Effects of Oxido-Reductants on Rheological Properties of Wheat Flour Dough and Comparison with Some Characteristics of Extruded Noodles

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ABSTRACT

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The effects of oxido-reductants on the rheological properties of wheat flour dough were evaluated by using a capillary rheometer and an oscillatory rheometer at three temperatures. The oxidants potassium iodate (KIO_3) and L-ascorbic acid (L -AA) significantly increased the apparent viscosity and *G′* and decreased loss tangent at low temperatures of 30 and 60°C due to enhanced formation of disulfide bonds. The reductant glutathione (GSH) had the opposite effect. Heating caused the gelatinization of starch, which diminished the effects of the oxido-reductants and produced doughs with similar rheological properties at 80°C. The correlation between dough rheology and characteristics of extruded noodles was also studied.

Almost half of the wheat flour in Asia is consumed as noodles. Wheat flour consisting of 10–12% proteins is generally used for making oriental noodles. In a commercial process for producing instant noodles, wheat flour is mixed with water, rested, kneaded by rolls, formed, cooked by steam, and then fried. It would be beneficial to industry if a process such as extrusion, combining the above processes into one unit operation, could be developed. Extruded noodles can be air-dried and provide low- or nonfat products meeting the market needs. More understanding about the characteristics of extruded noodles is necessary to pursue the feasibility of an extrusion process.

Dough rheology is one of the important factors affecting extrudate characteristics. Composition affects the viscosity of wheat flour dough. Raising the protein content increases the consistency (Sharma et al 1993a) and shear moduli (*G′* and *G″*) (Navickis et al 1982). Ferry (1980) pointed out that an increase in cross-linkage in a synthetic polymer resulted in higher *G′* and lower loss tangent (tan δ). Similarly, the interactions between protein molecules influence the conformational structure as well as rheological properties. Some reductants such as cysteine and mercaptoethanol reduced *G′*, and the oxidant KIO_3 increased *G′* but had no effect on tan δ (Dreese et al 1988b). In addition to protein, starch also plays a role on determining viscosity of wheat flour dough during heating. The gelatinization of amylopectin favored a synergistic increase in viscosity with the addition of gliadin and glutenin (Chedid and Kokini 1992), which could increase tensile strength (Bloksma 1990). The interactions between gluten and gelatinized starch may affect the characteristics of extruded noodles.

Oxidants such as potassium bromate remove SH groups by oxidizing them, forming SS bonds of increased molecular weight, and they are used as the dough improvers for breadmaking. Reducing agents such as glutathione (GSH) increase the rate of thiol-disulfide interchange reaction, which decreases the size of large proteins, resulting in lower molecular weight and less elastic dough (Dong and Hoseney 1995). The oxidants KIO_3, $KBrO_3$, and L-ascorbic acid (L-AA) enhanced the resistance to extension, but GSH had the opposite effect (Bloksma 1972, Lillard et al 1982, Wolt and D'Appolonia 1984, Walter and Grosch 1987, Kieffer et al 1990). Low concentrations of GSH had no effect on rheological properties. As the concentration of GSH was raised to 50–150 ppm, *G′* and *G″* decreased, but the flow behavior index (*n*) increased (Berland and Launay 1995). Effects of the oxidoreductants on rheological properties were mostly addressed to bread volume and quality (Kuninori and Matsumoto 1963, Jackel 1977, Bloksma 1990, Kuninori and Nishiyama 1993, Yamada and Preston 1994). There are few reports in the literature concerning the effects of oxidizing and reducing agents on the qualities of oriental noodles.

The objectives of this study were to investigate the effects of oxido-reductants on the rheological properties of wheat flour dough and compare the characteristics of extruded noodles.

MATERIALS AND METHODS

Materials

Unblanched patent wheat flour was purchased from Chiao Thaihsing Enterprise Co. Ltd. (Taipei, Taiwan). The proximate composition (dry basis) was 12.5 ± 0.6% crude protein, 0.52 ± 0.03% crude fat, 0.48 ± 0.02% ash, and 86.5 ± 0.6% carbohydrate as determined by Approved Methods (AACC 1995), The starch content was 80.3 ± 1.5% as determined by the method of Chiang and Johnson (1977). All the chemicals were of reagent grade.

Preparation of Dough

Distilled water, premixed with oxidant or reductant to achieve a final concentration of 0.2 mmol/kg, was mixed with wheat flour in a Hobart mixer (model SP-15, Bao Ma Co., Taipei, Taiwan) using the slowest speed for 5 min to form a dough with a moisture content of 40% (wb). After mixing, the dough was placed in a covered stainless steel pan and rested for 30 min at room temperature.

Apparent viscosity was measured using a capillary rheometer (model RH 7-2, Rosand Precision Ltd., West Midlands, England) equipped with an infrared die swell measuring device and a tensile strength measurement system. The die diameter was 2 mm and the length of die was 30 mm. Three barrel temperatures (30, 60, and 80°C) were evaluated. The dough was loaded into the capillary rheometer after the barrel temperature reached the set point. Care was taken to eliminate any entrapped air during loading process. The temperature of dough in the capillary rheometer was measured using a thermocouple inserted from the die orifice. The thermocouple was removed when both the barrel and noodle dough temperatures reached equilibrium in 5 min. The experiment was conducted using a plunger at various speeds. A transducer was used to measure the die pressure. Viscosity software was provided by Rosand Precision Ltd. Methods of both Rabinowitsch (Lenk 1978) and Bagley (1957) were used to correct the data before recording the viscosity. These procedures were conducted in triplicate. Data obtained were used to fit the power law equation by regression method:

$$\tau = k\,\dot{\gamma}^{n} \qquad (1)$$

where τ is shear stress, *k* is the consistency coefficient, $\dot{\gamma}$ is the shear rate, and *n* is the flow behavior index.

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The capillary rheometer was used to simulate extrusion process and to prepare extruded noodles in triplicate for each condition using the same procedures as above, except that the plunger speed was 20 mm/min. The extruded noodles were dried to 12% moisture content in an air oven at 45°C for further analyses of cooking loss and degree of gelatinization of starch.

Physical Properties of Dough and Extruded Noodles

The dynamic viscoelastic properties of doughs were measured in triplicate using a controlled stress rheometer (Carri-Med CSL 500, England) operated with a parallel-plate geometry of 40 mm diameter and a gap of 3 mm. From the preliminary tests, the linear range was found at torque <800 μN·m corresponding to a strain of 0.12%. Therefore, a strain of 0.1% was used in this study to ensure that the tests were conducted within the linear range. The dough was rolled by seven steps to attain a thickness of 3 mm using a laboratory sheet-rolling machine. Then the sheeted dough was cut using a mold with a diameter of 40 mm to fit the plate geometry of the rheometer. The outer edge of dough was coated with silicone oil to minimize the water loss during the measurements. Frequency sweep of 0.5–5 Hz was performed at 25°C. Temperature sweep was conducted from 30 to 90°C at a heating rate of 2.4°C/min using a frequency of 1 Hz.

Four parameters were obtained using the software analysis program of the rheometer and the averaged values of two parameters, G' and tan δ, were reported.

The tensile strength of extruded noodle was measured using the method of Cavella et al (1992). The capillary rheometer was operated at a plunger speed of 20 mm/min. The extruded noodle passed through the die and was immediately wound on an accelerating wheel (0.083 cm/sec^2). As the driving wheel rotated, the extruded noodle was stretched and the force was recorded. The tensile strength was recorded as the maximum force for breaking the extruded noodle. The measurements were made in triplicate.

The cutting force of extruded noodles was measured using a texture analyzer (model NMR-2020J, Fudoh Rheometer, Japan) fitted with a No. 30 adapter. The extruded noodle (8 cm long) from the capillary rheometer was cooled to room temperature (≈25°C) on a covered petri dish for 7 min. Then a platform with an ascending speed of 6 cm/min was used to measure the cutting force of extruded noodle. The maximum force to cut the extruded noodle was recorded. Measurements were performed in 20 replicates and the average reading was reported.

To measure the die swell of extruded noodle, the dough was extruded at a plunger speed of 20 mm/min. An infrared detector installed near the die measured the diameters of extruded noodles. The swell ratio was calculated as the ratio of diameter of extruded noodle to 2 mm (diameter of the die orifice). The measurement was conducted in triplicate.

Differential Scanning Calorimetry

The temperature and heat of gelatinization of starch were determined in triplicate using a differential scanning calorimeter (DSC 121, Setaram Co., France) equipped with a liquid-nitrogen intercooler. Samples (≈120 mg) of wheat starch, gluten, or wheat flour with the desired water content were hermetically sealed in a stainless steel crucible and equilibrated overnight in a refrigerator. The scanning temperature was increased from 40 to 110°C at a heating rate of 5°C/min. The data was analyzed using a data analysis system provided by the manufacturer. Wheat starch and gluten were prepared according to the method of Oda et al (1980). The wet starch and gluten were freeze-dried and ground to pass a 100-mesh sieve before differential scanning calorimetry measurements.

Cooking Loss

The cooking loss of dried extruded noodle was determined using the method of Yeh et al (1991). Dried extruded noodles (10 g) were cut into 1-cm strips and placed into a beaker containing 100 mL of boiling, distilled water on a hot-plate. The beaker was covered with a watch glass. During cooking, distilled water was added to compensate for evaporation loss. The mixture was stirred slightly with a glass rod. After a total boiling time of 10 min, the cooked noodles were filtered through a 20-mesh nylon screen. The beaker, noodles, and screen were washed with distilled water. The combined filtrates and wash water were placed in a clean, dry, tared beaker (W_1) and dried at 45°C to a constant weight (W_2). The moisture content of the dried extruded noodle was predetermined (W_3). The cooking loss was calculated as:

$$\text{Cooking loss (\%)} = (W_2 - W_1)/(10 - W_3) \times 100\% \qquad (2)$$

Degree of Gelatinization

Degree of gelatinization of starch of the extruded noodles was determined by an enzymatic method (Chiang and Johnson 1977) with modified sample preparation. The oligosaccharides were removed from the samples before analysis using the method of McCready et al (1950) to ensure the accuracy of the analysis.

Extractable Protein

The extractable protein of dough was determined using the method of Osborne (1907). The dough was freeze-dried and ground to flour in two steps. Initially, the freeze-dried dough was hammer-milled (Tong-Fung Machinery Co., Taiwan) to pass through

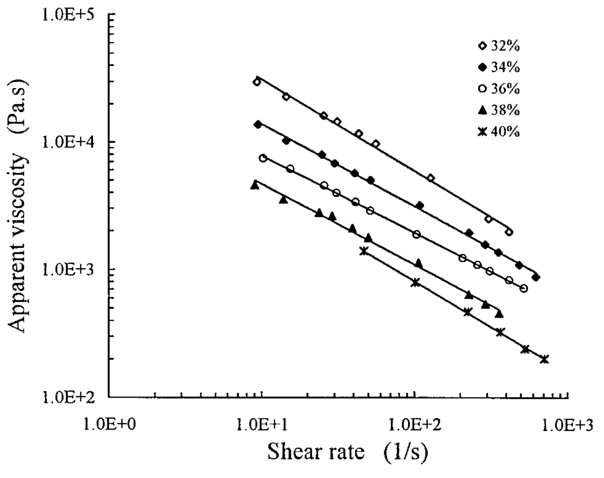

Fig. 1. Effect of water content on the apparent viscosity of wheat flour dough at 30°C.

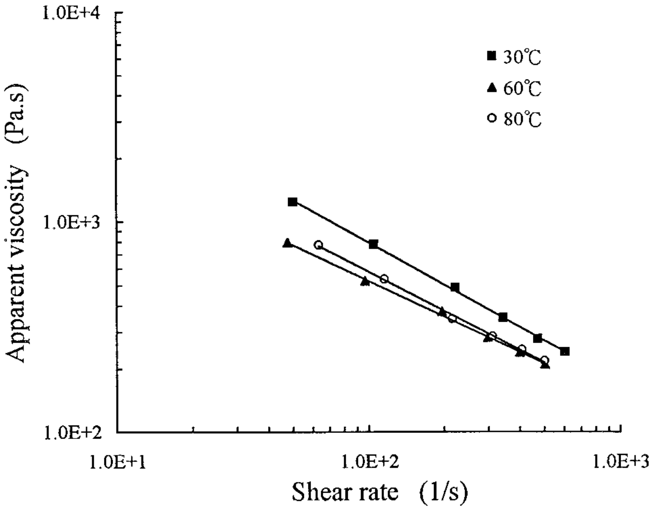

Fig. 2. Effect of temperature on the apparent viscosity of wheat flour dough with 40% moisture (wb).

a 40-mesh sieve, followed by a rotary speed mill (Pulverisette 14, Fritsch GmbH, Idar-Oberstein, Germany) to grind the particles to pass through a 100-mesh sieve. Sodium hydroxide (0.01*N*, 25 mL) was used to extract protein from the ground flour (0.5 g) using an ice bath to prevent flour oxidation. The suspension was stirred at 300 rpm for 1 hr and then centrifuged at 8,000 × *g* for 10 min. The extractable protein content in the supernatant was measured by the biuret method (Gornall et al 1949). A standard curve was obtained by measuring the absorbance of different concentrations of bovine serum albumin solutions at 550 nm. The crude protein in the ground flour was determined by the Kjeldahl method. Protein extractability was calculated as the ratio of the extractable protein to the crude protein.

The supernatant from protein extraction by NaOH was further analyzed to determine the contents of SH groups using the method of Buttkus (1971) with modifications. The supernatant (2 mL) was neutralized by 2 mL of 0.01*N* HC1 and mixed with 6 mL of 8*M* urea Tris-HC1 buffer (pH 8.2). This solution (3 mL) was mixed with 5,5′-dithiobis-2-nitrobenzoic acid (DTNB) reagent (0.02 mL). Absorbance at 412 nm was read at 30 min with a spectrophotometer (model 7800, Jasco, Japan). The SH content was expressed in µmol/g of protein extracted.

Total SH and SS content was determined according to the method of Opstvedt et al (1984). Disulfide bonds were reduced to SH by adding 0.8 mL of 0.6*M* $NaBH_4$ in 8*M* urea into 1 mL of neutralized supernatant. One drop of *n*-octyl alcohol was used to avoid foaming. The solution stood in a water bath (25°C) for 2 hr. The residual $NaBH_4$ was reacted with 0.22 mL of 2*N* HC1 to minimize the noise on measurements. Urea buffer (7.2 mL, 8*M*) was mixed with the solution. DTNB (0.02 mL) was added to 3 mL of solution before measuring the absorbance of SH at 412 nm. The result was the total SH content which was the summation of SH and SS/2. The SS content was calculated as half the difference between total and determined SH content.

Statistical Analyses

Statistical analyses were made using the procedures of the SAS software system, release 6.04 (SAS Institute, Cary, NC).

RESULTS AND DISCUSSION

The wheat flour dough fitted the power law equation well ($r^2 \geq 0.994$) at 30°C (Fig. 1). Increasing either water content or shear rate decreased the apparent viscosity. This is in agreement with the report of Mackey and Ofoli (1990). When the water content was increased from 34 to 40%, there was no significant difference ($P < 0.5$) in the flow behavior indices, and *n* ranged from 0.31 to 0.37. It appeared that *n* was independent of water content (Sharma et al 1993b, Berland and Launay 1995). The averaged *n* value was 0.34 ± 0.01, which was the same as 0.34 reported by Sharma et al (1993a). But the consistency coefficient *k* (an index of viscosity) decreased from 67.7 ± 4.2 kPa sec$^{0.35}$ to 19.3 ± 1.3 kPa sec$^{0.31}$. As the water content was reduced to 32%, *n* dropped to 0.26 ± 0.04 and *k* was 173.3 ± 7.7 kPa sec$^{0.26}$; these values were significantly different from those obtained above. The results indicated that *n* was independent of water content at some limited ranges. Figure 2 illustrates the effect of temperature on the flow behavior of dough with a water content of 40% (wb). In general, the apparent viscosity decreased as the temperature was raised. As the temperature was raised from 30 to 60°C, *n* increased from 0.31 to 0.44 (Table I). It implied that heating produced a dough with less shear thinning. Nevertheless, *k* decreased from 19.3 kPa sec$^{0.31}$ to 6.8 kPa sec$^{0.44}$. Also, the apparent viscosity at a shear rate of 50/sec dropped from 1,298 to 760 Pa sec. There was a slight decrease in *n* and the increase in both *k* and the apparent viscosity at a shear rate of 50/sec when the temperature was continuously raised to 80°C. This may be due to the occurrence of starch gelatinization. However, the dough exhibited similar viscosity at 60 and 80°C when the shear rate was >130 sec (Fig. 2).

The addition of KIO_3 and L-AA reduced *n* and increased *k* (Table I). GSH had the opposite effect and resulted in a dough with less shear thinning. The effect of L-AA was less significant than that of KIO_3, possibly because not all of L-AA was converted to dehydroascorbic acid acting as an oxidizing agent. When the temperature was raised from 30 to 60°C, generally there was an increase in *n* and a decrease in *k*. The dough with KIO_3 had the most increase (65%) in *n* and the dough with GSH had the least increase (15%). The doughs had ≈65% decrease in *k*, except that GSH resulted in a decrease of 44%. As the temperature raised to 80°C, there were no significant differences in *n* and *k* values among the samples. The average for *n* was 0.37 ± 0.01 and the average for *k* was 10.7 ± 0.3 kPa sec$^{0.37}$. The oxido-reductants did not affect the dough viscosity (Table I) at high temperature, which may be due to the gelatinization of starch.

The storage modulus (G') of dough increased with the frequency (Fig. 3A). As with the apparent viscosity, KIO_3 yielded the highest G' among the samples tested, and GSH yielded the lowest G'. As illustrated in Fig. 3B, the oxidants resulted in lower tan δ, indicating the presence of a more solid phase. The results concurred with the reports of Dreese et al (1988b) and Dong and Hoseney (1995). GSH led to weakening of the dough with more a liquid phase. The sensitivity of rheological properties of dough to oxido-reductants suggested that SS bonds play a major role in dough rheology.

Sulfhydryl Groups and Disulfide Bonds

The SH and SS contents were affected by the oxido-reductants as listed in Table II. KIO_3 and L-AA reduced the content of SH but increased the content of SS bonds. This is in agreement with literature data (Sullivan et al 1963, Tsen and Bushuk 1963, Bloksma 1972). The ratio of SH to SS dropped from 0.22 to 0.15 and 0.16, respectively, as KIO_3 and L-AA were added. GSH had the opposite effect and yielded a SH to SS ratio of 0.27. Linborg et al (1997) pointed out that the breakdown of SS loosened the entanglement, thus GSH yielded a dough with the least G'. Both the formation of large glutenin aggregates due to the existence of oxidants (Panozzo et al 1994) and the interchange of SH and SS during mixing (Mauritzen 1967) could alter the protein extract-

TABLE I

Effects of Additives on Flow Behavior Index (*n*) and Consistency Coefficient (*k*) of Dough at Different Temperatures

	Capillary Rheometer Barrel Temperature								
	30°C			60°C			80°C		
Oxido-Reductant[a]	*n*	*k* (kPa.sec^n)	η (Pa.sec)[b]	*n*	*k* (kPa.sec^n)	η (Pa.sec)	*n*	*k* (kPa.sec^n)	η (Pa.sec)
None	0.31 ± 0.02f[c]	19.3 ± 1.3c	1,298 ± 16b	0.44 ± 0.01ab	6.8 ± 0.3f	760 ± 16g	0.37 ± 0.01c	10.7 ± 0.5d	920 ± 21cd
KIO_3	0.23 ± 0.01h	30.1 ± 1.5a	1,452 ± 11a	0.38 ± 0.02cd	10.6 ± 0.9d	940 ± 17d	0.37 ± 0.01c	10.7 ± 0.3d	918 ± 10cd
L-Ascorbic acid	0.28 ± 0.02g	23.5 ± 1.9b	1,426 ± 20a	0.42 ± 0.01bc	8.4 ± 0.2c	863 ± 19f	0.36 ± 0.02c	11.1 ± 1.0d	914 ± 11cd
Glutathione	0.41 ± 0.02cd	10.1 ± 1.7d	1,016 ± 18c	0.47 ± 0.03a	5.7 ± 0.9f	702 ± 14h	0.38 ± 0.02c	10.4 ± 0.9d	906 ± 12c

[a] Concentration of additive was 0.2 mmol/kg of flour.

[b] Apparent viscosity at a shearing rate of 50/sec.

[c] Values within a column followed by the same letter are not significantly different ($P < 0.05$).

ability. The data indicated that the increase in SS bonds enhanced the cross-links in gluten and led to the formation of large molecules with less extractable protein. The results were similar to the effect of mixing on extractable protein (Bushuk et al 1997) and the reduction of ethanol-soluble protein by SS bonds (Jeanjean et al 1980). GSH decreased SS bonds, which increased protein extractability. This is in agreement with the report of Kim and Bushuk (1995), who used dithiothreitol as a reducing agent.

Heating changed *G′* as illustrated in Fig. 4A. *G′* slightly decreased as the temperature was raised from 30 to 55°C. Continuous heating dramatically increased *G′* to a maximum at 78.5°C. When the temperature was continuously raised to 90°C, *G′* decreased. Since the increase in *G′* of glutenin and gliadin was very slight from 60 to 90°C (Dreese et al 1988a, Kokini et al 1995), the gelatinization of starch may play an active role in the dramatic increase in *G′* at >55°C. KIO_3 yielded the highest *G′* among the samples tested from 30 to 90°C, and GSH yielded the lowest *G′*. As the temperature was raised, the difference in *G′* between samples lessened and approached the same value as at >80°C. The dough with KIO_3 exhibited smallest tan δ due to the formation of large molecules as discussed above. GSH enhanced the formation of small molecules and resulted in higher tan δ, indicating more liquid phase in the dough. Heating resulted in a decrease in tan δ (Fig. 4B), which indicated that the doughs tended to be more solid phase at high temperature. As for *G′*, tan δ of all samples also approached the same value at >80°C.

Wheat starch (75%, wb) exhibited a gelatinization peak (the first peak in Table III) from 54.1 ± 0.5 to 77.8 ± 1.9°C with an enthalpy of 7.9 ± 0.6 J/g, and a lipid-amylose endothermic peak from 93 ± 1.4 to 107 ± 0.5°C with an enthalpy of 1.7 ± 0.2 J/g. When the water content was reduced to 40% (wb), there existed an additional endothermic peak (the second peak in Table III) from 77.8 ± 1.5 to 101.6 ± 1.7°C with an enthalpy of 1.2 ± 0.3 J/g. In this case, the gelatinization heat was reduced to 1.0 ± 0.2 J/g. This is similar to rice starch in that the first peak is associated with the gelatinization and the second coincided with the melting of starch crystallites (Biliaderis et al 1986). Gluten denaturation temperatures were not affected by reducing water content from 75 to 40%. Wheat flour (40% water content, wb) exhibited three endothermic peaks similar to those of wheat starch, except that the onset temperatures (T_o) were raised for gelatinization and melting peaks. Comparing differential scanning calorimetry thermograms with dynamic measurements, gelatinized starch had an increase in *G′* at >55°C. This concurred with the report of Dreese et al (1988a). The coincidence of conclusion temperature (T_c) (79.2°C) with the temperature (78.5°C) of maximum *G′*, indicated that the completion of starch gelatinization resulted in a maximum *G′*. After that, higher temperatures caused a drop in *G′*. This demonstrated that the gelatinized starch played an active role in determining the rheological properties of dough at >55°C. Therefore, the doughs exhibited similar flow behavior index, consistency index, *G′*, and tan δ after starch gelatinization at >78.5°C.

TABLE II
Effects of Oxido-Reductants on Extractable Protein and Contents of Sulfhydryl Groups (SH) and Disulfide Bonds (SS)

Oxido-Reductant[a]	Extractable Protein (%)	μmol/g of Extractable Protein SH	SS
None	85.75 ± 0.42b[b]	9.14 ± 0.46b	41.72 ± 0.72b
KIO_3	76.82 ± 1.91d	6.72 ± 0.33c	46.18 ± 0.95a
L-Ascorbic acid	80.05 ± 0.36c	7.22 ± 0.35c	45.52 ± 0.74a
Glutathione	92.74 ± 0.50a	10.57 ± 0.45a	39.86 ± 0.45c

[a] Concentration of additive was 0.2 mmol/kg of flour.

[b] Values within a column followed by the same letter are not significantly different ($P < 0.05$).

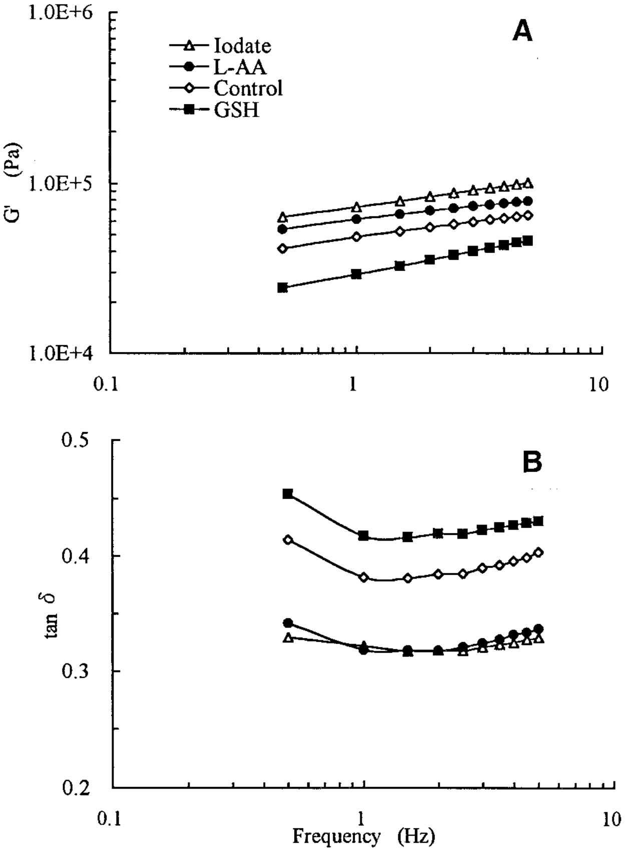

Fig. 3. Frequency sweep of wheat flour dough (40% moisture, wb) at 30°C. *G′* = shear modulus (**A**); tan δ = loss tangent (**B**). Oxido-reductants: iodate = potassium iodate (KIO_3); L-AA = L-ascorbic acid; GSH = glutathione.

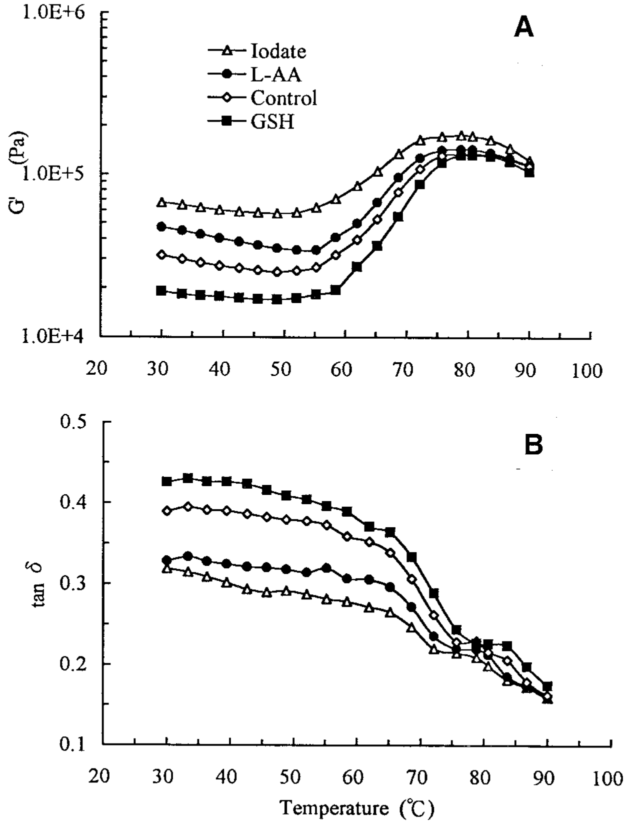

Fig. 4. Temperature sweep of wheat flour dough with 40% moisture (wb). *G′* = shear modulus (**A**); tan δ = loss tangent (**B**). Oxido-reductants: iodate = potassium iodate (KIO_3); L-AA = L-ascorbic acid; GSH = glutathione.

Characteristics of Extruded Noodles

Die swell became much greater when the polymer chains were long enough to contain significant numbers of entanglements, being a direct consequence of the elastic energy stored by the polymer in the tube (Sperling 1993). The entanglement in the dough was increased by the formation of SS bonds. Thus, the swell ratio of extruded noodle was increased by KIO_3 and L-AA and reduced by GSH (Table IV). The extruded noodles (except with GSH) exhibited the largest swell ratio at 30°C. As the temperature was raised, the swell ratio decreased and the difference in swell ratio among the samples became less and less. This indicated that the formation of SS bonds in protein affected the die swell at low temperature, but the gelatinized starch diminished the effects of oxido-reductants at moderate (60°C) temperature. The die swell was primarily attributable to the gelatinized starch at high temperature as all the extruded noodles had similar swell ratios at 80°C.

Also, the tensile strength of extruded noodle was increased by the oxidants and reduced by GSH. This indicated that the formation of cross-links increased the tensile strength of extruded noodles. In addition, gelatinized starch also contributed to the tensile strength. Thus, among all the samples tested, the extruded noodles with KIO_3 had the highest tensile strength at 80°C. However, the heterogeneity caused by partial gelatinized starches in extruded noodles resulted in a decrease in tensile strength measured before cooling. Therefore, the extruded noodles had the lowest tensile strength at 60°C among the three temperatures tested.

Again, the addition of oxidants enhanced the cutting forces of extruded noodles as listed in Table IV. With the most SS bonds formed, KIO_3 yielded the highest cutting force among three additives. The attributes of both gelatinized starch and SS bonds resulted in dramatic increase (at least double) in cutting force as the temperature was raised from 30 to 80°C. For example, the extruded noodles with KIO_3 yielded a cutting force of 26.2 ± 1.2 g at 30°C and 56.5 ± 2.6 g at 80°C.

The degree of starch gelatinization in extruded noodles increased with temperature (Table V). The addition of oxido-reductants did not interfere with the gelatinization of starch. The degree of gelatinization approached 80% at 80°C, and the gelatinized starch played

TABLE III
Differential Scanning Calorimetry Data[a] for Wheat Starch, Gluten, and Wheat Flour

		First Endothermic Peak				Second Endothermic Peak				Peak for Amylose-Lipid Complex			
Material	**MC[b]**	T_o °C	T_p °C	T_c °C	ΔH, J/g	T_o °C	T_p °C	T_c °C	ΔH, J/g	T_o °C	T_p °C	T_c °C	ΔH, J/g
Starch	75	54.1 ± 0.5	61.7 ± 0.7	77.8 ± 1.9	7.9 ± 0.6	···	···	···	···	93.0 ± 1.4	99.5 ± 0.7	107.0 ± 0.5	1.7 ± 0.2
Starch	40	54.1 ± 0.8	60.4 ± 0.8	71.4 ± 0.5	1.0 ± 0.2	77.8 ± 1.5	87.5 ± 2.1	101.6 ± 1.7	1.2 ± 0.3	109.4 ± 0.7	118.6 ± 0.2	131.8 ± 0.9	1.9 ± 0 .1
Gluten	75	81.7 ± 0.6	85.7 ± 0.5	89.8 ± 0.6	0.6 ± 0.2	95.6 ± 1.2	102.5 ± 1.1	121.7 ± 0.9	1.7 ± 0.3	···	···	···	···
Gluten	40	81.1 ± 0.7	84.5 ± 0.8	90.8 ± 0.4	0.4 ± 0.1	93.6 ± 1.3	101.7 ± 1.7	116.4 ± 1.1	0.7 ± 0.1	···	···	···	···
Flour	40	62.4 ± 0.1	69.8 ± 0.6	79.2 ± 1.5	0.6 ± 0.1	89.6 ± 1.3	96.9 ± 1.6	106.6 ± 0.5	1.0 ± 0.2	110.9 ± 0.9	120.0 ± 0.8	130.7 ± 0.9	1.4 ± 0. 2

[a] T_o = onset temperature; T_p = peak temperature; T_c = conclusion temperature; ΔH = enthalpy of transition.
[b] Moisture content (H_2O%, wb).

TABLE IV
Effects of Oxido-Reductants on Swell Ratio, Tensile Strength, and Cutting Force of Extruded Noodles at Different Temperatures

	Swell Ratio			Tensile Strength, mN			Cutting Force, g		
Oxido-Reductant[a]	**30°C**	**60°C**	**80°C**	**30°C**	**60°C**	**80°C**	**30°C**	**60°C**	**80°C**
None	1.17 ± 0.02c[b]	1.13 ± 0.04b	1.13 ± 0.03a	59 ± 2de	33 ± 4g	72 ± 3b	16.1 ± 1.8g	39.3 ± 2.9d	47.7 ± 4.5c
KIO_3	1.26 ± 0.02a	1.18 ± 0.04a	1.15 ± 0.02a	64 ± 2cd	69 ± 3bc	81 ± 4a	26.2 ± 1.2ef	52.5 ± 3.3b	56.5 ± 2.6a
L-Ascorbic acid	1.20 ± 0.02b	1.13 ± 0.02b	1.14 ± 0.01a	65 ± 1c	54 ± 4e	80 ± 1a	24.7 ± 1.9f	48.4 ± 2.8c	50.5 ± 2.4bc
Glutathione	1.11 ± 0.02d	1.10 ± 0.02b	1.15 ± 0.02a	42 ± 2f	19 ± 3h	59 ± 6de	11.9 ± 0.9h	28.8 ± 1.8e	42.3 ± 4.5d

[a] Concentration of additive was 0.2 mmol/kg of flour.
[b] Values within a column followed by the same letter are not significantly different ($P < 0.05$).

TABLE V
Degree of Gelatinization and Cooking Loss of Extruded Noodles

	Degree of Gelatinization, %			Cooking Loss, %		
Oxido-Reductant[a]	**30°C**	**60°C**	**80°C**	**30°C**	**60°C**	**80°C**
None	28 ± 2c[b]	52 ± 4b	82 ± 5a	3.72 ± 0.36c	7.33 ± 0.82b	16.9 ± 0.60a
KIO_3	29 ± 3c	54 ± 4b	79 ± 6a	5.12 ± 0.27c	7.32 ± 0.71b	16.9 ± 1.03a
L-Ascorbic acid	27 ± 2c	51 ± 3b	81 ± 5a	4.92 ± 0.37c	6.22 ± 0.68b	18.8 ± 0.37a
Glutathione	28 ± 4c	50 ± 4b	81 ± 5a	4.19 ± 0.49c	6.71 ± 0.41b	18.1 ± 0.42a

[a] Concentration of additive was 0.2 mmol/kg of flour.
[b] Values within a column followed by the same letter are not significantly different ($P < 0.05$).

TABLE VI
Correlation Coefficients Dough Rheological Properties and Some Characteristics of Extruded Noodles at 30, 60, and 80°C[a,b]

	η	G'	tan δ	SR	TS	CF	CL
η	1.00, 1.00, 1.00	0.93*, 0.96**, 0.44	–0.97**, –1.00**, –0.79	0.92*, 0.90*, –0.15	0.99**, 0.99**, 0.73	0.93*, 0.98**, 0.69	0.52, 0.12, –0.70
G'		1.00, 1.00, 1.00	–0.98**, –0.93*, –0.89*	1.00**, 0.98**, 0.44	0.89*, 0.96**, 0.71	0.96**, 0.89*, 0.93*	0.69, 0.36, –0.14
tan δ			1.00, 1.00, 1.00	–0.97**, –0.90*, –0.16	–0.93*, –1.00**, –0.88	–0.99**, –0.99**, –0.98**	–0.71, –0.09, 0.38
SR				1.00, 1.00, 1.00	0.88*, 0.92*, –0.29	0.95*, 0.87, 0.11	0.68, 0.50, –0.35
TS					1.00, 1.00, 1.00	0.89*, 0.98**, 0.92*	0.42, 0.12, –0.06
CF						1.00, 1.00, 1.00	0.79, 0.08, –0.19
CL							1.00, 1.00, 1.00

[a] η = Viscosity; G' = storage modulus; tan δ = loss tangent; SR = swell ratio; TS = tensile strength; CF = cutting force; CL = cooking loss.
[b] *,** = Significant at $P < 0.05$ and $P < 0.01$, respectively.

an active role in determining the rheological properties as well as the swell ratio. The combined effects of gelatinized starch and formation of SS bonds increased the tensile strength and cutting force as discussed earlier. The presence of a low degree of gelatinization (≈50%) at 60°C may create some heterogeneity that weakened the structure of extruded noodles. Thus, partial gelatinization reduced the tensile strength of noodles extruded at 60°C°C except those with KIO_3 because of the formation of SS bonds which compensated for the negative effect of the heterogeneity. The reductant GSH caused the largest reduction (54.8% compared with that at 30°C) in tensile strength at 60°C due to the heterogeneity and decrease in SS bonds.

Cooking loss is a key quality characteristic of noodles (Oh et al 1983, Malcolmson and Matsuo 1993). It indicates the quantity of the solid released from noodles during cooking and is an index of surface characteristics of noodles. The noodles with cooking loss <10% are considered desirable in Taiwan. It appeared that the addition of oxido-reductants did not significantly affect the cooking loss (Table V). High cooking loss was associated with high degree of gelatinization. A significant ($P < 0.05$) correlation between cooking loss and the degree of gelatinization at different temperatures was observed ($r^2 = 0.986$) which was similar to that for spaghetti (Abecassis et al 1994). Reducing the cooking loss will be a major task if the extrusion is conducted at >60°C.

Table VI lists the correlation coefficients between rheological properties of dough and some characteristics of extruded noodles. The viscosity and G' had significant positive effects on swell ratio, tensile strength, and cutting force of extruded noodles at 30 and 60°C. Also, the tensile strength was positively correlated with cutting force. The loss tangent (tan δ) had significant negative effect on these characteristics of extruded noodles. It appeared that the cooking loss of extruded noodles did not significantly correlate with dough rheology at the three temperatures tested. When the temperature was raised to 80°C, the viscosity did not significantly affect the properties of extruded noodles. Only tan δ had negative effect on tensile strength and G' had a positive effect on cutting force. This implies that the formation of SS bonds in gluten affects the dough rheology as well as some characteristics of the extruded noodles at <60°C. Increased numbers of SS bonds raised swell ratio, tensile strength, and cutting force. At high temperatures (80°C), the gelatinized starch abated the effects of SS bonds.

CONCLUSIONS

The oxidants (KIO_3 and L-AA) enhanced the formation of SS bonds, which affected rheological properties of dough as well as swell ratio, tensile strength, and cutting force of extruded noodles. The addition of GSH resulted in formation of SH groups and yielded the opposite effects. Heating caused the gelatinization of starch, which played an active role in determining dough rheology and abated the effects of SS bonds at >78.5°C. Therefore, the wheat flour doughs tended to yield the same rheological properties at high temperature (80°C). The dough rheology significantly correlated with the characteristics of extruded noodles at low temperatures. When the temperature was raised to 80°C, only the loss tangent negatively correlated with both tensile strength and cutting force. The addition of oxido-reductants did not interfere with the gelatinization of starch and cooking loss. High cooking loss was associated with high degree of gelatinization. The results indicated that extrusion would be appropriate for producing noodles at low temperatures. Reducing cooking loss would be a major task if extrusion were conducted at >60°C.

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