Effect of Smooth Roll Grinding Conditions on Reduction of Hard Red Spring Wheat Farina[1]

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ABSTRACT

A roll stand of the Grain Research Laboratory experimental mill equipped with 254 mm diameter frosted smooth rolls was used to examine the effect of feed rate, roll velocity, and roll differential on the reduction of hard red spring wheat farina. By increasing roll velocity or decreasing feed rate flour release was increased, milling energy consumption rose, and flour quality (ash and color) was improved. Increasing roll differential led to an increase in flour starch damage, flour water absorption, and milling energy consumption and a deterioration in flour quality (ash and color). These effects can be explained by the relative contribution of compressive and shearing forces acting on farina particles as they pass through the grinding zone.

For fracture to occur in a wheat endosperm particle during roller milling, the stress in the region that fractures must exceed internal forces. Wheat endosperm, like many composite materials, exhibits viscoelasticity when fracturing (MacRitchie 1980). This is a condition intermediate between complete brittleness and gross plastic yielding. In hard wheat endosperm the starch granules adhere strongly to the surrounding protein matrix (Simmonds 1974). As a result, during roller mill reduction of hard wheat endosperm, fracture can occur through, rather than around, starch granules, thereby inducing starch damage (Moss et al 1980).

According to Jones (1940), roller milling induces two types of starch damage in flour starch granules. Compressive forces cause internal granule damage, whereas shearing forces effect surface granule damage from the attritive breakdown of endosperm particles. In either case, generation of starch damage requires fracture in the starch granule.

The nature of the stress imposed on endosperm particles during roller milling will vary according to grinding conditions. Feed rate of stock to rolls, roll velocity, and roll differential (the ratio of fast roll velocity to slow roll velocity) will influence the magnitude of stress and the relative contributions of compressive and shearing forces. The magnitude and the nature of the forces acting on endosperm particles will determine the degree of particle size reduction and will influence flour starch damage and bran contamination.

The two principal components of starch granules are the linear glucose polymer, amylose, and the α (1–6) branched glucose polymer, amylopectin. Starch granules from different sources exhibit structural differences, but amylose is thought to be interdigitated in the amylopectin contributing to the granule's amorphous nature (Banks and Greenwood 1975, Blanshard et al 1984). Not all the amylopectin is in a crystalline form (Nara 1979). However, it is the amylopectin that imparts the crystallinity to the starch granule (Banks and Greenwood 1975), possibly in the form of a two-dimensional structure (Geddes and Greenwood 1969).

The crystallinity of intact starch granules excludes water and restricts access by amylolytic enzymes (Lelievre 1974). When starch granule crystallinity is disrupted, as in flour roller milling, the resulting amorphous zone permits water penetration, and makes the starch more susceptible to amylolytic attack. The numerous flour starch damage assays available (Williams and LeSeelleur 1970) make use of these effects either by measuring the susceptibility of starch to digestion by α-amylase, or by measuring the extractability of amylose.

Increasing flour starch damage has the advantage of increasing flour water absorption capacity, thereby improving pan bread yield per unit of flour weight (Jones et al 1961). However, excessive starch damage can impair baking quality (Tipples 1969), and more rigorous grinding conditions can have detrimental effects on flour color and flour ash (Holas and Tipples 1978).

The purpose of this work was to examine, under simulated commercial conditions, the effect of roll velocity, roll differential, and feed rate on the reduction of hard red spring wheat farina. The changes observed in the degree of particle size reduction, milling energy requirements, flour starch damage, flour ash, and flour color are discussed in terms of the forces acting on the farina particles.

MATERIALS AND METHODS

Farina Preparation

An export cargo of No. 1 Canada Western red spring wheat from the 1984 crop was milled by the Grain Research Laboratory pilot mill (Black 1980). Farina that normally would have gone to the first and second middlings was intercepted, rebolted over a 10xx flour cloth to remove residual flour, and thoroughly blended. Ninety percent of the rebolted stock (as determined by sieving on a Buhler MLU 300 Laboratory plansifter) was in the 132–247 μm size range. Moisture content, ash and Kent-Jones color grade for the rebolted stock were 14.8%, 0.45% (14% moisture basis), and 1.0, respectively.

Grinding Experiments

The reduction roll stand of the Grain Research Laboratory Ross research mill (Black et al 1980) was used for all grinding experiments. The rolls have a lightly frosted finish and are 254 mm (10 in.) in diameter with an effective grinding length of 115 mm (4.5 in.). Roll gap was set at 38 μm (0.0015 in.) while rolls were at room temperature (21° C).

Prior to grinding, the rolls were preheated to 40° C, the stable operating temperature. Mill room conditions were controlled at 21° C and 60% relative humidity.

Roll velocities, differentials, and feed rates were chosen to give a variety of grinding conditions near the range likely to be encountered commercially (Table I). All possible combinations of roll velocities, differentials, and feed rates were used. Experiments were performed on 0.5-kg lots and replicated four times in completely random design.

TABLE I
Roll Speeds, Differentials, and Feed Rates Used to Generate 27 Milling Conditions

Fast Roll Velocity (rpm)	Differential	Feed Rate (kg/m^{-1} min^{-1})
780	2.0:1	10.0
550	1.41:1	7.1
460	1.19:1	5.9

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Milling energy consumption during grinding was determined as described previously (Kilborn et al 1982).

Flour Characterization

Milled stock was blended, and a 100-g portion was sieved for particle size analysis on a Buhler MLU 300 laboratory plansifter. Sieve openings were 247, 183, 153, 132, 107, and 91 μm. Preliminary experiments established that 2 min of sieving time gave the best reproducibility.

The remaining 400-g portion of each sample was sifted for 2 min on an Allis-Chalmers box sifter over a 10xx (136 μm) bolting cloth to obtain flour for analysis.

All analytical data were corrected to 14% moisture. Flour starch damage was estimated by an enzymatic method (Farrand 1964) and a nonenzymatic method (McDermott 1980). In the second method the degree of starch damage is related to the extractability of amylose by measuring the absorbance of the diluted extract at 600 nm after complexation with iodine. Flour water absorption capacity was determined by an ultracentrifuge method (Preston and Tipples 1978).

Flour color was determined with a Kent-Jones and Martin series 2 flour color grader (Holas and Tipples 1978). AACC method 08-01 (1983) was used to determine flour ash.

Statistical Analysis

Data were analyzed by analysis of variance (ANOVA) using factorial design (Snedecor and Cochran 1967). The significance of differences between treatments was tested by the method of Duncan (1955).

RESULTS AND DISCUSSION

Particle Size Reduction and Energy Consumption

Figure 1 depicts the idealized situation for one particle being drawn into the grinding zone of the rolls. In reality there is a collection of particles passing through the grinding zone in a ribbonlike fashion. The particles are subjected to two types of force: shear forces from contact between points on a particle and the roll surface, and compressive forces on the particles as a whole on passing through the grinding zone. The degree of particle size reduction should be dependent on the treatment the particle receives while in the grinding zone.

Flour production (stock less than 132 μm) was significantly ($P<0.001$) related to roll velocity, roll differential, and feed rate (Fig. 2A). Flour production was directly related to roll velocity and inversely related to feed rate. This supports the ribbon theory (Perry and Chilton 1973) for flour production, which predicts that grinding action is proportional to the ratio of roll velocity to feed rate. Increased feed rate reduces the amount of grinding any given particle receives. When roll velocity is increased the feed ribbon spreads out, reducing the load in the grinding zone. The increased grinding action on farina particles resulting from reduced ribbon width causes greater flour release as roll velocity increases (also shown by Schumacher 1966). As roll velocity increases the particles are drawn through the grinding zone more quickly, enhancing their brittleness, which would also contribute to increased flour production.

Milling energy consumption exhibited similarly significant relationships ($P<0.001$) to flour release as roll velocity and feed rate were altered (Fig. 2B). This was not the case when roll differential was altered. Flour release increased significantly ($P<0.001$) when differential was increased from 1.2:1 up to 1.4:1, but levelled off and showed no increase ($P<0.05$) when differential

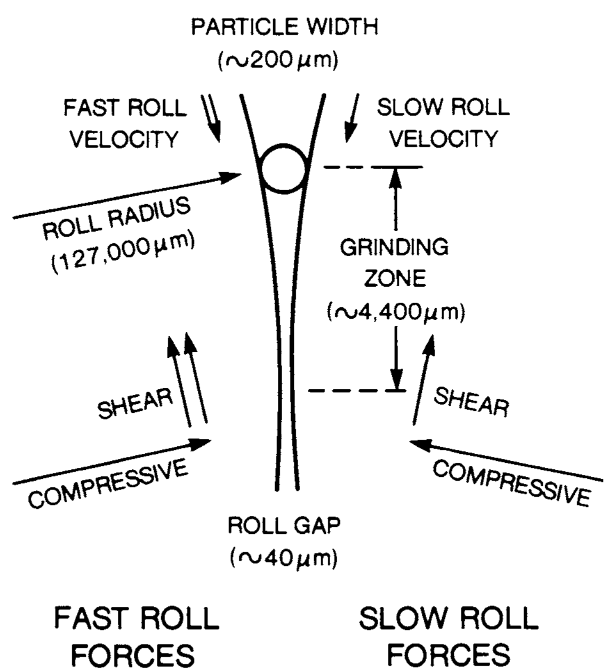

Fig. 1. Idealized grinding zone and forces acting on an individual particle.

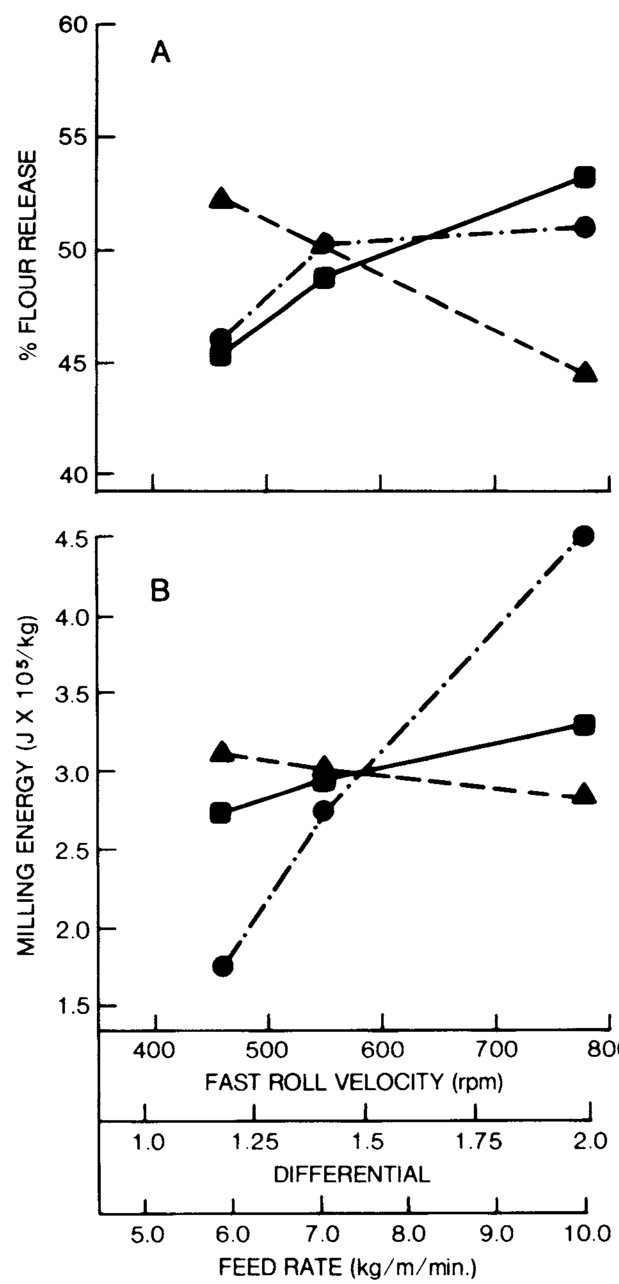

Fig. 2. Effect of fast roll velocity (■), roll differential (●), and feed rate (▲) on **A**, the release of flour and **B**, milling energy consumed.

was increased from 1.4:1 up to 2:1 (Fig. 2A). In contrast, milling energy exhibited a near linear response ($P < 0.001$) to differential (Fig. 2B). The relationship between roll differential and milling energy observed in the current study concurs with the results of Wanzenreid (1970) and Zwingelberg et al (1983). To assess how the increased energy at 2:1 differential is used, changes in overall particle size distribution must be considered.

ANOVA verified highly significant effects ($P < 0.001$) of roll speed, differential, and feed rate on the proportion of particles in each size range. As expected, the proportion of particles in each size fraction greater than 132 μm decreased proportionately as flour release increased; i.e., as roll velocity increased, differential increased and feed rate decreased (results not shown, but the converse of Fig. 3B).

The leveling off of total flour production as differential increased from 1.4:1 to 2:1 (Fig. 2A) was accounted for by a decrease in the proportion of the coarse flour fraction (Fig. 3A). Apparently, increased differential is of limited importance in forming flour particles in the 91–132 μm range. Coarse flour particles are more likely formed by compressive fracture than shear fracture.

The proportion of fine flour (<91 μm) increased progressively as differential increased (Fig. 3B). The increased shear force imparted by increased differential to the semolina particles as they passed through the grinding zone resulted in creation of a greater

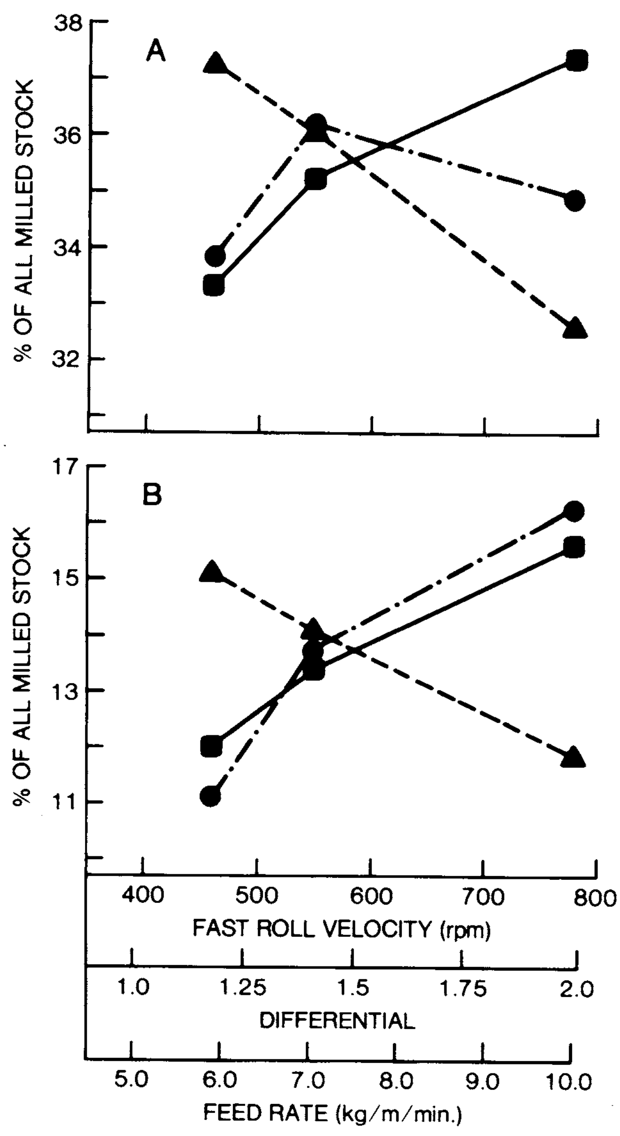

Fig. 3. Effect of fast roll velocity (■), roll differential (●), and feed rate (▲) on **A,** the proportion of material of particle size 91–132 μm and **B,** the amount of material of particle size less than 91 μm.

proportion of fine flour and additional milling energy requirements.

Flour Starch Damage

The relationship between estimates of flour starch damage based on amylolytic susceptiblity and amylose extractability can vary depending on such factors as flour granulation, endosperm hardness, and method of particle size reduction (Evers et al 1984a,b; McDermott 1980). Therefore, in this study flour starch damage was estimated by an enzymatic (Farrand 1964) and an extractability (McDermott 1980) method.

Starch damage was not significantly ($P < 0.05$) affected by either roll velocity or feed rate (Fig. 4A and B). When flour starch damage was estimated by either the enzymatic or extractability method, differential was found to exert a strong ($P < 0.001$) effect. A strong dependence of starch damage on roll differential was reported previously (Evers et al 1984a, Wanzenreid 1970, Willm 1977, Zwingelberg et al 1983). As seen in Figure 4C, flour water absorption also exhibits a significant ($P < 0.001$) positive relationship to roll differential.

Results from these experiments, where roll gap and stock granulation were held constant, show that enhanced flour starch damage is primarily dependent on shear forces imparted by roll differential. Of course, the shear imparted during grinding is a function of roll surface. The lightly frosted finish on the rolls used in this study would impart a greater shearing effect than completely smooth rolls. Shear forces alter the starch granule such that amylolytic digestibility, amylose extractability, and flour water absorption are all increased proportionately to increased shear. Although the rate of loading is high (order of microseconds), hence favoring brittle fracture, shear force will produce plasticity and ductile yielding. Plastic fracture requires continued energy consumption to create small particles and disrupt crystalline regions of the starch granule. Jones's (1940) observation of tear marks in some starch granules lends support to plastic fracturing occurring during flour milling. Craig and Stark showed that size reduction of sorghum (1984a) and wheat (1984b) caused breakdown of the fracturing material (amylopectin) into lower molecular weight species. This is not necessarily a result of intense milling action causing locally high temperatures as Craig and Stark (1984a) suggest. Simple crack propagation can induce covalent bond cleavage with subsequent formation of smaller products. This was shown by Enikolopian et al (1985) where brittle fracture caused breakdown in the molecular structure of the polymer and liberation of small molecules from the fractured faces.

Bond cleavage is not necessary to induce starch damage. The liberation of small components (such as water) caused by fracture may be sufficient in itself to cause amorphization of the crystalline structure of potato starch (Banks and Greenwood 1975). Nevertheless, the additional milling energy required (Fig. 2B) in the absence of greater flour release (Fig. 2A) when differential is increased to 2:1 from 1.4:1 can be attributed to greater disruption of the crystalline nature of starch granules within the fine flour particles caused by shear forces creating higher starch damage (Fig. 4).

Flour Ash and Color

Flour ash and flour color were significantly related ($P < 0.001$) to roll velocity, feed rate, and differential (Fig. 5). The effects of feed rate and roll velocity are inversely related, consistent with the ribbon theory (Perry and Chilton 1973) discussed earlier. Increasing roll velocity or reducing feed rate reduces the load in the grinding zone, increasing the grinding action on farina particles. The resulting enhanced flattening of the bran allows improved separation of bran from endosperm, leading to lower flour ash and improved flour color. By manipulating roll pressure, Ward and Shellenberger (1951) showed the beneficial effect on flour ash of enhanced bran flattening.

Increased roll differential caused increased flour ash and darker flour color ($P < 0.001$). The deterioration in flour quality as differential increases can be ascribed to bran powdering from shear forces imparted by differential. Bran, being tough and fibrous, is more prone to the ductile fracture imparted by shear forces than to brittle fracture.

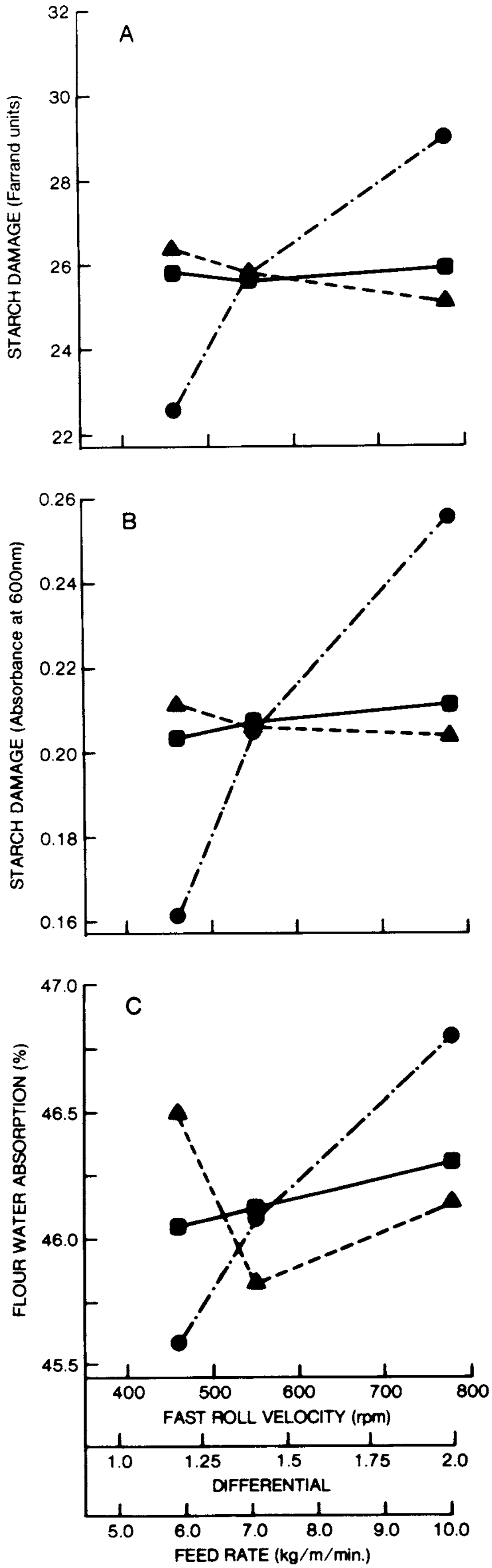

Fig. 4. Effect of fast roll velocity (■), roll differential (●), and feed rate (▲) on starch damage estimated by **A,** the enzymatic method of Farrand (1964); **B,** the amylose extractability method of McDermott (1980); and **C,** flour water absorption.

CONCLUSIONS

The effects of roller milling conditions on hard red spring wheat reduction can be explained on the basis of the forces imparted on farina particles in the grinding zone. The effects of roll velocity and feed rate are inversely related. By either increasing roll velocity or reducing feed rate the load in the grinding zone is reduced. Individual farina particles are then subjected to greater grinding action, causing more fracture, which results in increased flour release and increased milling energy requirement. Flour quality

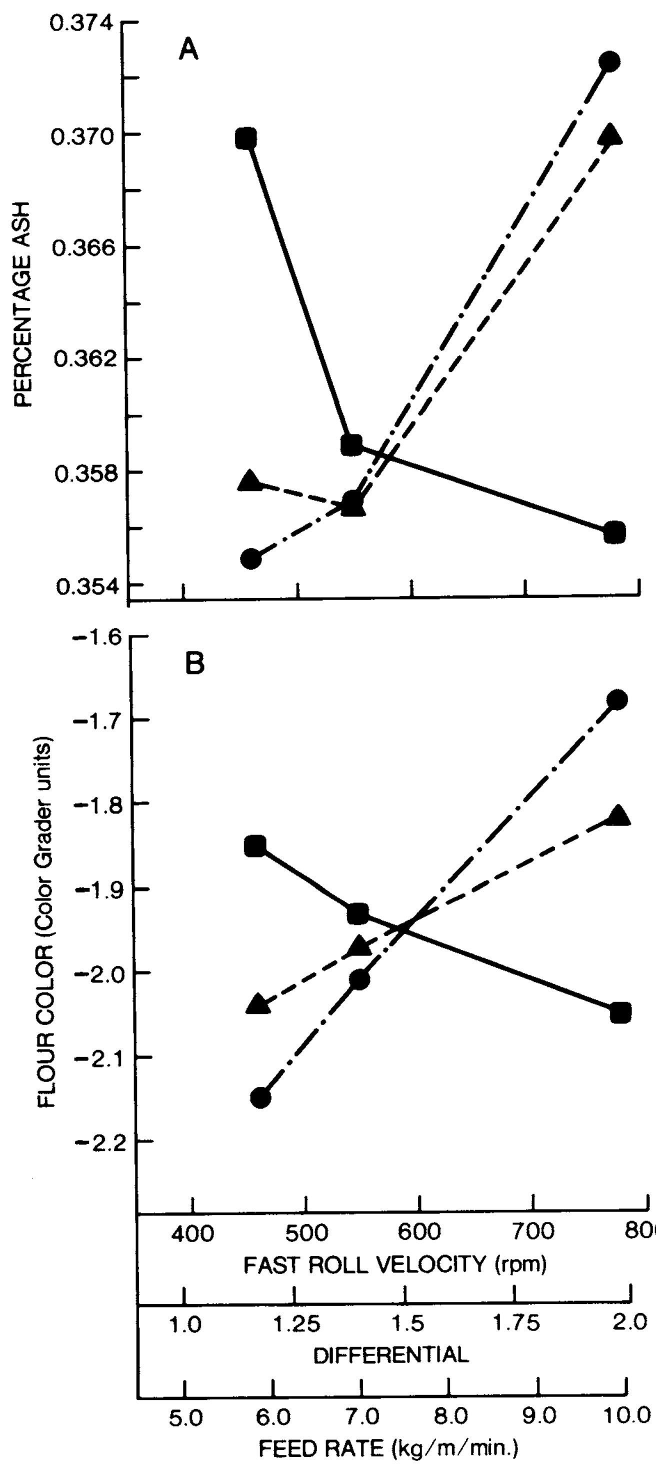

Fig. 5. Effect of fast roll velocity (■), roll differential (●), and feed rate (▲) on **A,** flour ash and **B,** flour color.

(ash and color) is improved because enhanced flattening of the bran allows improved separation of bran from endosperm.

Flour starch damage, estimated by amylolytic digestion and amylose extractability, and flour water absorption are primarily influenced by roll differential. As differential is increased, greater shear forces are imparted to the farina particles. Flour release levels off when differential is increased to 2:1 from 1.4:1, but milling energy continues to increase. The increased shear force induced by increased differential will produce plasticity and ductile yielding of the farina. The increased milling energy needed at greater differential is not expended in frictional losses, but is used to create a greater proportion of fine flour particles and to disrupt crystalline regions of the starch granule, possibly by inducing covalent bond breakage of amylopectin. The amorphization that occurs results in greater susceptibility of starch to amylolytic digestion and allows solvents greater access to the starch granules, resulting in increased amylose extractability and increased flour water absorption.

The greater shear associated with increasing roll differential induces more bran powdering causing greater bran contamination in the flour. As a result, flour ash increases and flour color becomes darker as differential increases.

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