



**SINGLE KERNEL EFFECTS ON BREAKAGE
DURING WHEAT MILLING**

A thesis submitted to the
University of Manchester Institute of Science and Technology
UMIST

for the degree of
Doctor of Philosophy in Chemical Engineering

April 2004

Ida Idayu MUHAMAD
Supervisor: Dr Grant M. CAMPBELL

Satake Centre for Grain Process Engineering
Department of Chemical Engineering
UMIST

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.

Ida Idayu MUHAMAD

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.

ACKNOWLEDGEMENTS

I gratefully acknowledge the Malaysian Government and Universiti Teknologi Malaysia for their funding of this study.

Blessed are those who give generously to others of their talents, knowledge and time. I would like to thank:

Dr Grant Campbell for his supervision, advice, thoughts, friendship, ideas, 'stories', continuous support, undying spirit and enthusiasm,

Professor Collin Webb for his advice and useful discussions,

Dr Delwen Samuel from Kings College, London for supplying the ancient wheats for this study,

Mrs Tracey, Dave Jones, Dr. Jintang Li, and Dr Zoe for their brilliant support and assistance,

With special thanks to Dr Chaoying Fang for his valuable input, excellent advice and help in using the SKCS and roller mill, Dr Ruohang Wang and Dr Peter Martin for their assistance, practical discussions, and co-operations at all times,

The SCGPE students since the first day of my PhD (16 October 2000) – Susanna, Henrietta, Phil, Sarwar, Nyuk Ling, Tuya, Marliya, Hemant, Siti, Lili, and also Haruhito, for living through it with me and adding a mosaic of colour, joy and friendship in my student life,

Dr Ari Sandhyavetri, Mr Fajar Restuhadi, Dr Zalini, Zurina and Murni for their help, constructive discussions and invaluable guidance,

All the Satake Centre and Chemical Engineering Dept. staffs, MCCH and to others not mentioned but who assisted in many ways to make this PhD thesis a reality,

To Zulkifli Khair (and the kids)

My collaborator

My philosopher

My tranquilliser

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)

TABLE OF CONTENTS

Declaration	i
Abstract	ii
Acknowledgements.....	iii
Table of Contents	iv
List of Figures.....	ix
List of Tables	xiii
Abbreviations	xiv
Nomenclature	xv
Glossary of terms.....	xvi
 CHAPTER 1 - THE WHEAT KERNEL IN RELATION TO FLOUR MILLING	
1.1 Introduction.....	1
1.2 Monitoring single kernel aspects to control the quality	2
1.3 Particle breakage during wheat milling	5
1.4 Scope of the thesis	7
 CHAPTER 2 - UNDERSTANDING THE GRAIN, THE BASIS OF THE MILLING PROCESS	
2.1 Introduction.....	10
2.2 Wheat history and origin	10
2.3 Wheat cultivation and development	11
2.4 Understanding the wheat kernel.....	14
2.5 Converting wheat to flour	17
2.6 Kernel characteristics related to milling	20
2.6.1 Moisture content and conditioning	20
2.6.2 Thickness and composition of endosperm walls	21
2.6.3 Bran thickness and compactness.....	21
2.6.4 Effect of hardness on wheat milling	24
2.6.5 Factors governing kernel properties related to the hardness of wheat.....	26

TABLE OF CONTENTS

2.7	Summary	31
------------	----------------------	-----------

CHAPTER 3 - SINGLE KERNEL CHARACTERISATION, CONTRIBUTION TO WHEAT QUALITY

3.1	Introduction	32
3.2	Determination of wheat parameters using single kernel methods.....	33
3.2.1	Single kernel hardness	33
3.2.2	Moisture content	34
3.2.3	Single kernel mass, size and shape	35
3.2.4	Single kernel density	36
3.2.5	Single kernel image analysis	37
3.2.6	Single kernel NIR analysis	38
3.3	Wheat hardness	40
3.4	Methods and measurement techniques to study hardness	41
3.4.1	Particle Size Analysis	43
3.4.2	Force to Fracture or Energy Measurement	45
3.4.3	Near Infra-red Analysis	47
3.4.4	Single Kernel Characterization System (SKCS 4100)	48
3.5	An interesting focus SKCS 4100	51
3.5.1	Principles of Operation	51
3.5.2	SKCS Design Description	53
3.5.3	Contributions of the SKCS to single kernel studies	55
3.6	Summary	61

CHAPTER 4 - WHEAT BREAKAGE DURING MILLING

4.1	Introduction	64
4.2	Particle technology	64
4.3	Wheat milling.....	65
4.3.1	Factors affecting wheat breakage in the roller mill	66
4.3.2	Modelling particle breakage during roller milling	69
4.3.3	Relating the single kernel properties to breakage in the roller mill..	75
4.4	Relating other single kernel properties to the breakage equation.....	82
4.5	Summary	83

CHAPTER 5 - RESEARCH METHODOLOGY

5.1	Introduction	86
5.2	Wheat samples used	86

TABLE OF CONTENTS

5.3	Equipment used.....	88
5.3.1	The Perten Single-Kernel Characterisation System (SKCS) 4100...	89
5.3.2	Test Roller Mill (Satake, Japan, STR-100AU).....	90
5.3.3	Fluoroscan F2000 (Branscan Ltd., UK)	91
5.3.4	Plansifter (henry Simon, UK, Laboratory)	92
5.3.5	GilSonic Autosiever	93
5.4	Methods employed.....	94
5.4.1	Preparation and conditioning of samples	94
5.4.2	Characterisation of wheat using Perten Single Kernel Characterization System (SKCS 4100)	96
5.4.3	Milling of wheat by Satake STR-100 roller mill	97
5.4.4	Sieving using GilSonic Autosiever	98
5.4.5	Analysis of milled stocks by Simon Plansifter	99
5.4.6	Measuring bran distributing using Fluoroscan F2000	100
5.4.7	Wheat kernel measurement using Image Analysis.....	102
5.5	Summary	105

CHAPTER 6 - WHEAT PROPERTIES AND BREAKAGE IN THE SKCS

6.1	Introduction	106
6.2	Experimental design.....	106
6.2.1	Effect of wheat hardness on breakage in the SKCS	106
6.2.2	Investigation of the effect of kernel size on breakage in the SKCS	107
6.2.3	Investigation of the effect of kernel moisture content on breakage in the SKCS	108
6.3	Results and discussion.....	108
6.3.1	Effect of Kernel Hardness on Particle Size Analysis	109
6.3.2	Effect of Kernel Hardness on Particle Size Distribution	111
6.3.3	Effect on Moisture Content on Particle Breakage	113
6.4	Summary	117

CHAPTER 7 - RELATING SINGLE KERNEL PROPERTIES TO MILLING PERFORMANCE

7.1	Introduction	118
7.2	Experimental design.....	118
7.2.1	Preparing milled fractions of wheat sample	120
7.2.2	Characterising the size and shape of the wheat kernels of different varieties	121
7.3	Results and discussion.....	122
7.3.1	Particle size distributions with hardness.....	122
7.3.2	Relating hardness to breakage during First Break milling	126
7.3.3	Incorporating mass into the breakage equation	130

TABLE OF CONTENTS

7.3.4	Characterising the kernel shape	135
7.3.5	Discussion.....	138
7.4	Summary	139
 CHAPTER 8 - EFFECT OF SHAPE ON WHEAT BREAKAGE		
8.1	Introduction	140
8.2	Experimental design.....	141
8.2.1	Characterising size and shape of wheat kernels of different varieties	141
8.2.2	Effect of kernel shape on breakage in the Single Kernel Characterisation System	142
8.2.3	Effect of kernel shape on breakage in the roller mill	143
8.3	Results and discussion.....	144
8.3.1	Spectrum of kernel sizes and shapes	144
8.3.2	Effect of kernel shape on breakage in the SKCS.....	153
8.3.3	Effect of kernel shape on breakage in the roller mill	157
8.4	Summary	166
 CHAPTER 9 - INCORPORATING COMPOSITION INTO BREAKAGE MODEL		
9.1	Introduction	167
9.2	Theory	168
9.3	Experimental details	172
9.3.1	Measuring bran content using the Fluoroscan.....	173
9.4	Results and discussion.....	175
9.4.1	Bran distributions of milled fraction	175
9.4.2	Cumulative bran distribution function.....	178
9.4.3	Confirming the validity of the bran distribution function	185
9.5	Summary	190
 CHAPTER 10 - CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK		
10.1	Introduction	191
10.2	Progress made in this thesis	191
10.3	Recommendations for future work.....	194
	References.....	196

TABLE OF CONTENTS

APPENDICES

Appendix 1A: Probability density function, $\rho(x)$ for 17 varieties from breakage in the SKCS	210
Appendix 1B: Analysis of Variance (ANOVA) for Chapter 6 section 6.3.2....	211
Appendix 2A: Analysis of Variance (ANOVA) for Chapter 7 section 7.3.3 ...	215
Appendix 2B: Analysis of Variance (ANOVA) for Chapter 7 section 7.3.3 - Evaluating R^2 without Incorporating Average Kernel Mass and R^2 with Incorporating Average Kernel Mass	218
Appendix 3A: Probability density function, $\rho(x)$ for twenty-two ancient wheat varieties.....	219
Appendix 3B: Probability density function, $\rho(x)$ for six modern wheat varieties.....	221
Appendix 4: Normalised bran concentration function, $a(x)$ for nineteen wheat varieties soft to hard	222
Appendix 5: Starch measurement using β-D-Glucose (dextrose) determination method for section 9.4.3.	223
Appendix 6: Measurement of ash using furnace method	225

LIST OF FIGURES

Figure	1.1	Grains of wheat	2
Figure	2.1	Ancient wheat varieties from left, Einkorn; Emmer; Spelt; and Kamut	11
Figure	2.2	The structure of a wheat kernel	15
Figure	2.3	The cross-section of a wheat kernel	15
Figure	2.4	Simplified diagram of the flour milling process	19
Figure	2.5	<i>Above</i> : the two main types of endosperm cell – prismatic (<i>left</i>), polyhedral (<i>right</i>) – showing large and small starch granules (white) embedded in protein matrix (black). <i>Below</i> : exposed endosperm cell contents (<i>left</i>) and products of further breakdown (<i>right</i>): 1. detached large starch granules (about 25 μm diameter); 2. ‘clusters’ of small starch granules (about 20 μm diameter); 3. detached small starch granules (about 7 μm diameter); 4. fragments of free wedge protein (less than 20 μm diameter)	25
Figure	3.1	The Perten Single Kernel Characterisation System 4100	51
Figure	3.2	Single Kernel Characterisation System (SKCS 4100) operating mechanisms	52
Figure	3.3	Figure 3.3 Schematic drawing of the crushing device	53
Figure	4.1	Raw material and process factors affecting wheat breakage during roller milling	67
Figure	4.2	Percentage smaller than x versus hardness under (a) sharp-to-sharp; and (b) dull-to-dull roll dispositions at roll gap 0.5 mm	82
Figure	5.1	Single Kernel Characterisation System 4100	89
Figure	5.2	Satake STR-100AU test roller mill	90
Figure	5.3	Fluoroscan F2000	91
Figure	5.4	Simon Plansifter	93
Figure	5.5	GilSonic AutoSiever	94
Figure	5.6	Schematic diagram of the STR-100 Roller Mill	97
Figure	5.7	An example of result window from the Fluoroscan 2000 showing bran percentage and speck count measurements	101
Figure	5.8	Two-dimensional image analysis system overview	102
Figure	5.9	Flow diagram of measuring dimensions and shape factors by two-dimensional image	104
Figure	6.1	Cumulative particle size distribution and probability density function resulting from milling sample of Drake (a soft wheat) conditioned to 16% moisture w.b.	109
Figure	6.2	x_{25} , x_{50} and x_{75} versus SKCS hardness of seventeen wheat varieties conditioned to 16% moisture w.b.	110
Figure	6.3	Cumulative size distribution of Hereward and Consort wheat of different kernel sizes at tempering moisture 13% w.b.	114
Figure	6.4	x_{50} versus kernel sizes of Consort at different tempering moistures	114
Figure	6.5	x_{50} versus kernel sizes of Hereward at different tempering moistures	114
Figure	6.6	SKCS hardness values of different kernel sizes of Consort and Hereward	114
Figure	6.7	Cumulative size distribution of wheats of different hardness at a tempering moisture of 16% w.b.	115
Figure	6.8	Average particle size, x_{50} of wheats of different hardness at different tempering moistures	115

LIST OF FIGURES

Figure 6.9	Cumulative size distribution of Soissons wheat at different tempering moistures	116
Figure 6.10	x_{25} , x_{50} and x_{75} versus different tempering moistures of Soissons wheat	116
Figure 7.1	Percentage smaller than x versus hardness under (a) dull-to-dull; and (b) sharp-to-sharp roll dispositions at roll gap 0.3 mm	123
Figure 7.2	Percentage smaller than x versus hardness under (a) dull-to-dull; and (b) sharp-to-sharp roll dispositions at roll gap 0.4 mm	124
Figure 7.3	Percentage smaller than x versus hardness under (a) dull-to-dull; and (b) sharp-to-sharp roll dispositions at roll gap 0.5 mm	124
Figure 7.4	Percentage smaller than x versus hardness under (a) dull-to-dull; and (b) sharp-to-sharp roll dispositions at roll gap 0.6 mm	125
Figure 7.5	Percentage smaller than x versus hardness under (a) dull-to-dull; and (b) sharp-to-sharp roll dispositions at roll gap 0.7 mm	125
Figure 7.6	Percentage smaller than x versus hardness under (a) dull-to-dull; and (b) sharp-to-sharp roll dispositions at roll gap 0.8 mm	126
Figure 7.7	Predicted (lines) and experimental (symbols) cumulative particle size distributions for (a) Consort; and (b) Spark wheats milled at different roll gaps under dull-to-dull disposition	128
Figure 7.8	Predicted (lines) and experimental (symbols) cumulative particle size distributions for Consort50/Spark50 wheats milled at different roll gaps under dull-to-dull disposition	128
Figure 7.9	Predicted (lines) and experimental (symbols) cumulative particle size distributions for (a) Malacca; and (b) Soissons wheats milled at different roll gaps under dull-to-dull disposition	129
Figure 7.10	Predicted (lines) and experimental (symbols) cumulative particle size distributions for Soissons50/Malacca50 wheats milled at different roll gaps under dull-to-dull disposition	129
Figure 7.11	Predicted and experimental cumulative size distributions of Consort at six different roll gaps under dull-to-dull disposition	131
Figure 7.12	Residual versus kernel mass for nineteen wheat varieties from milling under dull-to-dull disposition	132
Figure 7.13	Residual versus kernel mass for nineteen wheat varieties from milling under sharp-to-sharp disposition	132
Figure 7.14	Comparing predicted and experimental values for Mercia (at a range of roll gaps under dull-to-dull disposition	133
Figure 7.15	Relationship between residuals and the SKCS ratio of kernel mass:diameter from (a) dull-to-dull milling and (b) sharp-to-sharp milling	135
Figure 7.16	Relationship between kernel ellipsoidal volume and the SKCS mass:diameter ratio	137
Figure 7.17	Relationship between kernel aspect ratio and the SKCS mass:diameter ratio	137
Figure 7.18	Relationship between kernel sphericity and the SKCS mass:diameter ratio	137
Figure 8.1	Twenty-eight kernel images of ancient and modern wheat varieties used in the study (magnification from original size $\times 4$)	145
Figure 8.1	(continued) Twenty-eight kernel images of ancient and modern	146

LIST OF FIGURES

	wheat varieties used in the study (magnification from original size ×4)	
Figure 8.2	Comparison between kernel sizes of modern and ancient varieties measured by Digital Image Analysis	147
Figure 8.3	Relationship between kernel area and SKCS mass:diameter ratio	149
Figure 8.4	Relationship between kernel perimeter and SKCS mass:diameter ratio	149
Figure 8.5	Relationship between kernel aspect ratio and SKCS mass:diameter ratio	150
Figure 8.6	Relationship between kernel ellipsoidal volume and SKCS mass:diameter ratio	150
Figure 8.7	Relationship between kernel sphericity and SKCS mass:diameter ratio	150
Figure 8.8	Relationship between SKCS hardness and average kernel mass of emmer and modern wheats	152
Figure 8.9	Kernel aspect ratio versus mass of ancient and modern wheats	152
Figure 8.10	Cumulative size distribution from breakage of six different varieties in the SKCS	153
Figure 8.11	Particle size distributions from breakage of six different varieties in the SKCS	153
Figure 8.12	Comparison between size fractions of modern wheats (□ unfilled) and emmer wheats (■ filled) versus hardness from breakage in the SKCS	155
Figure 8.13	Comparison between size fractions of modern wheats (□ unfilled) and emmer wheats (■ filled) versus kernel sphericity from breakage in the SKCS	155
Figure 8.14	Cumulative size distribution versus hardness under disposition dull-to-dull for roll gap (a) 0.3; (b) 0.5; (c) 0.7 and (d) 0.8 mm	158
Figure 8.15	Comparison between size fractions of modern wheats (■ filled) and emmer wheat (□ unfilled) versus kernel sphericity	159
Figure 8.16	Density distributions of (a) Consort; (b) Claire; (c) Emmer; (d) CWRS; (e) Soissons and (f) Spanish wheats from breakage during First Break roller milling	161
Figure 8.17	Variation in $B(x,D)$ with G/D for (a) Consort; (b) Claire; (c) Emmer; (d) CWRS; (e) Soissons and (f) Spanish wheats from breakage during First Break roller milling	162
Figure 8.17	(continued) Variation in $B(x,D)$ with G/D for (a) Consort; (b) Claire; (c) Emmer; (d) CWRS; (e) Soissons and (f) Spanish wheats from breakage during First Break roller milling	163
Figure 9.1	Illustration of the effect of the ash concentration function on the relationship between the particle size distribution and the ash distribution pdf's	170
Figure 9.2	Cumulative output particle size distribution, $P(x)$, and cumulative ash distribution, $A_2(x)$	170
Figure 9.3	Normalised bran concentration function of total milled Consort wheat versus particle sizes at six roll gaps under disposition dull-to-dull	177
Figure 9.4	Normalised bran concentration function of total milled Hereward	177

LIST OF FIGURES

	wheat versus particle sizes at six roll gaps under disposition dull-to-dull	
Figure 9.5	Percentage of bran in samples of seven different varieties versus particle sizes at roll gap 0.5 mm dull-to-dull	179
Figure 9.6	Cumulative bran distribution contained in particle sizes smaller than x of Consort at different roll gaps, 0.3-0.8 mm, dull-to-dull	179
Figure 9.7	Cumulative bran distribution contained in particle sizes smaller than x of Hereward at different roll gaps, 0.3-0.8 mm, dull-to-dull	179
Figure 9.8	Cumulative bran distribution, x_{b50} of wheat of different hardness from dull-to-dull milling at four different roll gaps	179
Figure 9.9	Variation in $A(x,D)$ with G/D for Consort (11.2). The x given in the equations on the right of this figure refer to the milling ratio G/D	181
Figure 9.10	Variation in $A(x,D)$ with G/D for Hereward (65.3). The x given in the equations on the right of this figure refer to the milling ratio G/D	181
Figure 9.11	Variation of α_0 and α_1 coefficients with the particle size (x) for Consort (11.2)	184
Figure 9.12	Variation of α_0 and α_1 coefficients with the particle size (x) for Hereward (65.3)	184
Figure 9.13	Average starch content versus particle size from Consort milled at roll gap 0.4 mm dull-to-dull	186
Figure 9.14	Average starch content versus particle size from Hereward milled at roll gap 0.4 mm dull-to-dull	186
Figure 9.15	Average starch content versus particle size from Consort milled at roll gap 0.5 mm dull-to-dull	186
Figure 9.16	Average starch content versus particle size from Hereward milled at roll gap 0.5 mm dull-to-dull	186
Figure 9.17	Average starch content versus particle size from Malacca milled at roll gap 0.5 mm dull-to-dull	186
Figure 9.18	Ash measurement from three samples milled at roll gap 0.5 mm dull-to-dull	187
Figure 9.19	Images of particles of size fractions (a) 2000 μm ; (b) 1700 μm ; (c) 1400 μm ; (d) 1180 μm ; (e) 850 μm ; (f) 500 μm ; (g) 212 μm and (h) less than 212 μm (magnification 15 \times)	188
Figure 9.20	An image of the particles of size fraction 2000 μm mixed with white flour showing the bran (brown) and flour particles (white) (magnification 15 \times)	189

LIST OF TABLES

Table 2.1	The objectives and advantages of wheat domestication	12
Table 2.2	Studies on wheat protein and its relationship to hardness	30
Table 3.1	Reports on single kernel parameter studies	39
Table 3.2	History of wheat kernel hardness measurement	43
Table 3.3	Methods of determining wheat hardness, the measurement factors and basis of analysis	49
Table 3.4	The applications of SKCS in wheat study and other cereals	60
Table 5.1	Modern wheat samples used during the project	87
Table 5.2	Ancient wheat samples used during the project	88
Table 5.3	STR-100AU manufacturer's specifications	90
Table 5.4	Range of variables on STR-100 AU test roller mill	91
Table 6.1	Average kernel properties of wheat samples SKCS	107
Table 7.1	Average SKCS properties of nineteen varieties of wheat for experiments investigating the outlet particle size distributions from First Break roller milling	119
Table 7.2	Roller mill settings for experiments investigating the effect of kernel hardness and mass on wheat breakage	120
Table 7.3	Example of data obtained from Consort under dull-to-dull milling at three different roll gaps	131
Table 7.4	Comparison of R^2 values evaluated with and without incorporating average kernel mass	134
Table 7.5	Variables generated as kernel shape descriptors	136
Table 8.1	The SKCS properties of twenty-eight varieties of wheat used to investigate the outlet particle size distributions (at 16% moisture content wet basis)	142
Table 8.1	(continued) The SKCS properties of twenty-eight varieties of wheat used to investigate the outlet particle size distributions (at 16% moisture content wet basis)	143
Table 8.2	The kernel shape descriptors of ancient and modern varieties of wheat	148
Table 9.1	Example of calculation of bran measurement using the Fluoroscans F2000	175
Table 9.2	Coefficients describing the bran distribution on breakage, for Consort and Hereward	183

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) 7
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.

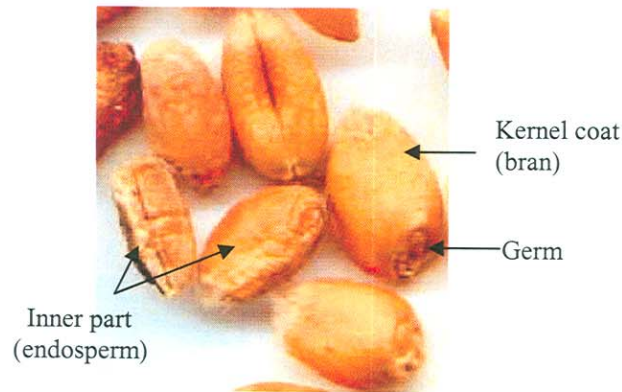


Figure 1.1 Grains of wheat

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.