the observations from sheeting, particularly the springback data (Table I).

CONCLUSIONS

A thorough examination of the sheeting process as applied to noodles doughs, in which successive dough manipulations occur in rapid succession, seems to exceed the capabilities of conventional dough rheology tests to predict dough behavior across the process, although conventional tests can rank gross differences in dough strength. This study applied two techniques that showed, using two wheat flours with contrasting dough properties, that the relative elastic responses of doughs changed depending on whether they were rested prior to reduction sheeting, whether they were salted or alkaline, and whether the treatments

Table II. Lubricated squeezing flow parameter values for relaxation time (sec) and apparent biaxial extension viscosity (ABEV) after each sheeting pass

	'Paul'				'Nick'			
	Salt		Alkaline		Salt		Alkaline	
Sheeting Pass	Zero-Rest	45'-Rest[a]	Zero-Rest	45'-Rest	Zero-Rest	45'-Rest	Zero-Rest	45'-Rest
Relaxation time (50% strain)[b]								
C	7.4	6.6	7.3	6.5	5.0	4.8	5.7	5.5
R1	5.2	4.4	4.8	4.9	3.7	3.5	4.4	4.3
R2	3.8	3.5	3.7	4.1	2.8	2.9	3.7	3.7
R3	3.0	3.0	3.1	3.5	2.2	2.4	3.2	3.3
R4	2.6	2.7	2.9	3.5	2.0	2.2	3.1	3.3
Relaxation time (90% strain)[c]								
C	18.8	10.3	11.7	10.5	10.1	8.4	11.1	10.5
R1	17.7	9.3	10.1	10.7	8.0	6.6	9.6	9.3
R2	17.7	9.3	10.1	11.8	6.8	5.6	9.2	9.1
R3	14.8	10.1	9.3	13.2	5.3	4.8	8.6	8.9
R4	13.0	9.7	9.3	14.5	4.3	4.0	6.4	8.4
ABEV[d]								
C	4.61	2.89	3.32	2.99	4.31	3.22	5.42	4.71
R1	3.92	2.75	2.88	2.89	3.23	2.95	4.62	4.45
R2	2.91	2.49	2.70	2.87	2.75	2.52	3.89	3.88
R3	2.24	2.14	2.25	2.50	2.29	2.16	3.24	3.28
R4	1.77	1.66	1.86	1.97	1.99	1.69	2.55	2.61

[a] 45-min rest.

[b] Time required for stress to dissipate to a value of $1/e$ of the maximum stress when strain is held constant at 50%. LSD ($P \leq 0.01$) between treatments = 0.21 and between sheeting passes = 0.35.

[c] Time required for stress to dissipate to a value of $1/e$ of the maximum stress when strain is held constant at 90%. LSD ($P \leq 0.01$) between treatments = 1.3 and between sheeting passes = 2.2.

[d] ABEV at a biaxial strain rate of 0.05 s^{-1}. LSD ($P \leq 0.01$) between treatments = 0.23 and between sheeting passes = 0.38.

were applied to flours, which by conventional assessment produced either weak or strong doughs. Being salted or alkaline in turn dictated whether resting and subsequent working through the reduction-sheeting process made the doughs either relatively more (45'-rested alkaline doughs from Paul) or relatively less (zero-rest salted doughs from Paul) elastic, as described by parameters such as springback measured in the rollers or relaxation time in an LSF technique that included a stress relaxation step.

In general, it seemed that the weaker doughs from Nick responded more strongly to the addition of alkali. However, the effect of alkali in the stronger dough appeared to become more pronounced when the dough was rested and later in the process, at which point these rested alkaline doughs became clearly more elastic than their salted counterparts. At 50% uniaxial strain, the general trend of increased maximum stress across the process (Fig. 3) agreed in principle with the observations of Edwards and coworkers (8), who reported that force exerted on the rollers by both alkaline and salted noodle doughs increased at each successive sheeting pass. However, at 90% strain, this relationship no longer held for all doughs.

Some elements of the sheeting process itself seemed less sensitive to differences in dough strength and formulation than LSF. Still, LSF shows considerable promise for investigating noodle doughs. It appears to be sensitive to changes in formulation and flour source and may serve to highlight areas in which dough characteristics could be manipulated to improve the process or guide processors or wheat breeding programs toward "ideal" dough attributes specific to this type of sheeting process. In particular, observation of additional relationships, for example the ratio of ABEV to springback or relaxation time, may give an indication of which doughs might fail structurally under a given sheeting or deformation protocol, as alkaline doughs from Nick did at times in this study. Nonetheless, challenges exist in using LSF to observe relative behaviors of noodle doughs across significant changes in thickness as sheeting progresses from wider to narrower roll gaps. These issues may be addressed using constant strain rate methods, but as noted above, this approach might provide it own artifacts of interpretation.

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