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SINGLE KERNEL EFFECTS ON BREAKAGE DURING WHEAT MILLING

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DECLARATION

I declare that no portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university, or other institution of learning.

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ABSTRACT

Single Kernel Effects on Breakage during Wheat Milling

Single kernel properties of wheat were investigated in order to improve predictive models of breakage during roller milling based on measured distributions of kernel properties. The breakage equation approach for describing First Break roller milling was also extended to include information about the composition of particles in the broken material. An image analysis-based approach to quantifying the bran content of flour stocks was adapted to allow a bran distribution function for First Break roller milling to be defined and quantified.

The Perten Single Kernel Characterisation System (SKCS) measures the distributions of kernel hardness, mass, moisture content and diameter in a mixture of wheat kernels. For the first time, the particle size distribution (psd) resulting from breakage of kernels in the SKCS itself was quantified. Wheat varieties of different hardness, as measured by the SKCS, gave surprisingly consistent psd's on breakage in the SKCS. This indicates that the psd produced by the SKCS cannot be related directly to that produced on breakage during industrial roller milling. More positively, however, it signifies that the hardness index reported by the SKCS indicates relatively unambiguously the energy required to achieve a constant degree of breakage. This implies that the hardness index is inherently meaningful, and explains why it has been possible in previous work to relate the hardness index directly to breakage during First Break roller milling.

Breakage equations have been constructed previously to predict the output particle size distribution from First Break roller milling based on distributions of kernel hardness, mass and moisture as measured by the SKCS. The current work added the fourth SKCS parameter, kernel mass, to breakage equations, and demonstrated that the ratio kernel mass:diameter was related to other kernel shape descriptors, thereby adding factors related to kernel shape to the breakage equation model.

Further studies of kernel shape investigated the breakage of ancient emmer wheat lines, which have much more elongated kernels than modern varieties. These studies demonstrated that the hardness values reported when the SKCS is applied to these ancient wheats are not meaningful in terms of indicating their breakage patterns. The reason for this was considered to be the unusual shape of the kernels of these wheats. Evidence for this was presented by plotting breakage patterns *versus* shape descriptors rather than hardness, which appeared to show a smooth continuum between the ancient and modern wheat varieties.

The particles produced on breakage of wheat kernels by roller milling vary in composition as well as size, such that large particles tend to have higher bran contents, and smaller particles higher endosperm contents. The breakage equation for First Break roller milling was extended to allow description of the composition of particles. A bran distribution function was defined, and the form of the function quantified by measuring bran contents in broken fractions using image analysis.

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To Zulkifli Khair (and the kids)
My collaborator
My philosopher
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My joy
My family.

****

The example of those who spend their wealth in the cause of God
is that of a grain that produces seven spikes,
with a hundred grains in each spike.
God multiplies this manifold for whomever He wills.
God is Bounteous, All Knowing.
(Holy Qur'an, 2: 261)

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ABBREVIATIONS

AACC	American Association of Cereal Chemists
A/D	Analogue to digital
ADAS	Agricultural Development and Advisory Service
AD	anno Domini (in the year of the Lord)
BC	Before Christ
CASK-HaT	Continuous Automated Single-Kernel Hardness Tester
CMP	Commercial milling performance
CWRS	Canadian Western Red Spring (wheat)
D-D	dull-to-dull
D-S	dull-to-sharp
DIA	Digital image analysis
FGIS	Federal Grain Inspection Service
HI	Hardness index
HRS	Hard Red Spring
HRW	Hard Red Winter
ICC	International Association of Cereal Science and Technology
ISO	International Standard Organisation
NABIM	National Association of British and Irish Millers
NIAB	National Institute of Agricultural Botany
NIR(S)	Near infra-red (spectroscopy)
NMR	Nuclear Magnetic Resonance
NIST	National Institute of Standards and Technology
NWHS	National wheat-hardness study
PAGE	Polyacrylamide gel electrophoresis
pdf	Probability density function
psd	Particle size distribution
PSI	Particle size index
S-D	sharp-to-dull
S-S	sharp-to-sharp
SCGPE	Satake Centre for Grain Process Engineering
SD	Standard deviation
SK	Single kernel
SKCS	Single Kernel Characterisation System 4100
SPSS	Statistics Package for Social Science
TKW	Thousand-kernel weight
UMIST	University of Manchester Institute of Science and Technology
USDA	United States Department of Agriculture

NOMENCLATURE

Roman

$a(x)$	Normalised bran concentration function
$a(x, D)$	Bran function
$A(x)$	Cumulative bran distribution
$A(x, D)$	Cumulative bran function
$B(x,D)$	Breakage function for fraction of material of outlet size x formed from breakage of material of inlet size D
$B(x,D,H)$	Breakage function for fraction of material of outlet size x formed from breakage of material of inlet size D of hardness H
$F(D)$	Feed particle size
$F(x)$	Fraction of material in the feed stream initially smaller than x
G/D	The milling ratio, G is roll gap, D is the kernel thickness
KM/KD	The ratio of kernel mass:diameter
m_0	Base moisture content
$P(x)$	Cumulative amount less than particle size x in the outlet stream
$\Pr\{0,D\}$	Probability of a particle being size between 0 and D
$S(D)$	The rate at which particles of size x are created from breakage of larger particles; and at steady state continuous grinding it does not change with time
x	Outlet particle size
x_{25}	Particle size below which 25% of the material (by mass) fell
x_{50}	Particle size below which 50% of the material (by mass) fell
x_{75}	Particle size below which 75% of the material (by mass) fell
x_{b50}	Particle size below which 50% of the bran is contained
y	Inlet particle size

Greek

τ	Average mill residence time
$\rho_1(D)$	Probability density function for feed particles of size D
$\rho_2(x)$	Probability density function of the outlet of size x
$\rho_m(D)$	Particle size distribution in the mill (steady state and fully mixed)
$\rho(x,D)$	The probability of producing an outlet particle of size x from an inlet particle of size D

GLOSSARY OF TERMS

Throughout this thesis a number of industry specific terms have been used. The majority of which are explained the first time that they occur. This section provides a reference section for terms that might not be familiar to the reader.

First Break	The first stage in the roller milling process; grains are sheared open using coarse roll fluting.
Aleurone	Layer of cells situated between the bran and endosperm of cereals. Contains enzymes that activate the growth during germination.
Aleurone Threshold	This defines the brightness of the aleurone particles compared to the background colour.
Aleurone Bleed Threshold	This defines the edge of the aleurone specks.
Bleed Range	The Bleed Range is an internal parameter and should always be set to 2.
Bran	Outer cover of wheat grain. Brown in colour, bran protects the nutrients in the endosperm from the atmosphere
Break rolls	Rolls at the start of a flourmill; fluted rolls that either break-open wheat grains or scrapes bran from endosperm.
Bushel weight	Measure of the bulk density of a sample, in mass per unit volume. Also known as specific or test weight.
Comminution	Breakage of particles
Conditioning	Adding moisture to wheat samples prior to milling to achieve a certain target moisture content in produced flour
Cultivar	Wheat variety
Debranning	Removal of bran layers using abrasion
Differential	Difference in operating speed of two rolls
Endosperm	Central white portion of the wheat grain. A structure made of protein and starch. Utilised in the production of flour.
Extraction yield	Percentage flour from the total milled products, also known as yield
Fluted	Containing flutes
Flutes	Saw-tooth roll corrugations
Gradual reduction	Series of break and reduction stages connected by sifting operations that gradually reduces the wheat to flour.
Grist	Blend of wheat samples prior to milling. A grist is specific to a grade of flour being produced and contains component wheat lots to achieve consistent flour quality.
Magnification	The magnification defines how many microns will be equal to one pixel. This is calculated when the system is set up, and need only be changed if the camera's focus or position has been modified.
Milling ratio	The ratio of roll gap to mean grain thickness (*G/D*)

GLOSSARY OF TERMS

Min Speck Diameter	The minimum speck diameter defines the size of the smallest group of particles (in microns) that the system will determine as a speck.
NIR(S)	Near-infrared spectroscopy. Equipment utilising wavelength of light to measure quality parameters.
Normalised	Expressed in a manner such that the sum of all the constituents is one
Once-through	A single pass operation.
Overtails	Materials remaining on a sieve mesh (after sifting) are known as the overtails of that sieve.
Pericarp Threshold	This defines the darkness of the pericarp particles compared to the background colour
Pericarp Bleed Threshold	The pericarp bleed threshold defines the edge of the pericarp stock
Range	The Range defines maximum speck size. This should be set larger than your anticipated speck radius, however this measurement is in pixels not microns.
Semolina	Coarse granules of endosperm fed to the reduction system.
Single kernel analysis	Testing of single kernel quality attributes and analysis of their distribution with a sample.
Specks	Broken cells and finer debris appear in intact endosperm cells
Specific weight	See Bushel weight.
Subsample Internal	The Subsample Interval is an internal parameter and should always be set to 1
Tempering	See Conditioning
Throughs	Material passing through a sieve mesh (after sifting) is known as the throughs of that sieve.
Yield (flour)	See Extraction yield.
Yield (wheat)	Growing return, tonnes per unit area.

CHAPTER 1 – THE WHEAT KERNEL IN RELATION TO FLOUR MILLING

1.1 INTRODUCTION

Wheat is a unique cereal and arguably the most important cereal crop in the world. It has been a staple food for human for thousand of years since people first began the move from nomadic to settled societies. The composition of the grain makes wheat a nutritious food of high energy value. It is a major source of protein and dietary fibre in the human diet, as well as providing several other nutrients, vitamins and antioxidants (Decker *et al.*, 2002). About 75% of the world's wheat is consumed directly by human, 15% is in the form of animal feed, and another 10% is used for seed and industrial use (Carter, 2001).

Wheat is by far the most important internationally traded grain, representing over 30% of the total world grain production (Dendy and Brockway, 2001). The major wheat exporters are North America, Canada, Australia, Europe and Argentina. The UK is self sufficient in flour with a small positive trade balance. A total of over 5.5 million tonnes of flour is produced each year (NABIM, 2001). Flour milling in the UK is operated by 33 companies and the two largest companies Allied Mills and Rank Hovis, account for approximately 50% of flour produced in the UK each year (NABIM, 2001). As a traded commodity, wheat is subject to wide variations in the price and available quality. This is because of the different harvesting time around the world as a result of the seasons, and different grading systems and classification (Bunn, 2001).

The wheat grain consists of three main constituents: the bran, the germ and the endosperm (Figure 1.1). The starchy endosperm is the inner part of the kernel that yields high-quality white flour which is extracted and separated from the bran and germ during flour milling.

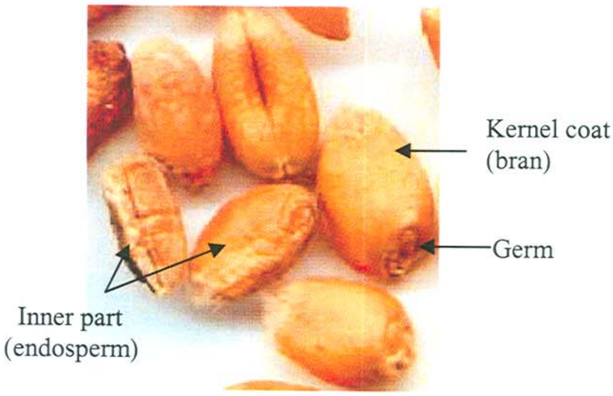

Figure 1.1 Grains of wheat

The grinding of grain is one of the major industries in the world and the one that has had the longest continuous existence of any industrial process (Kent and Evers, 1994). Archaeologists have noted that man first started his quest for more edible food by fractionating various wild seeds by grinding them between his teeth because the interior portion of grain kernels tasted better than the outer kernel cover (Harlan, 1981). Stones were then used to pound grain to release edible seeds from hulls. From this primitive beginning about 10,000 years ago, milling technology gradually evolved. The history of the flour milling industry started with animal-driven and hand-powered milling. The first known mechanically driven mill was introduced by the Greeks in about 450-400 BC in the form of an ungeared water mill. A hundred years later the Romans introduced the geared water mill. In about 600 AD the windmill was invented with arms revolving on a tripod stand. Later, steam-powered units were introduced and in 1784 the first steam driven mill was erected in London. This was followed by the introduction of electrically driven mills in the late 19th century (Bass, 1998).

Today modern milling equipment and processes have been largely standardized. Milling procedures are controlled in the same manner to accommodate different wheat types and different characteristics within the same type. Processing alterations depend on both the physical and chemical composition of the grain and on the objectives of the miller (Pomeranz, 1990). Recent advances in biotechnology for wheat hybridisation have enabled wheat breeders to develop new cultivars with good yield potential without sacrificing quality (Cline and Esfeld, 1998). Nevertheless, improvements to wheat and flour quality and to the milling process are constantly sought in order to produce consistent flour quality.

1.2 MONITORING SINGLE KERNEL ASPECTS TO CONTROL THE QUALITY

The quality of wheat depends on a complex number of factors dependent on how it grows, mills and adapts to an end use in any one of many different kinds of products. Hence defining wheat quality is complex because producers, millers and bakers view it differently. Producers are concerned primarily with wheat yield, yield stability and disease resistance (Shellenberger, 1961; Carter, 2001). Millers evaluate wheat by analysing the purity of the wheat and its physical characteristics such as wheat hardness, size and shape, response to conditioning, behaviour during milling, and flour yield. Wheat quality from the baker's perspective is related to flour properties such as protein, water absorption, starch damage, mixing parameters, fermentation tolerance and loaf volume potential, where many of these depend on protein quantity and quality. The complex and varied processing methods and the multiplicity of products produced from wheat have created a major demand for wheat having specific quality characteristics and nutritional values (Satumbaga *et al.*, 1995). Hence the important goal of milling processes is to obtain suitable consistency for the targeted consumer end use.

In recent years, wheat quality testing has started to move from bulk methods to single kernel methods. This emerging trend gives additional information about the distribution of quality parameters of individual grains and allows correlations between single kernel parameters and processing performance to be identified. Several innovative techniques have been investigated in order to provide accurate, rapid, convenient and informative methods of measuring and predicting quality from tests on single kernels (Evers, 1996; Osborne and Anderssen, 2003). The concept behind this approach is that bulk tests (*e.g.* 1,000 kernel weight hardness, grain protein and moisture content measured by near-infrared spectroscopy) only give an estimate of the whole sample but do not measure individual kernels and thus do not provide any information on sample uniformity. In order to describe a sample's bulk characteristics from single kernel tests, a mean value of all the grains still has to be derived from the individual data and the advantages of the more detailed approach may not at once be appreciated. However the new single kernel testing approach reveals additional information about the degree of variation within the sample and also about systematic associations not previously known to exist (Regnér, 1995; Evers, 1996).

The most developed example of this approach is the Single Kernel Characterisation System (SKCS) developed by the USDA Research Centre at Beltsville, MD and commercialised by Perten Instruments AB (Sweden) for evaluating the quality characteristics of individual wheat kernels (Martin *et al.*, 1993a; Psotka, 1995; Gaines *et al.*, 1996; Osborne *et al.*, 1997; Sissons *et al.*, 2000). The SKCS measures the mass, diameter, hardness and moisture of (usually) 300 individual kernels within 5 minutes, and provides information in the form of means and distributions (Martin *et al.*, 1993b). Interest in single kernel parameters of wheat grains and the distribution of those parameters within a sample has grown in recent years. Researchers have measured wheat properties with the SKCS and reported on the usefulness of the results comparable with conventional methods (Satumbaga, *et al.*, 1995; Gaines *et al.*, 1996; Osborne *et al.*, 1997, 2000). Knowing the mean value of a parameter (such as hardness) and also how that parameter varies within a sample (*i.e.* its distribution about the mean) provides the opportunity to gain a greater understanding of wheat breakage in the actual milling system. In the short term, the main driving force for the acceptance of single kernel technology by the milling industry will be improved milling performance. There is convincing evidence that the single kernel technology provides the possibility of obtaining data on the uniformity of a grain sample with essentially the same speed as bulk tests that offer an average value only (Psotka, 1995; Gaines *et al.*, 1996; Sissons *et al.*, 2000). The challenge, however, is to relate single kernel parameters to actual wheat breakage in the mill.

1.3 PARTICLE BREAKAGE DURING WHEAT MILLING

Conceptually milling involves breaking the wheat kernel to release the endosperm and separate the bran and germ. This process uses repeated size reduction and separation operations. Good milling performance means the separation of bran from the floury endosperm is highly efficient, producing a high yield of good quality flour. Hence, understanding wheat breakage is critical in order to be able to mill wheat into flour effectively. Roller milling is particularly suited to milling of wheat to produce flour; the broad and even distribution of particle sizes produced allows effective separation of bran and efficient recovery of white flour (Campbell *et al.*, 2001a). This is perhaps explained by the breakage patterns of each kernel in the roller mill, which depend only on the roller mill design and operation (speed, differential, disposition) and their interaction with the grain's physico-chemical properties including size, mass, moisture and protein content, density and hardness (Campbell and Webb, 2001; Campbell *et al.*, 2001a,b; Bunn *et al.*, 2001).

Wheat hardness is not clearly defined, and is a complex parameter dependent upon a number of kernel properties (Simmonds, 1974; Wu *et al.*, 1990). The hardness index reported by the SKCS itself is an arbitrary indicator, nominally varying from 0 to 100, with no units. Also, in addition to hardness, several other single kernel parameters, including weight, size, shape, moisture content and density are believed to affect milling (Williams *et al.*, 1987; Pomeranz *et al.*, 1988). In relation to wheat breakage, the effects of other factors, *i.e.* kernel shape, kernel mass, bran composition and distribution, are another focus in this research.

An understanding of the relationship between feed characteristics and resultant particle-size distributions from roller milling operations is crucial for effective design and control of flour mills (Campbell and Webb, 2001). Recent studies have verified that during First Break roller milling of wheat, each kernel breaks independently according to its own physico-chemical properties, independent of the mixture of kernels surrounding it

(Campbell and Webb, 2001). Knowing the distribution of kernel properties in a sample, the particle size distribution of the milled stocks can be predicted for a heterogeneous feed milled at any roll gap (Campbell and Webb, 2001; Campbell *et al.*, 2001b; Bunn *et al.*, 2001; Fang and Campbell, 2002b). Campbell and Webb (2001) developed an understanding of roller milling based on the concept of a 'breakage equation', which is a mathematical relationship between the inlet and outlet particle-size distributions. Campbell *et al.* (2001b) described further studies on the First Break milling of narrowly sized fractions of wheat. They showed that the average particle size of the outlet stream increased linearly with roll gap setting G and decreased with increasing feed size D. They demonstrated that the milling ratio (G/D) is relevant to milling and postulated that the 'breakage function' approach which relates the inlet and outlet particle-size distributions provides a potential link between single kernel testing and milling performance.

Subsequently, Campbell and Fang (2002) extended the work to incorporate single kernel hardness into the breakage equation. They noted that the effect of hardness is greater under dull-to-dull milling, which produces a larger proportion of very large and very small particles, with fewer in the mid-size range, compared with sharp-to-sharp. The results from different wheat varieties show consistent trends, indicating that the SKCS hardness measurement is meaningful in terms of actual breakage during roller milling.

Fang and Campbell (2003b) further demonstrated that the breakage equation could be extended to account for moisture content distribution. They investigated the effect of wheat moisture content on the First Break milling of Hereward and Consort wheats, and noted that the effect of adding water was to change an initially inverted U-shaped distribution at low moisture contents to a linear distribution at 16% moisture, then to a U-shaped distribution at higher moisture contents.

The progress made so far has demonstrated that if the distribution of single kernel properties in a sample is known, and if predictive equations of breakage of individual kernels in terms of their physico-chemical properties exist, then it is feasible, in principle, to predict the breakage of the mixture based on the distributions of single kernel properties.

The objective of the work presented here was to extend predictive models of wheat breakage during roller milling to include other single kernel parameters, specifically kernel mass, shape and composition. As a step towards this objective, a primary goal was to determine the breakage produced in the SKCS itself. This would help in identifying the basis of the hardness index reported by the SKCS and thus interpreting its physical significance, and in relating wheat mass and shape to breakage during roller milling.

The second objective was to develop predictions of bran size distribution resulting from breakage of wheat mixtures during First Break roller milling, based on measurement of distributions of single kernel parameters in the SKCS and bran distributions, and further to examine the feasibility of incorporating compositional information into the breakage equation.

1.4 SCOPE OF THE THESIS

Relating single kernel characteristics of wheat to breakage during roller milling has been identified as an important area of research and the subject of this thesis. The remainder of this thesis is organised into seven chapters as follows.

Chapter 2 reviews wheat origin and development, the flour milling process and important single kernel aspects of wheat that govern the quality of flour. Hardness is identified as the major property that influences milling performance. The factors that govern hardness properties are described, highlighting the importance of moving from bulk methods to single kernel analysis for cereal quality testing. The chapter describes the reasoning behind the project and its potential benefits with respect to flour milling technology.

A comprehensive review of the literature on single kernel studies and wheat breakage during milling is presented in Chapters 3 and 4. Chapter 3 discusses single kernel analysis and its contribution to cereal study, in particular wheat. Some of these methods are reviewed, both bulk and single kernel, and the design, development and application of the Perten Single Kernel Characterisation System (SKCS) are described. Chapter 4 discusses wheat breakage with particular emphasis on the breakage models used in the current work to relate single kernel parameters, *i.e.* distributions of size, hardness, and moisture content to First Break roller milling performance. It draws on related work in order to understand wheat milling processes and discusses concepts and design choices related to the feasibility of prediction of milling performance based on single kernel breakage.

Chapters 5 through 9 detail the experimental studies carried out within this project. Chapter 5 describes the equipment used in this project, the materials and the preparatory work employed. Chapter 6 presents results of the breakage of different wheat varieties used in the SKCS to investigate the effects of single kernel hardness, mass, size and moisture content of wheat. Chapter 7 presents results on breakage of different wheat varieties during First Break roller milling. This chapter highlights some of the novel features offered by breakage in the SKCS and relates them to the breakage in the roller mill. The effects of kernel mass and shape on breakage are particularly explored. Continuing this theme, Chapter 8 then investigates breakage of samples of an ancient wheat line, emmer wheat, which has an unusually long and elongated shape compared with modern varieties. Chapter 9 reports a study on bran distribution analysis from breakage in the roller mill. A model to predict the breakage of wheat mixtures in the roller mill based on SKCS measurements is discussed examining the feasibility of incorporating compositional information.

Finally, Chapter 10 highlights the findings and conclusions of this study, indicates its relevance and identifies areas requiring further attention.

The work has resulted in one paper published in a journal, two papers published in conference proceedings, an oral presentation and two posters presented at conferences:

Muhamad, I.I., and Campbell, G.M. (2004). "Effect of kernel hardness and moisture content on wheat breakage in the single kernel characterization system." *Innovative Food Science and Emerging Technologies*, 5(1): 119-125.

Fang, C.Y., Muhamad, I.I., and Campbell, G.M. (2003). "Prediction of breakage during roller milling of mixtures of wheat kernels, based on single kernel measurements." In *Proceedings of Particulate System Analysis conference*, 11-12 September 2003, Harrogate UK.

Muhamad, I.I., Fang, C.Y., and Campbell, G.M. (2002) "Study of the breakage of wheat in the SKCS and during First Break roller milling". In *Proceedings of 1st Annual Conference of Malaysian Research Group UK*, 10-12 October 2002, Manchester.

Fang, C.Y., Muhamad, I.I., and Campbell, G.M. (2002) Comparison of the particle size distributions produced by breakage of wheat in the SKCS and during first break roller milling. An oral presentation at *87th AACC Annual Meeting*, 13-16 October 2002, Montreal, Canada.

Muhamad, I.I., Fang, C.Y., and Campbell, G.M. (2002) "Breakage of wheat in the Single Kernel Characterization System and during First Break roller milling". Poster presented at *1st Annual Conference of Malaysian Research Group UK*, 10-12 October 2002, Manchester.

Muhamad, I.I., and Campbell, G.M. (2002). "Wheat breakage in the Single Kernel Characterization System". Poster presented at *87th AACC Annual Meeting*, 13-16 October 2002, Montreal, Canada.