CHAPTER 7

Roller Milling of Wheat

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1. INTRODUCTION

The grinding of wheat into flour is mankind's oldest continuously practised industry and the parent of all modern industry; all modern particle breakage operations have wheat milling in their ancestry. In pursuing the need for efficient and ubiquitous milling of wheat, millers and millwrights of old developed a practical mastery of several of the fundamental engineering disciplines: fluid dynamics and aerodynamics for power generation from water wheels and windmills, mechanical engineering for the transmission of power via gearing and control mechanisms, and particle handling, breakage and separation operations. Oliver Evans, American designer of the original highly automated flour mills, has been described as "the first thoroughgoing plant engineer" [1], while Professor Friedrich Kick (Fig. 1), author of the first scientific treatise on flour milling in 1871 [2], also furnished comminution science with one of its most beloved laws [3–6]. Securing the grain supply motivated the construction of ancient empires and triggered the more recent development of national and international transport infrastructures and trading

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Hofrat Proffessor Kick.

Fig. 1. Professor Friedrich Kick.

systems [7–9]. Meanwhile, the anatomical difference between the structures of the wheat kernel and the rice kernel, that the former features a crease while the latter does not, required different approaches to milling that fundamentally altered the respective technological evolution of Western and Eastern civilisations.

Through direct consumption and indirectly via animal feed, cereals supply more than half of our global food consumption [10]. Around 2 billion tonnes of cereals are produced annually, with wheat, maize and rice each contributing around 600 million tonnes [11,12]. Rice is mostly eaten directly by humans, while wheat and maize are also used as animal feed and increasingly as a feedstock for production of non-food products. Wheat is the most widely grown cereal and the most extensively traded internationally [9,13,14] and has had the greatest impact on the history of the human race, both in ancient times and in recent centuries and decades [15]. The milling of cereal kernels, in particular wheat kernels, to release their multi-functional potential is an industrial activity that underpins all human society.

This chapter describes how the flour milling process interacts with the wheat kernel structure to separate it into its functional components. It traces briefly the historical development of flour milling technology leading to the introduction of roller mills a century ago, introducing the themes of wheat hardness, bread quality and the international grain trade that brought about modern flour milling and dominate its practice still. The initial breakage of the wheat kernels is the most critical operation in flour milling; the development of mathematical models to predict breakage based on the distribution of kernel characteristics in the feed is reviewed. Finally, kernel breakage is considered in the context of fractionation and bioconversion to produce non-food products as a renewable and sustainable alternative to oil.

2. THE STRUCTURE OF THE WHEAT KERNEL

Understanding the flour milling process begins with understanding the structure of the wheat kernel. Figure 2 illustrates the structure of the wheat kernel, which is generally around 4–10 mm in length and consists of three major parts: the germ, the endosperm and the bran [16–18]. The germ comprises around 2.5–4% of the kernel, the bran around 14–16%, and the endosperm around 81–84%. The oil-rich germ is the baby plant, consisting of an embryonic axis which includes a rudimentary shoot and root and the scutellum which serves as a storage, digestive and absorbing organ. The endosperm is the storage reserve for the nutritional needs of the germinating plant until it emerges from the soil and is able to begin photosynthesising its food needs. The endosperm is therefore rich in starch and protein, for energy and construction needs, respectively. These nutritious components are also valuable for other living organisms including humans, animals, insects and microorganisms. For this reason, the germ and endosperm are

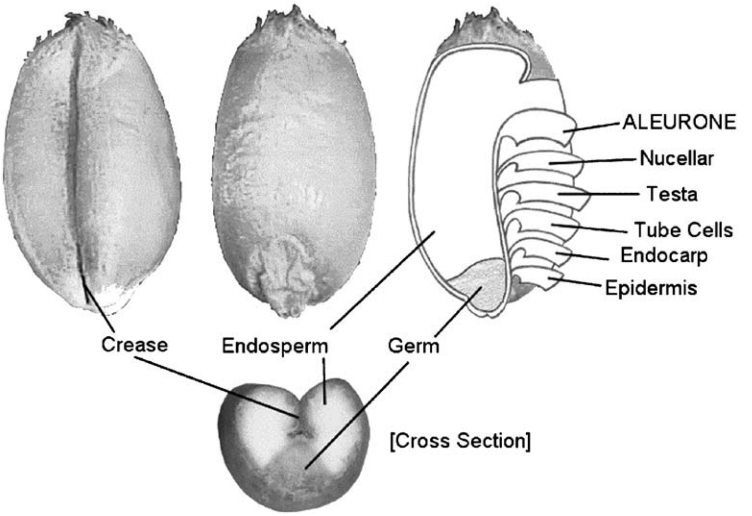

Fig. 2. Illustration of the wheat kernel, showing the germ, the endosperm, the layers making up the bran and the crease.

covered with several protective layers known collectively as bran (a milling rather than a botanical term), which provide a physically tough barrier to intrusion. While the physiological benefits of bran are now widely recognised, it is nutritionally poor in comparison with endosperm. Wholemeal flour also has poor storage properties in comparison with white flour and produces less appealing bread. The purpose of flour milling is therefore to break open the wheat kernel and separate its structural components in such a way as to recover as much endosperm as possible, as free as possible from contamination with bran and germ, at minimum cost. Pure white flour can be obtained by accepting a low yield (extraction), but as endosperm extraction rates approach the theoretical maximum of 81–84%, the flour becomes increasingly contaminated with bran. The economics of flour milling are therefore dictated by the balance between yield and quality, with the skill of the miller measured in terms of the amount and purity of white flour that he can produce.

Figure 2 also illustrates the distinctive anatomical feature of wheat kernels that makes the goal of recovering pure white flour such a challenge – the crease. The crease is a deep furrow that runs the length of the kernel and extends the bran layers deep into the kernel. The rice kernel, by contrast, does not exhibit a crease, and bran and germ can be removed simply by polishing, such that rice endosperm is eaten in a pure and intact form. (Of the other major cereals, barley, oats and rye also feature a crease, while maize kernels and the spherical kernels of sorghum and millet do not have a crease.) The presence of the crease in the wheat kernel means that milling of wheat to separate bran from endosperm ultimately requires breaking open the kernel.

While several of the cereals have kernels that exhibit a crease, wheat is unique in one respect. Wheat flour alone has the ability to form a dough that is able to retain fermentation gases to produce a raised, highly aerated and palatable loaf of bread. This unique ability arises from the gluten proteins of wheat that form on hydration a viscoelastic, strain hardening network that is able to retain inflating gas bubbles [19–23]. (Rye also has gluten proteins and gives some retention of leavening gases, but this ability is vastly inferior to that of wheat and insufficient to challenge wheat's claim of uniqueness is this respect.) The desirability of raised bread (enhanced by the mysterious nature of the leavening process) has been a major socio-economic factor that has influenced trade, technology, religion and politics for centuries, and continues to do so [7,8,23–26]. Bread can therefore rightly be ascribed the status of the world's most important food, and the reason that wheat is the world's most important cereal. The light and palatable texture of raised bread is so appealing, and the raising process so amenable to the creation of a great and diverse range of distinctive breads, that even if wheat did not exhibit a crease, it would still be milled into flour and turned into bread.

A further feature to note from Fig. 2 is the aleurone layer, a single layer of cells that almost completely surrounds the starchy endosperm and the germ, separating them from the outer bran layers. Botanically, the aleurone layer is part of the endosperm, serving to provide starch-degrading enzymes during seed germination, but during conventional milling the aleurone layer adheres strongly to the outer bran layers and is therefore removed as a part of the bran [17,27–29]. The aleurone layer is rich in protein (although this protein, unlike gluten proteins, is non-functional with respect to breadmaking) and in vitamins and minerals. Its inclusion in flour can increase milling yield and the nutritional quality of the flour; millers aim as much as possible to recover aleurone material without also causing bran to enter the flour.

Flour quality is often indicated by measuring the ash (mineral) content of the flour. Ash levels are higher in bran than in endosperm, so ash levels in flour indicate the degree of undesirable bran contamination [27,29]. However, it is increasingly recognised that aleurone material is particularly high in mineral content but does not have negative consequences on flour colour or functionality and indeed is nutritionally beneficial [27,28]. The value of ash measurements has therefore been questioned, and the use of image analysis to quantify dark bran specks in flour is being increasingly adopted [27].

3. THE INTERNATIONAL DEVELOPMENT OF MODERN FLOUR MILLING

The history of flour milling is a story of innovative incremental development over millennia to develop increasingly sophisticated technologies to break wheat kernels and separate the endosperm material from the bran and germ, efficiently and where and when needed, in order to supply the nutritional and social underpinnings of societies throughout Western civilisation. Its importance in earlier times and still now cannot be overrated. Storck and Teague [30] observe ‘‘In these two operations the story of milling … begins: the breaking up of cereal grain seeds, [and] the removal from the resulting meal of the unwanted portions … The story … is of how we men have learned to do these tasks better and better, devising improved tools and new skills as time passed; enlisting the forces of nature to help us; enlarging our mechanical arts and our mental capacities as we struggled with the twin problems of increasing the quantity and improving the quality of our product; adopting new ways of life, forming new social organizations as a result of a growing dependence on this increasing food supply. There is no other single thread of development that can be followed so continuously throughout all [Western] history, and none which bears so constant a cause-and-effect relation to every phase of our progress in civilization.’’

While separation of the distinct parts of the broken grain (originally by hand, later by sifting and air classification) is an integral operation, the breakage aspect of the processing of wheat kernels into flour dominates, such that ‘‘milling’’ refers to the entire process as well as to the specific operations of breakage. The

Fig. 3. Wooden figure of a woman grinding grain, from Egypt, *ca*. 2300 BC. Figures like these were placed in tombs to ensure an eternal supply of food. Printed with permission from The Manchester Museum.

technology of breaking wheat, from prehistory to the current time, moved from pounding grains between two stones to saddlestones (illustrated in Fig. 3), slab, push and lever mills, the more sophisticated hourglass mill introduced by the Greeks and leading to the more long-lived rotary quern, eventually scaled up to the millstones of sufficiently recent history to be familiar to us still (and even now serving a small but growing specialist market), and mechanised over time via water, wind, steam and electrical power [24,31]. Then, in the late 1800s a revolution occurred in milling with the rapid introduction and adoption of roller milling technology. The timing and success of this transformation are attributable to an intricate combination of agricultural, social and technological circumstances occurring principally across three countries, Hungary, America and Britain. The story of this revolution bears re-telling briefly here (based on Storck and Teague [24], Morgan [7] and Jones [31]), as it introduces the fundamental themes of gradual reduction, hardness, global trade and feedstock variability that underpin an appreciation of the nature and significance of wheat breakage.

Wheats are broadly divided into soft, hard and very hard, the former two arising from common wheat (*Triticum aestivum*) and suitable for bread and biscuit making, the latter describing durum wheat (*Triticum durum*) and being the wheat of choice for pasta making. Wheat kernel hardness is a genetically determined factor, but is also influenced by growing environment and agronomic practice [32]. Wheat hardness therefore exhibits a continuous spectrum rather than sharp transitions. Millstones (illustrated in Fig. 4, typically 1.5 m in diameter and operated in pairs) are adequately suited to grinding soft wheats, which tend naturally to break such that bran material remains as large fragments while endosperm

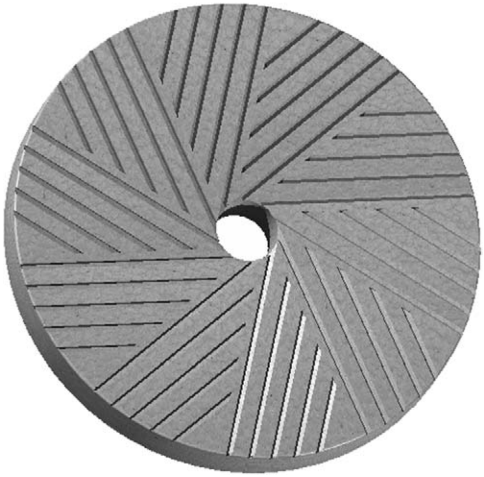

Fig. 4. Illustration of a millstone.

shatters into small particles, facilitating separation of bran from endosperm by sifting. By contrast, the bran and endosperm layers of hard wheats tend to break together, such that separation of bran from endosperm is difficult. Hard wheats tend to give flour with better breadmaking properties, but in the less affluent past, the absence of sufficient markets for excellent bread flour and the difficulty of milling hard wheats using millstones combined to favour the production and processing of soft wheats and the consumption of, to the modern palate, rather inferior bread.

While the traditional millstones were generally operated as a single pair, over time the benefits of repeated milling and sifting using a sequence of millstone pairs were recognised. This ‘‘gradual reduction’’ approach developed first in France from the 16th century and became known as the French system or *mouture économique*. The concept was taken further in the 1800s by Austrian and Hungarian mills to create the *mouture en infini* (milling to infinity) system. This was an incredibly complex and labour-intense arrangement involving more than 80 intermediate product streams manually conveyed between operations by scores of men. It yielded more than 10 final products of varying quality, of which the finest was a flour whiter than had ever been previously experienced. Such a system was only conceivable in the highly stratified Hungarian society, which gave ready markets for such a refined product and at the same time for the entire portfolio of lower quality flours produced elsewhere in the process. It was also only applicable to the hard wheats typical of that region that could withstand the harsh treatment. In time, this superior flour production developed into a lively export market that reached as far as England, raising the bar for the expectations of bread quality obtainable from the miller’s product.

Meanwhile, in the more egalitarian and expanding American population, production efficiency to supply a single grade of product to a mass market, rather than differentiation of flour quality to serve different social classes, was the driver for technological innovation. The American contributions to the development of flour milling technology were therefore the introduction of automation within flour mills, initially by Oliver Evans, along with scale-up and advances in particle separation systems based on improved sifting and air classification. The latter advances also facilitated the processing of hard wheats and encouraged increased planting of these varieties by American farmers.

America was becoming the breadbasket of Britain, with the continent's rapid settlement driven in large part by the need back in Britain for wheat and flour. Morgan [33] notes: "At the end of the eighteenth century a human need … developed on a scale that had never been experienced before in history. That need was for bread … Workers in Paris, London and Manchester in 1800 paid half their wages for bread alone. Eating bread was a badge of attainment and social status. Once achieved, it was not easily given up, as governments invariably found when they took administrative measures to lower the quality of bread to conserve wheat. It was no coincidence that the century in which bread eating finally extended downward to all elements of society in Western Europe … was also the century of revolution … An adequate wheat supply was, therefore, a prerequisite of social order and political stability."

By the late 1800s Britain had initiated the Industrial Revolution and was at the height of Empire. Its need for wheat to feed the growing and increasingly urbanised population was having dramatic influences globally. "Parliament, with its stroke of repeal [of the Corn Laws in 1846], had changed the world. Repeal of the protectionist system had opened England to the wheat of all the world, created incentives for the settlement of vast territories across the oceans, and established the conditions for modern international trade"[34]. The British climate suits the production of soft wheats, while the imported hard wheats and flours tended to be better suited to breadmaking. This cultivated in the public a taste for the superior breads and added to the pressure on millers to obtain foreign wheats and process them, with all their variability, into consistent quality flour. As a result, as Jones [35] observes, "One essential for success in Britain was the production of high yields of good quality flour from mixtures of different wheats, with the added difficulty that the resources varied through the cereal year. The British situation was unique in the requirement to deal with varying characteristics of the material to be processed; Hungarian and American millers had comparatively uniform raw materials."

The gradual reduction approach using millstones was partially successful in processing the hard wheats of Hungary and increasingly of America and of Britain's imports, particularly when combined with air classification to separate flour stocks. However, the problems of processing the increasingly prevalent hard wheats prompted the successful invention in Hungary of an alternative approach to open up the wheat kernel, using roller mills. Thus, the revolution that was to replace millstones wholesale with rollers was driven by the push resulting from the availability of hard wheats and the need to process them, combined with the pull of increasing markets for the excellent breadmaking flour that hard wheats, suitably processed, can yield.

The new Hungarian innovation was adopted enthusiastically across Europe and particularly by British millers. This was because, in addition to allowing milling of hard wheats, the roller mills offered great advantages over millstones in terms of versatility and control. Thus, roller milling helped the miller address the particularly British problem of wheat variability and thus to deal at a practical level with Thomas Malthus's observation a century earlier that ‘‘No two grains of wheat are exactly alike’’ [36].

4. ROLLER MILLING OF WHEAT KERNELS

Manchester in the UK, Minneapolis in America and Budapest in Hungary can all lay claims of similar validity for the first installation by about 1880 of a ‘‘modern’’ flour mill, judged by three defining factors [37]: the use of the gradual reduction approach, full automation, and the complete displacement of millstones by roller mills. From its invention in 1873, the roller mill triumphed rapidly over millstones, such that by the turn of the century the revolution was essentially complete. The factors of wheat hardness, international grain trade and bread quality that gave rise to its birth are still those that dominate the practice of flour milling today.

As noted above, rollers gave the miller vastly superior control over the process compared with the less precise and more temperamental behaviour of millstones, thereby facilitating the processing of a great variety of wheats of widely varying characteristics. The versatility of the roller mill arose in several ways: the roll gap could be adjusted, rolls could be operated at different relative speeds to give a differential cutting action, different roll surfaces and fluting profiles could be used and successive roll pairs could be arranged in a variety of configurations. Nevertheless, the miller's first obligation remained: to produce flour of consistently uniform quality, day after day and year after year, in the face of a constantly changing feedstock. In this respect, the very versatility of the roller mill was also its greatest challenge, as small changes in its operation could severely disrupt the intricate balance of downstream processes and hence the final flour quality.

Figure 5 illustrates a typical modern flour milling process flowsheet employing the gradual reduction system using, in this example, 16 roll pairs with accompanying sifters. (Wheat flour milling is a dry process that produces an impure starch-rich product, in contrast to the wet milling process used to process maize into

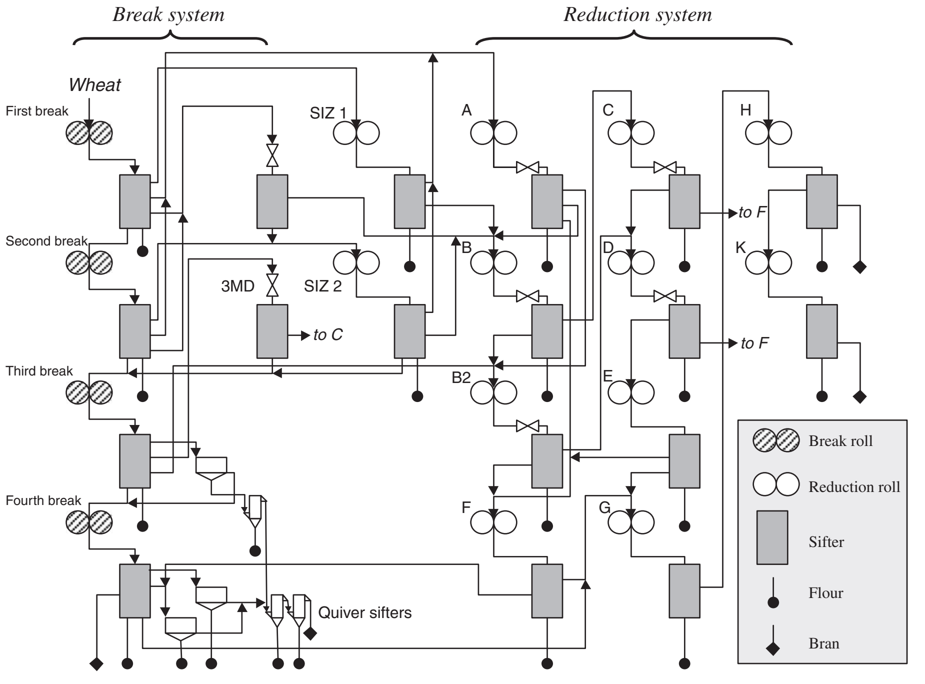

Fig. 5. Typical flour milling flowsheet with four break rolls. Reprinted with permission from [38].

cornflour, which is pure starch and much more expensive than flour.) The process can be broadly divided into the break and reduction systems. The break system uses fluted rolls of increasingly fine fluting to break open the wheat kernel and to scrape the endosperm material from the bran. Some flour is produced at each stage, while the larger endosperm material is sent to the reduction system for further grinding and bran and germ separation. In this example, flour (endosperm material smaller than about 212 μm) is produced at 21 different points in the mill. The quality of flour recovered from each different stage varies [29]. The flour is usually combined into a single composite product, the quality of which depends on the proportions and characteristics of the various daughter flours.

Figure 6 illustrates a roller mill, with each roll typically around 1 m in length and 250 mm in diameter. Break rolls are fluted, as illustrated in the figure, while reduction rolls have a smooth, slightly frosted surface. Break rolls are fluted with an asymmetric saw tooth profile and operate with a gap between the rolls and under a differential (i.e. ratio of fast roll speed to slow roll speed) of about 2.5:1. Operating the rolls under a differential reduces the energy consumption [39]. The fluting breaks open the wheat kernel such that the bran tends to stay relatively intact in large particles, while the endosperm shatters into small particles, facilitating the separation of endosperm from bran by sifting. Reduction rolls are smooth and

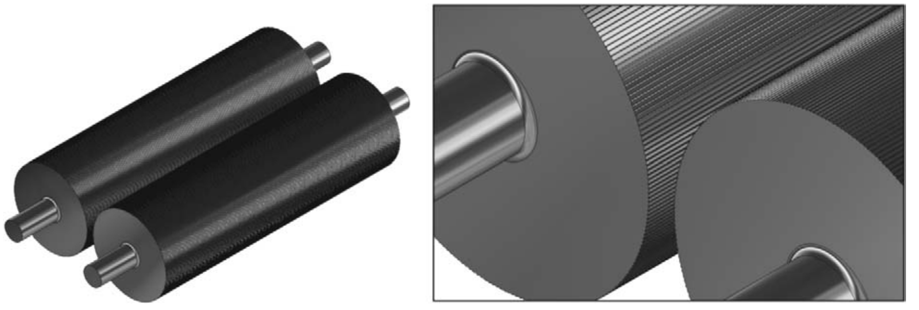

Fig. 6. Illustrations of roll pairs from the flour milling break system.

operate under pressure at lower differentials of about 1.25:1. This causes damage to starch granules and thereby affects the water absorption properties and baking performance of the flour; the degree of starch damage in the composite flour is therefore one of the factors that the miller must control.

The introduction of roller mills in the late 1800s was accompanied by a frenzy of experimentation to establish the best roll designs and operational characteristics, particularly of First Break. Eventually this converged on a saw-tooth break roll profile with a sharp leading edge followed by a flat ‘‘land’’ and a dull following edge, which gives a cleaner cutting action than rounded profiles. The precise angles and depths of the sharp and dull edges and the lengths of the land portions are matters of variation and distinction between different roll manufacturers. In addition, the flutes exhibit a slight twist or spiral along the length of the roll, such that the roll pair imparts a scissor-like cutting action on the wheat kernel or the later part-broken stocks.

The asymmetric saw-tooth profile of the break rolls and the speed differential between them allow the rolls to be operated under different dispositions: sharp-to-sharp (S-S), sharp-to-dull (S-D), dull-to-sharp (D-S) and dull-to-dull (D-D). Figure 7 illustrates the fluting profile and the four possible dispositions. Over time flutes become worn and rolls must be reground, such that frequently a roll pair will be operated D-D initially, then changed progressively as the rolls wear to D-S, S-D and finally S-S, to try to keep the breakage patterns relatively consistent over time.

Returning to Fig. 5, it is immediately evident that the particle size distribution produced from First Break, the first roller milling operation that the wheat encounters, determines the balance of stream flows through the rest of the milling process. First Break is therefore a critical control point in milling, the importance of which cannot be overstated [40,41]. To a first approximation, if the miller could maintain a constant particle size distribution from First Break in the face of a constantly changing feedstock, the rest of the mill would run more or less consistently. The detailed study of particle breakage within flour milling has therefore focussed thus far almost exclusively on First Break.

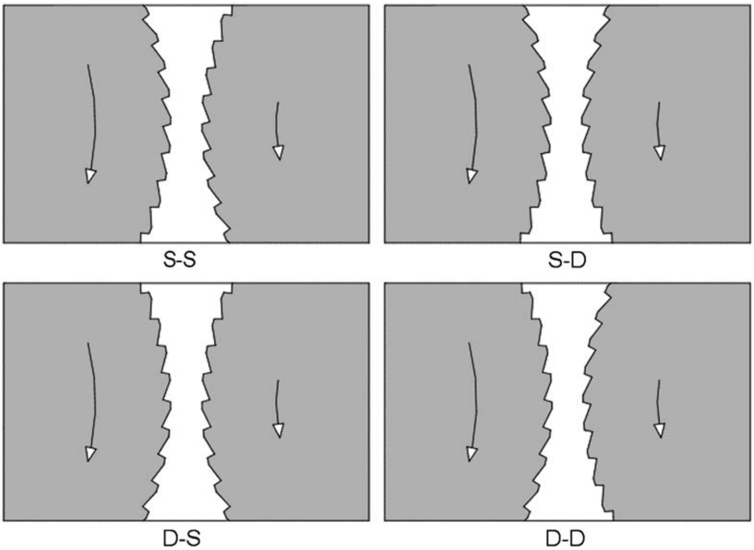

Fig. 7. The four possible break roll dispositions: sharp-to-sharp (S-S), sharp-to-dull (S-D), dull-to-sharp (D-S) and dull-to-dull (D-D).

4.1. Grist to the mill

The "golden rule" of the flour miller is to maintain consistent flour quality, as consistency of raw materials is the baker's number one priority. In pursuing this goal, the major tool employed by the miller is blending of different wheats together, known as gristing [41–44]. Pyler [45] highlights this emphasis on consistency and the contribution that gristing makes: "This is a vital operation … since correct blending of wheats constitutes the basis for the uniformity of flour performance in the bakery." Typically, at least half a dozen wheat varieties of widely differing origins and characteristics will be mixed together to give the desired flour quality at least cost. Milling the wheats separately and blending the final flours has considerable merits, and some millers have invested in the necessary facilities and benefit from fewer grist changes to enable a "just in time" response to customer orders (B. McGee, personal communication). However, in practice it is easier to blend wheat than flour, so most millers grist prior to milling [46].

The practice of gristing exacerbates the problem of wheat variability entering First Break and of maintaining consistent performance from the mill in terms of flour yield and functionality. The latter depends not only on composition, which is easily controlled through gristing, but also on the different processing histories of the daughter flours from the different parts of the mill that are combined into the final composite product. These histories depend on the grist's initial breakage characteristics, which determine the proportions of streams flowing through the different parts of the rest of the mill, described by Storck and Teague [47] as ‘‘that great desideratum, the balance of the mill.’’

In addition to gristing, the second major tool for altering flour quality by adjusting the feedstock is conditioning (or tempering) [48–51]. Conditioning is the controlled addition of water (and/or heat) to the wheat to alter its breakage characteristics. Wheat can be stored almost indefinitely provided its moisture content is maintained below about 14% (wet basis). However, when it comes to milling the wheat, it is preferable to raise its moisture content to about 16%. This has the effect of toughening the bran while making the endosperm more friable, such that the bran tends to stay more intact as larger particles, while the endosperm shatters more readily into smaller particles. Hence, conditioning facilitates the separation of bran from endosperm based on size. Conditioning also compensates for moisture loss during handling and pneumatic conveying of flour stocks, thereby maintaining the moisture content of the final flour. Once again, the peculiarities of flour milling in Britain have given rise to a unique mastery of conditioning practice: as Storck and Teague [52] observe, ‘‘Under stress of necessity English millers have learned … to alter [wheats’] character by removing or adding moisture or heat. The Englishman uses this conditioning constructively to improve the strength and baking quality of the flour, prescribes special forms of treatment suited to individual wheats, makes mill mixes out of a half-dozen or more kinds of wheat drawn from all over the globe according to price and what they can contribute to his flour, and in general is a versatile master of the possibilities of diverse wheats.’’

5. KEY ISSUES IN MILLING OF WHEAT

Milling wheat into flour for human consumption is a mature industry that operates on highly efficient processes at low economic margins. The key issue is how to process a variable feedstock to produce a consistent quality product economically.

However, in the 21st century, cereal milling will increasingly be applied to meet a new challenge, that of supplying and processing a renewable feedstock that can provide the energy and chemical needs of society [53–55]. Oil, on which the enormous technological and social strides of the 20th century were based, is a finite resource and increasingly recognised as so, as reflected in increasing prices and the regular featuring of oil concerns in scientific pronouncements and government initiatives. In addition, oil processing and consumption is a source of pollution and environmental hazard, including the production of greenhouse gases and their contribution to global warming. For these reasons, there is an urgent need to find renewable alternatives to oil to supply the energy and material needs of modern society. This need is urgent for at least three reasons: (i) to address the pollution problems inherent in oil usage; (ii) to ensure finite oil supplies are conserved for as long as possible; and (iii) to ease the transition from an oil-profligate to an oil-depleted global village. And in terms of production levels, chemical density, infrastructure and ease of processing, cereals present themselves as the most promising candidate to form the basis of a sustainable chemical industry. In the UK, of the 22 million tonnes of cereals produced annually, wheat contributes 14–15 million tonnes and is the UK's largest crop [56]. A sustainable UK chemical industry based on benign processing of renewable feedstocks is likely to be dominated, at least in the medium term, by wheat.

At present, the economics of cereal processing for non-food uses are generally unfavourable compared with oil. With increasing oil prices, in time the economics will become favourable, but as noted above, there is an urgent need to develop technologies and approaches to accelerate the economic feasibility of cereal-based products. To meet this need, the concept of the cereal biorefinery, analogous to oil refineries in co-producing a range of added value products from cereals, is the way forward. In order to make cereal biorefineries economic, the key issue is to maximise the value that can be extracted from every last component of the cereal grain. Again, analogous with oil refining, the necessary approach is one of fractionation followed by extraction and/or conversion into added value products.

In both conventional flour milling for human food and novel wheat (or other cereal) processing for non-food products, the key issue is fractionation of the grain into its compositionally distinct structural components prior to further processing of each component. Thus, breakage of the wheat kernel is critical, particularly the initial breakage which determines the subsequent processing.

6. BREAKAGE OF WHEAT KERNELS DURING FIRST BREAK ROLLER MILLING

Hardness is, as implied in the foregoing discussion, a major aspect of wheat quality and, not unexpectedly, a major factor affecting breakage [32]. Pomeranz and Williams [57], in a comprehensive survey of wheat hardness research up until 1990, note ‘‘Kernel texture is the most important single characteristic that affects the functionality of a common wheat … a parameter of great significance in both the wheat and flour industry and in domestic and world trade [that] affects every aspect of wheat functionality except gluten strength and its associated factors.’’

Numerous hardness tests have been developed over the last century, broadly divided into the power or time required to grind a sample to a given particle size, or the particle size resulting from grinding a sample under standardised conditions. These are empirical tests that give relative rather than absolute indications of wheat kernel hardness. Pomeranz and Williams note that over 100 different methods for measuring wheat hardness have been documented [57]. Near-infrared reflectance (NIR) spectroscopy of wheat samples milled under standardised conditions is the most common method currently used for measuring hardness. The Stenvert test, measuring the time to produce a given volume of flour through a 2 mm screen mesh using a standardised hammer milling procedure, has also been widely used [57–59]. Hardness tests are mostly applied to bulk samples of wheat, reporting an average hardness value for the sample. In recent years, however, the trend has moved to the measurement of the hardness of each individual kernel in a sample and the reporting of the entire distribution of hardness values. The most well developed commercial example of this wheat testing philosophy is the Perten Single Kernel Characterisation System (SKCS), developed by the USDA Research Centre and commercialised by Perten Instruments, Sweden. The SKCS crushes usually 300 individual kernels within 5 min and reports the distributions of their hardness values, along with the kernel weight, diameter and moisture content distributions [32,60–66]. The challenge remains to relate these distributions of kernel characteristics to milling performance and flour quality.

Breakage of wheat kernels during First Break roller milling depends on the characteristics of the wheat (including the distributions of kernel size, hardness and moisture content) and on the design and operation of the roller mill (including roll speeds and differential, roll disposition, fluting profile, number of flutes, fluting spiral, roll gap, the degree of roll wear and the feed rate). The effects of these factors are manifest in the particle size distribution exiting First Break, the compositional distribution of those particles (as large particles tend to be richer in bran, while small particles are pure endosperm), the power required to mill the wheat and the rate of roll wear. Figure 8 illustrates these interrelationships.

Work in our laboratories has introduced the breakage equation for First Break roller milling of wheat, based on the paradigm of flour milling as “the evolution of the particle size distribution.” Previous work on wheat breakage has tended not to focus so strongly or quantitatively on the particle size distribution, preferring to report break releases (the amount of flour produced by individual break rolls) or, if straying into attempts to apply fracture mechanics to wheat breakage, stresses on the wheat kernel or its components under slow uniaxial compression or tension [67–73]. The breakage equation approach offers a practical basis for relating the distributions of single kernel information measured by the SKCS to breakage during First Break and hence for relating wheat variability to initial breakage patterns and their consequences for mill balance and flour yield and quality.

The breakage equation for roller milling of wheat kernels in terms of the size of the input and output particles is given in its cumulative form by

$$P_2(x) = \int_{D=0}^{D=\infty} B(x, D)\rho_1(D)\,\mathrm{d}D \tag{1}$$

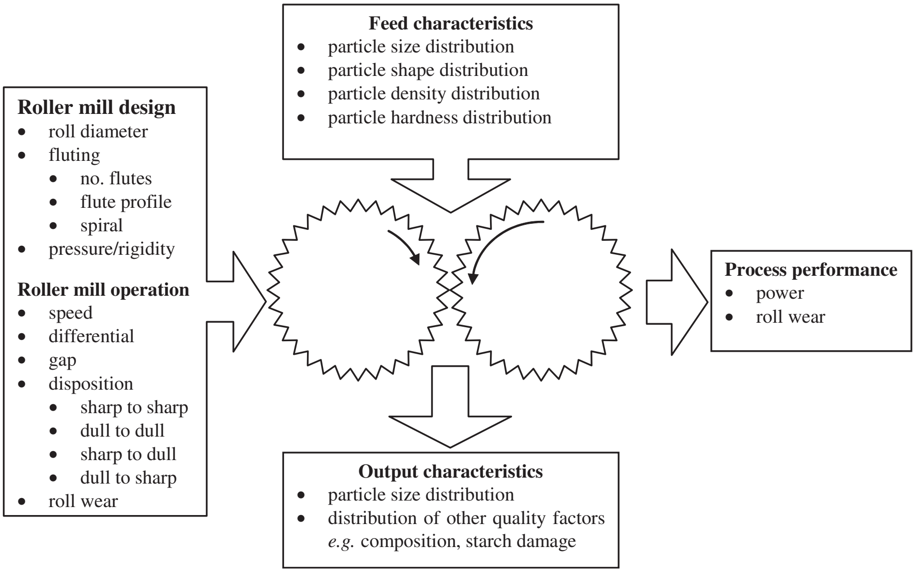

Fig. 8. Feed, design and operational factors affecting particle breakage during First Break roller milling of wheat. Reprinted with permission from [74].

where $\rho_1(D)$ is the particle size distribution of the feed entering the roller mill, $P_2(x)$ the cumulative particle size distribution of the output, and $B(x,D)$ the cumulative breakage function describing the proportion of material smaller than size x in the output, originating from an input particle initially of size D.

Campbell *et al.* [41] explain that, in contrast with similar breakage equations for once-through milling operations such as those reviewed by Austin [75], the lower limit of the integration in equation (1) is $D = 0$ rather than $D = x$. The reason is that D and x are measuring different things and are not directly comparable. D is kernel thickness as measured by the SKCS (or by image analysis or using slotted sieves), while x is the smallest square aperture through which a particle will pass, as measured by sieve analysis. It is therefore meaningless in this context to write $D = x$. Previous workers studying breakage have performed the integration from $D = x$ on the basis that they were measuring the size distributions of their input and output material in the same way, e.g. using the same sieve analysis procedure. They therefore argued that the breakage process implied that output particles of size x could only have arisen from inlet particles originally larger than x, a reasonable argument that simplifies the mathematics. However, this approach renders the breakage equation less general and less flexible, by excluding the possibility that inlet and outlet particles might be measured differently, and that the particular dimension chosen to characterise an outlet particle size might be larger in magnitude than the dimension used to characterise the size of the original inlet particle. In the case of wheat, the roller milling process tends to open up the initially compact wheat kernel to create large bran flakes along with finer endosperm material. Thus, it is quite possible for a kernel, initially of 2 mm diameter, to yield a bran flake measuring 3 mm across when measured by sieve analysis. Hence, the appropriate range for the integration in equation (1) is from zero to infinity.

Campbell and Webb [76] also discuss the issues of selection functions and normalisation that feature strongly in other breakage equations but that are, in our view, inappropriate or unnecessary for a breakage equation describing First Break roller milling of wheat kernels. First, all wheat kernels are broken during First Break, so there is no concept of selection. The notion of a selection function has arisen in previous work from the observation that following breakage, some outlet material is still of the same size range as the inlet material, implying that a portion has not been selected for breakage. However, in wheat breakage, even if some of the outlet material is of the same ‘‘size’’ as the original inlet material, the sizes are, as noted above, not actually comparable physical entities. Second, much of the literature on breakage functions assumes that normalised functions apply, in which the daughter distribution scales directly with inlet particle size, implying that larger inlet particles break to give larger outlet particles. In roller milling, the finite size of the gap between the rolls requires more breakage for a larger kernel to pass through than for a smaller one, such that the output particles resulting from breakage of a large wheat kernel are smaller than those resulting from breakage of a small kernel. Thus, the common concepts of normalisation and selection that are applied to other breakage processes are inappropriate for describing roller milling of wheat. Some may argue that the relationship between inlet and outlet particle size distributions for roller milling of wheat could indeed be modelled using repeated selection within the breakage zone of the roll pair, with normalised breakage functions describing each breakage event. However, in our view this introduces unverifiable assumptions about the details of the wheat kernel breakage process (such as the number of separate breakage events occurring during a single passage through the roll pair, and the appropriate normalised function to apply on each occasion).

Campbell *et al.* [74] derived the form of the breakage function that describes the particle size distribution resulting from breakage of an individual wheat kernel as a function of kernel size and roll gap, from which the breakage of a mixture containing a distribution of kernel sizes could be predicted. This work showed that wheat kernel breakage is determined by the ratio of roll gap to kernel thickness (the third longest dimension, which equates to the diameter reported by the Perten SKCS), called the milling ratio, G/D. This work also led to the important conclusion that underpins the breakage equation, that wheat kernels break independently during roller milling, such that a small, hard kernel will break as a small, hard kernel even if it is surrounded by large, soft kernels, and vice versa. Bunn *et al*. [77] demonstrated that this form of the breakage function was adequate for a wide range of wheat varieties. Fang and Campbell [78] investigated the effect of the four roll dispositions on the breakage function, and Fang and Campbell [79] added a term to account for kernel moisture content as well as size, thereby accounting for two of the four SKCS parameters. Campbell *et al*. [41] completed the work by extending the breakage function to include SKCS hardness and investigated the possibility of adding the fourth SKCS parameter, kernel mass, in order to allow for the effects of kernel shape on breakage.

Based on Fang and Campbell [78] and Campbell *et al*. [41], an empirically determined cumulative breakage function cubic in x and quadratic in G/D is appropriate to describe breakage under S-S, S-D, D-S and D-D roll dispositions:

$$\begin{aligned} B(x, D) = {} & a_0 + b_0 x + c_0 x^2 + d_0 x^3 \\ & + (a_1 + b_1 x + c_1 x^2 + d_1 x^3)\left(\frac{G}{D}\right) \\ & + (a_2 + b_2 x + c_2 x^2 + d_2 x^3)\left(\frac{G}{D}\right)^2 \end{aligned} \tag{2}$$

leading to

$$\begin{aligned} P_2(x) = {} & \int_{D=0}^{D=\infty} \left[\begin{matrix} a_0 + b_0 x + c_0 x^2 + d_0 x^3 + (a_1 + b_1 x + c_1 x^2 + d_1 x^3)\left(\frac{G}{D}\right) \\ +(a_2 + b_2 x + c_2 x^2 + d_2 x^3)\left(\frac{G}{D}\right)^2 \end{matrix} \right] \rho_1(D)\, \mathrm{d}D \\ = {} & \left(a_0 + a_1 G \overline{\left(\frac{1}{D}\right)} + a_2 G^2 \overline{\left(\frac{1}{D^2}\right)}\right) + \left(b_0 + b_1 G \overline{\left(\frac{1}{D}\right)} + b_2 G^2 \overline{\left(\frac{1}{D^2}\right)}\right) x \\ & + \left(c_0 + c_1 G \overline{\left(\frac{1}{D}\right)} + c_2 G^2 \overline{\left(\frac{1}{D^2}\right)}\right) x^2 \\ & + \left(d_0 + d_1 G \overline{\left(\frac{1}{D}\right)} + d_2 G^2 \overline{\left(\frac{1}{D^2}\right)}\right) x^3 \end{aligned} \tag{3}$$

where

$$\overline{\left(\frac{1}{D^n}\right)} = \int_{D=0}^{D=\infty} \frac{1}{D^n} \rho_1(D) \mathrm{d}D \approx \sum_{i=1}^{N} p_i \frac{1}{D_i^n} \tag{4}$$

N is the number of discrete size fractions into which kernels are separated, and p_i the proportion of kernels in size fraction i. Thus, knowing $\overline{(1/D)}$ and $\overline{(1/D^2)}$ and the 12 coefficients of equation (2) for the particular wheat sample and roll disposition, the particle size distribution of the output from First Break can be predicted for any roll gap.

Figure 9 illustrates the effects of roll disposition and roll gap on wheat breakage, for a typical UK hard wheat, Hereward, and a typical UK soft wheat, Consort. Under S-S milling, the particle size distribution is relatively even over the size range 200–2000 μm, with larger roll gaps tilting the balance towards larger particles. Moving through S-D and D-S through to D-D milling, the particle size distribution becomes progressively more ‘‘U-shaped’’, indicating that D-D milling produces greater proportions of both large and small particles, with fewer in the mid-size range. As the large particles are bran-rich and the small particles starch-rich, this distribution will be easier to separate by size into compositionally distinct fractions for further processing; D-D milling is therefore preferred by millers. As noted above, as rolls wear down, millers may change from D-D to D-S, S-D and finally S-S milling to counteract the effect of roll wear. Fang and Campbell [80,81] analysed the fracture mechanics of wheat breakage during roller milling to explain the effects of roll disposition on the observed breakage patterns.

Figure 10 presents the same data in its cumulative form, to facilitate comparison with predictions based on the breakage equation (the coefficients being derived from independent data). The predictions are in excellent agreement with the experimental data and would give a good first approximation for the breakage behaviour of these wheats.

Fang and Campbell [79] added a correction function to account for the effect of moisture content, to give

$$P(x) = \int_0^{m_{\max}} \int_0^{\infty} B(x, D, m)\, \rho_1(D)\, \rho_1(m)\, \mathrm{d}D\, \mathrm{d}m \tag{5}$$

where m is the moisture content of an individual kernel, and $\rho_1(m)$ the probability density function describing the distribution of individual kernel moisture contents in the sample. Equation (5) assumes that the size distribution and moisture distribution in a sample are independent, i.e. that large kernels have the same moisture distribution as small kernels (or, equivalently, that wetter kernels have the same size distribution as drier kernels). Thus, if the extended cumulative breakage function $B(x,D,m)$ is known, then the outlet particle size distribution could be predicted for any size distribution and moisture distribution of a given wheat sample. They then simplified the cumulative breakage function by separating it into two components, the cumulative breakage function at a nominal moisture content m_0 (say 16%) and a correction term to account for the variation

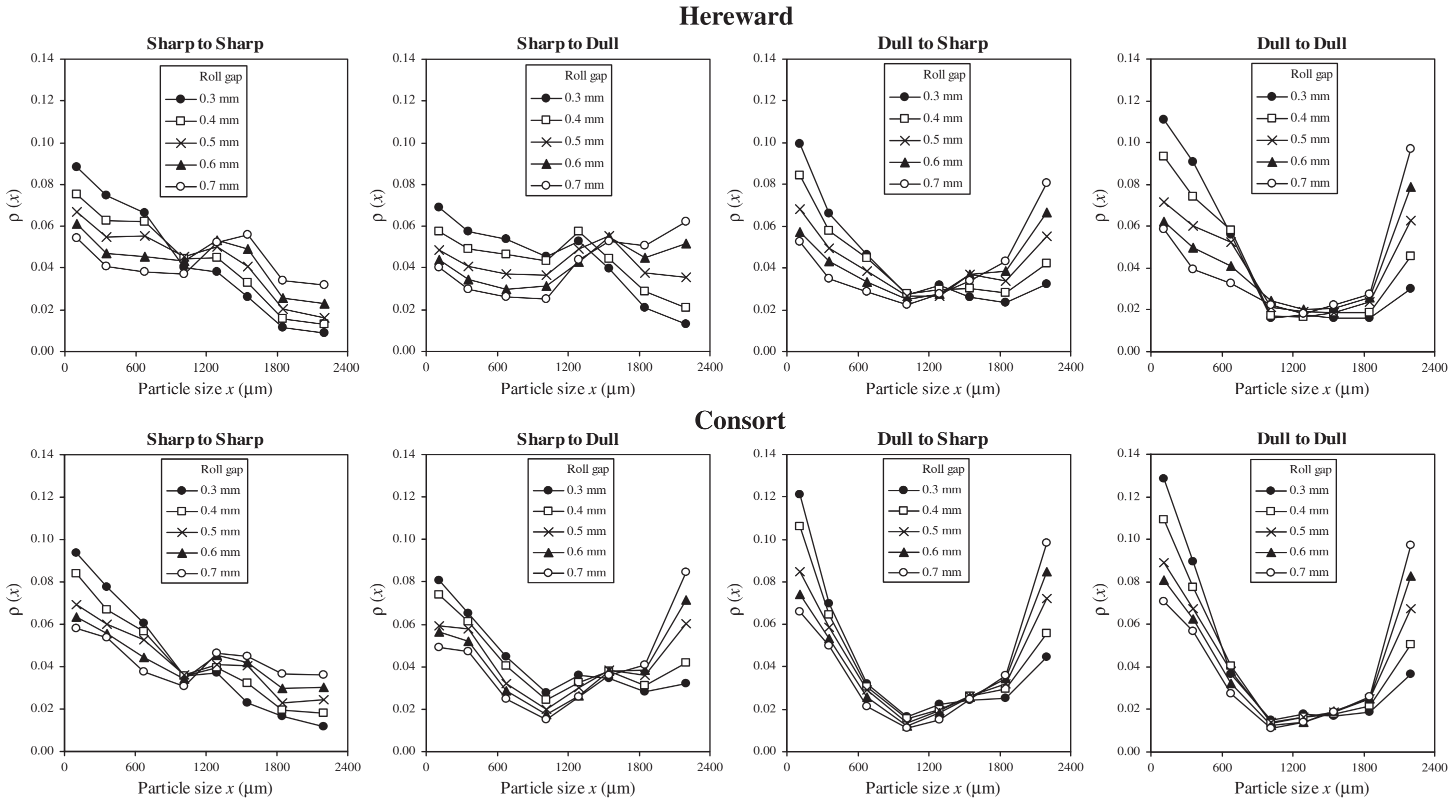

Fig. 9. The particle size distribution resulting from First Break roller milling under four roll dispositions of Hereward (a hard wheat) and Consort (a soft wheat). Reprinted with permission from [81].

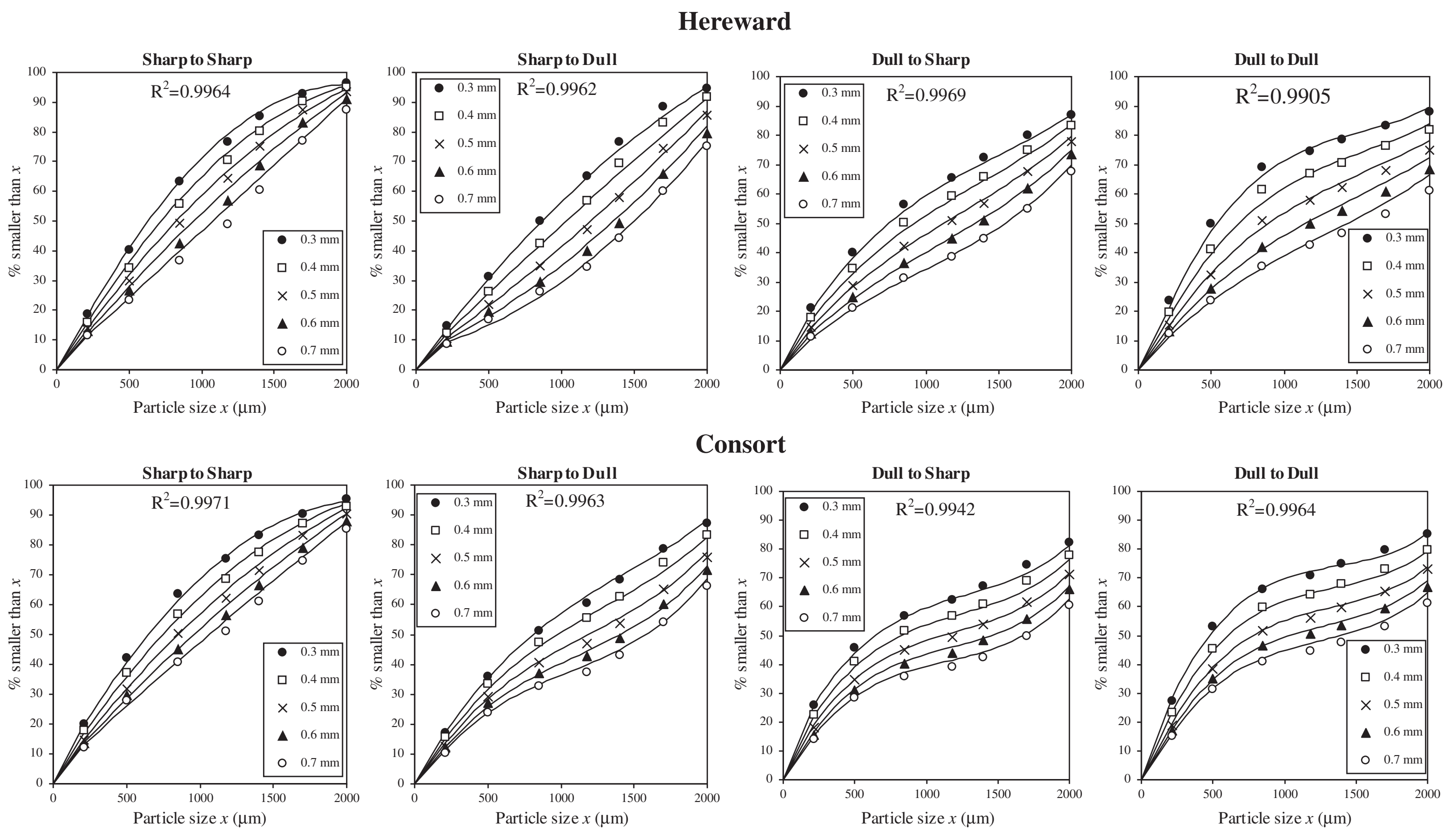

Fig. 10. Comparison between experimentally determined cumulative particle size distributions and predictions based on the breakage equation, for First Break roller milling under four roll dispositions of Hereward and Consort. Reprinted with permission from [78].

in breakage that occurs at moisture contents other than 16%:

$$B(x, D, m) \approx B(x, D)_{m_0} + K(x, m - m_0) \tag{6}$$

leading to

$$\begin{aligned} P(x)_m &= \int_0^{m_{\max}} \int_0^{\infty} \left[B(x, D)_{m_0} + K(x, m - m_0)\right] \rho_1(D) \rho_2(m) \mathrm{d}D \, \mathrm{d}m \\ &= P(x)_{m_0} + \int_0^{m_{\max}} K(x, m - m_0) \rho_2(m) \mathrm{d}m \end{aligned} \tag{7}$$

They found that an equation cubic in x and quadratic in (m−16%) was appropriate to describe the effect of a departure from 16% moisture on breakage of the wheat. This implied that the effect of adding moisture to wheat was to turn an initially inverted "U-shaped" distribution at low moisture contents into a progressively more U-shaped distribution at higher moisture contents. In other words, at low moisture, kernels broke to give a large proportion of particles of much the same mid-range size, with little size distinction, while increasing moisture gave larger proportions of both large and small particles, with fewer in the mid-size range. Figure 11 illustrates this effect of increasing moisture content. As noted above, the main purpose of conditioning (adding moisture to the wheat) is to toughen the bran particles and soften the endosperm, such that the former stay more intact and the latter shatter more readily. The increasingly U-shaped distribution on adding moisture confirms this effect, as large particles are predominantly composed of bran while small particles are essentially endosperm material. The breakage equation with the moisture correction factor allows this effect to be described quantitatively.

The above breakage equations need to be determined for each wheat sample individually, preventing their practical application for predicting the milling behaviour of a grist of several wheat varieties. As noted above, blending wheats of widely varying origins and properties is the major tool employed by the miller to produce consistent flour quality. The ability to predict and control the breakage of today's particular grist during First Break would help the miller to control the performance of the whole mill. When different wheats are blended and milled, it is the differences in their kernel hardnesses that have the major effect on breakage. Campbell *et al*. [41] therefore extended the above work to include, in addition to kernel size and moisture content, the effects of wheat kernel hardness on breakage. They also investigated the effect of the fourth SKCS parameter, mass, which when combined with kernel size can give an indication of kernel shape. This work thereby demonstrated the potential to construct a "universal" breakage

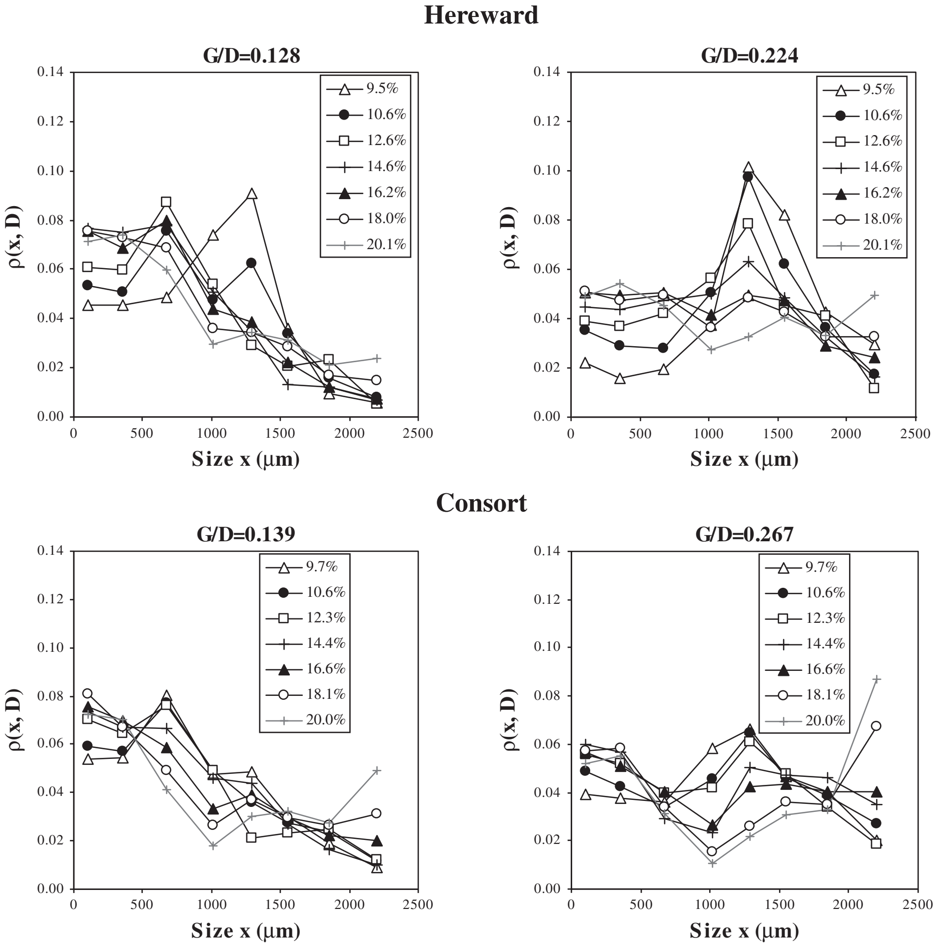

Fig. 11. Effect of moisture content on the particle size distribution of stocks exiting First Break, following S-S milling of Hereward and Consort at different milling ratios.

equation that allows prediction of the breakage of an unknown mixture of wheat kernels directly from SKCS data.

The effect of kernel hardness on wheat breakage could be adequately described by linear functions, leading to an extended breakage equation and function as follows:

$$P_2(x) = \int_{H=0}^{H=\infty} \int_{D=0}^{D=\infty} B(x, D, H)\, \rho_1(D)\, \rho_1(H)\, \mathrm{d}D\, \mathrm{d}H \tag{8}$$

$$
\begin{aligned}
B(x,D,H) = {} & (a_{01} + b_{01}x + c_{01}x^2 + d_{01}x^3) \\
& + (a_{02} + b_{02}x + c_{02}x^2 + d_{02}x^3)H \\
& + (a_{11} + b_{11}x + c_{11}x^2 + d_{11}x^3)\left(\frac{G}{D}\right) \\
& + (a_{12} + b_{12}x + c_{12}x^2 + d_{12}x^3)\left(\frac{G}{D}\right)H \\
& + (a_{21} + b_{21}x + c_{21}x^2 + d_{21}x^3)\left(\frac{G}{D}\right)^2 \\
& + (a_{22} + b_{22}x + c_{22}x^2 + d_{22}x^3)\left(\frac{G}{D}\right)^2 H
\end{aligned} \tag{9}
$$

where $B(x,D,H)$ is the extended breakage function describing the proportion of material smaller than size x produced by breakage of an inlet particle originally of size D and hardness H. Equation (8) assumes that there is no interaction between kernel size and hardness with respect to their effects on breakage; the good agreement between predictions and independent experimental data confirmed the adequacy of this assumption. The coefficients of equation (9) were determined by milling 19 wheat varieties of widely varying hardness at six different roll gaps under both S-S and D-D roll dispositions. For a given roll disposition, knowing the 24 coefficients, the particle size distribution in the range 200–2000 μm resulting from breakage of an unknown mixture of wheat kernels varying in size and hardness, at any roll gap in the range 0.3–0.8 mm, could be predicted directly from the distribution of SKCS characteristics. Figure 12 illustrates the good agreement between the cumulative particle size distribution

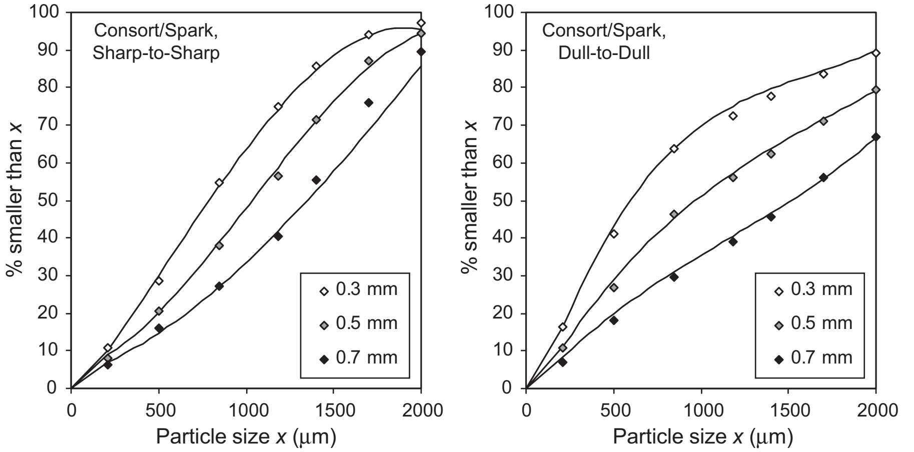

Fig. 12. Comparison of predicted (lines) and experimental (symbols) cumulative particle size distributions for a 50:50 mixture of Consort (a soft wheat) and Spark (a hard wheat) milled at different roll gaps under S-S (left) and D-D (right) roll dispositions. Adapted from [41].

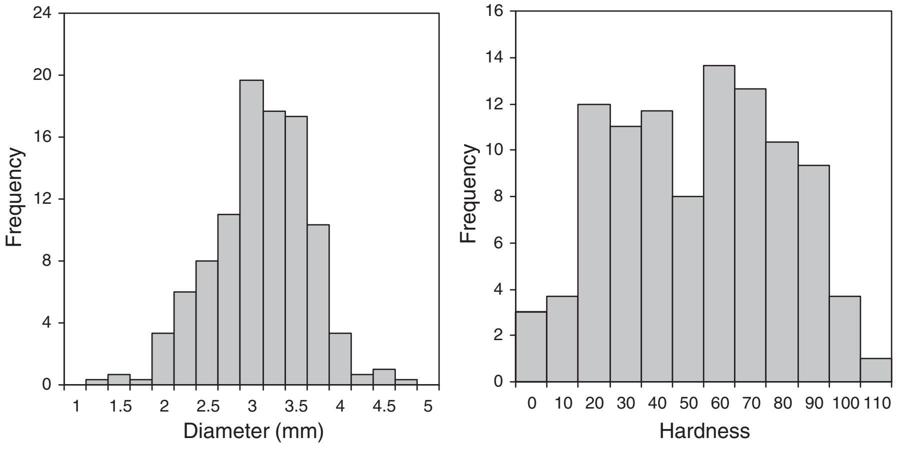

Fig. 13. SKCS hardness distribution for a 50:50 mixture of Consort and Spark. Adapted from [41].

predicted from equations (8) and (9) and that resulting from independent milling of a 50:50 mixture of a hard and a soft wheat variety. Figure 13 shows the SKCS diameter distribution and the bimodal hardness distribution used to predict the breakage of the mixture.

Figures 14 and 15 illustrate the effect of wheat hardness on breakage (with all wheat samples conditioned to 16% moisture prior to milling). Campbell *et al.* [41] present this data and discuss its implications more fully, and also consider the effects of kernel shape on breakage. Briefly, Fig. 14 shows the percentage smaller than *x vs.* average kernel hardness for each aperture size used in the sieve analysis and for selected roll gaps. The fitted extended breakage functions are also shown as solid lines, illustrating the linear effect of kernel hardness on breakage. Under both S-S and D-D milling there is a divergent pattern, such that the percentage smaller than 2000 μm increases with hardness (implying the percentage of large particles decreases), while the percentage smaller than 212 μm decreases with increasing hardness. This demonstrates that soft wheats tend to break to produce relatively larger proportions of both larger and smaller particles, with fewer in the mid-size range, compared with hard wheats which produce fewer particles at the extremes and more in the middle. The divergent patterns are more pronounced under D-D than S-S, indicating that D-D milling is more sensitive to wheat hardness than S-S.

Figure 15 illustrates the effect of wheat hardness with the particle size distributions resulting from breakage of Claire, a soft wheat, and Mercia, a hard wheat, at different roll gaps and under the two dispositions. Under S-S, Claire gives a relatively straight-line distribution across the range, while Mercia gives a pronounced peak in the distribution, with increasing roll gap increasing the

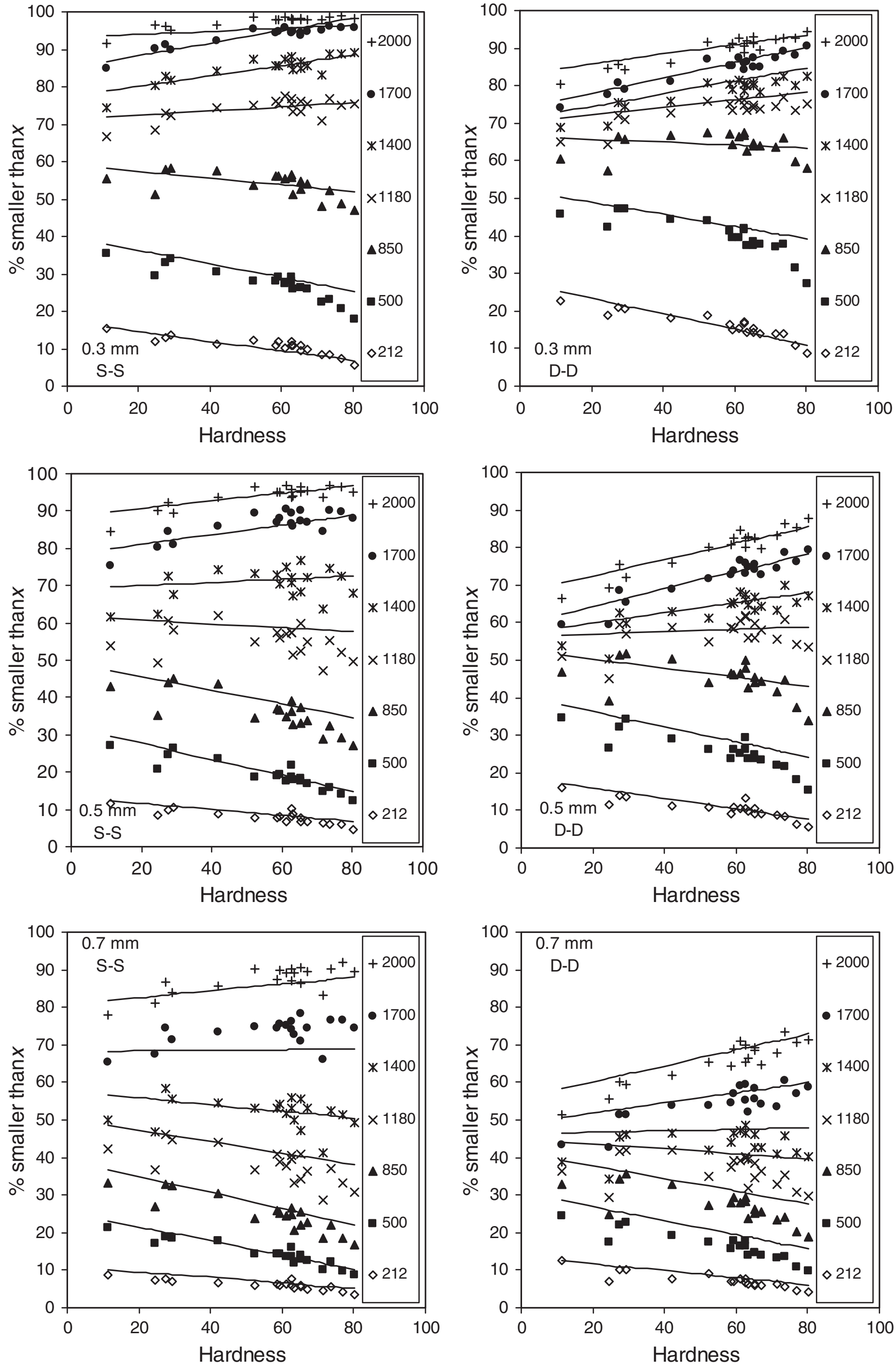

Fig. 14. Percentage smaller than *x vs.* average SKCS hardness for wheats milled under S-S (left) and D-D (right) roll dispositions, at roll gaps of 0.3, 0.5 and 0.7 mm. Adapted from [41].

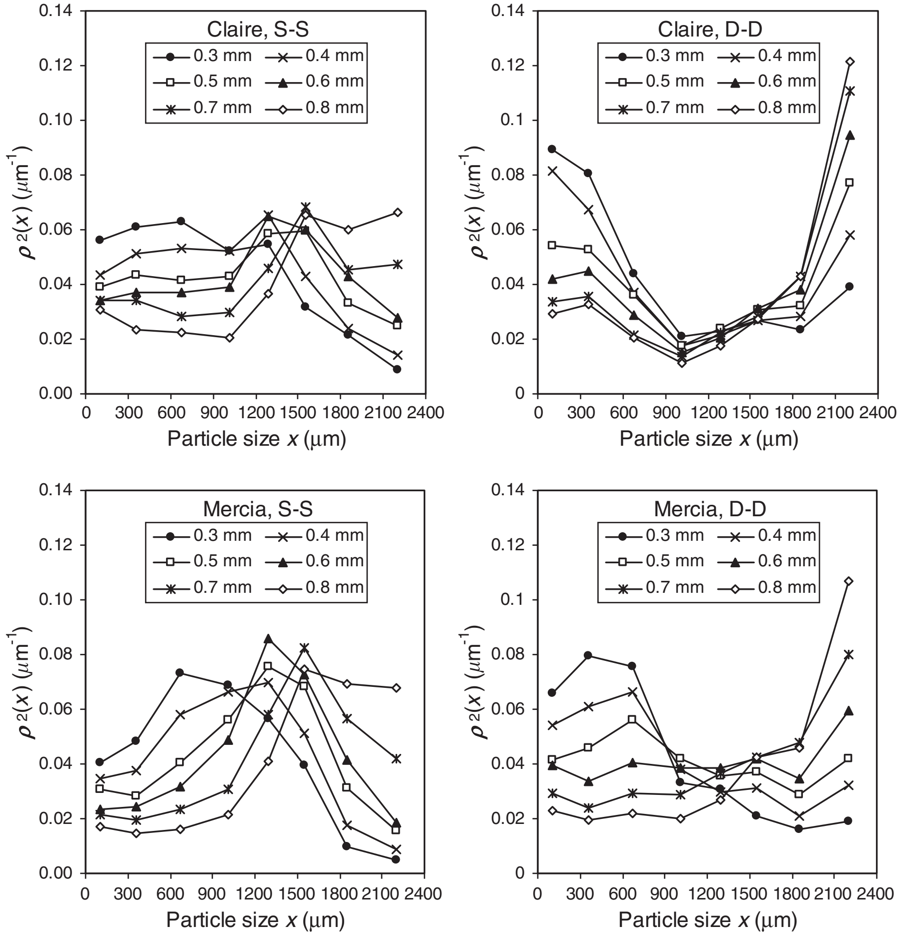

Fig. 15. Particle size distributions from Claire (a soft wheat, SKCS hardness = 24.6) and Mercia (a hard wheat, SKCS hardness = 73.6) at different roll gaps under S-S (left) and D-D (right) roll dispositions. Reprinted with permission from [41].

proportion of larger particles and moving the peak to the right. Under D-D the peak has disappeared for Mercia, while Claire has moved to a pronounced U shape with large proportions of both large and small particles and few in the mid-size range. This indicates that soft wheats tend to shatter easily into numerous small endosperm particles, while leaving the bran material relatively intact as large particles. Hard wheats, by contrast, transmit the stresses throughout the kernel, such that the endosperm resists shattering into numerous small particles and breaks together with the bran [57]. D-D milling gives more of a crushing action, which encourages shattering of the brittle endosperm but leaves the bran layers relatively intact, while the shearing action of S-S milling cuts through both the bran and the endosperm material, slicing the kernel into smaller particles but not shattering it to the same extent as D-D [78,80,81]. Thus, wheat hardness and roll disposition have similar effects, such that a soft wheat such as Claire under D-D gives a pronounced U shape, while at the other extreme, a hard wheat under S-S gives quite a peak or an inverted U.

As noted above, adding moisture also tends to favour U-shaped distributions by toughening the bran while making the endosperm more friable. In summary,

- soft wheats
- high moisture contents
- D-D milling

tend to give good fractionation of bran and endosperm into large and small particles, respectively, while

- hard wheats
- S-S milling
- low moisture contents

tend to give broken particles of more uniform size and composition. (However, despite these differences in the initial breakage patterns that would appear to favour soft wheats for clean bran separation, the bran from hard wheats is in fact easier to ''clean up'' subsequently [29,57]. Also, flour stocks from hard wheats flow and sift more easily [82], so that hard wheats are generally easier to process into flour than soft wheats.)

This work also demonstrates that SKCS hardness is meaningful in relation to breakage of wheat during roller milling. This is a surprising finding, as the breakage mechanism in the SKCS, involving a single rotor with a relatively fine sawtooth profile crushing kernels against a smooth stationary crescent with a large gap between [61], is very different from the breakage action occurring during First Break roller milling. This surprising but convenient finding means that distributions of SKCS data could be used directly to predict breakage during First Break roller milling, either off-line or as part of an automatic control system. This would aid millers in delivering consistent quality flour to bakers in the face of a constantly varying feedstock.

The breakage equation describing roller milling of wheat is a simple example of a population balance model. Future work will formulate the population balance explicitly in order to allow extension of the breakage equation to predict particle composition as well as size following First Break milling and to include the energy of breakage. The quantitative nature of the breakage equation approach could also be applied to subsequent break operations and to reduction milling. This would form a basis for developing complete flour milling simulations and for clarifying more directly the mechanistic relationships between wheat kernel characteristics and the various facets of milling performance and the baking functionality of flour.

Other workers have also studied particle breakage during roller milling of wheat kernels and of flour stocks, giving results that are generally consistent with those presented above and giving additional insights into effects on particle composition as well as size following breakage. Cleve and Will [83] investigated effects of roll gap and corrugation (flute profile) on breakage, concluding that the corrugation profile of First Break was more important than of subsequent breaks. Hsieh *et al.* [40] studied the effects of conditioning moisture, feed rate, roll gap, differential and roll speed on First Break milling of a Canadian wheat sample under a D-D disposition. First Break release (the amount of fine material produced) increased with moisture content and roll differential and decreased as roll gap was increased, while feed rate and roll speed had little effect. They also investigated the effects on the composition of the size fractions exiting First Break. This demonstrated that adding moisture not only increased the break release but also improved the purity of the released flour, by maintaining the bran more intact as large particles and avoiding production of bran powder. Increasing roll differential similarly increased break release but at the cost of greater bran contamination in the break flour due to the increased scraping of bran particles at higher differential.

Scanlon and Dexter [84] present one of the few studies on reduction roller milling of flour stocks. They examined the effects of roll speed, differential and feed rate on size reduction, energy requirements, starch damage and the degree of bran contamination in the final flour as indicated by ash levels and colour. Increasing roll velocity or differential, or decreasing feed rate, gave greater breakage and greater energy consumption. Increasing roll differential also gave greater starch damage due to the greater shear exerted on the starch granules within endosperm particles.

Pujol *et al.* [85] described a micromill designed to measure accurately the mechanical energy consumption during milling of small quantities of wheat. Specific milling energy under the conditions of their study ranged from 13.2 kJ/kg for a soft wheat to 19.6 kJ/kg for a hard wheat, and correlated well with NIR hardness. This work underlines the importance of including the energy consumption in models of wheat breakage during roller milling and relating this to the particle size distribution produced.

Yuan *et al.* [86] presented a unit operations-based analysis of the break subsystems in a pilot-scale flour mill. They highlighted the need for models of particle breakage throughout the milling process and the benefits of incorporating such models into computer simulations to aid mill control and optimisation as well as the training of millers.

Al-Mogahwi and Baker [87] investigated breakage in both break and reduction roll systems in a commercial mill and suggested some alternative approaches for characterising the particle size distribution relationships of flour stocks from these operations. Their approaches might allow simpler forms of the breakage function to be developed, as well as facilitating extension of the breakage equation approach developed here for First Break to the rest of the milling process.

Greffeuille *et al.* [29] presented a study that focussed on the fate of the aleurone layer during milling of hard and soft wheats, using biochemical markers to identify the aleurone content in flours from different stages of the mill. This study gave additional insights into how kernel hardness affects initial breakage patterns and hence the fractionation of the kernel into compositionally distinct components at different stages of the milling process.

Fistes and Tanovic [88] similarly focussed on the composition of flour particles following breakage. They demonstrated that the breakage matrix approach (the discretised form of the breakage equation) can be extended to include prediction of the compositional distribution of flour stocks as well as their size distribution.

7. PEARLING OF WHEAT PRIOR TO MILLING

Just over 100 years since the revolution that saw the rapid and comprehensive replacement of millstones with roller mills, another revolution has been proceeding quietly in the milling industry, particularly in the UK, over the last decade or so. That revolution is the introduction and rapid adoption of pearling technology within flour milling, arguably the most significant advance within wheat milling for several decades [89,90]. Pearling wheat prior to milling gives superior breadmaking performance in terms of organoleptic quality (larger loaf volume, more uniform crumb texture, extended shelf-life), nutrition (inclusion of the aleurone layer in flour), safety (removal of undesirable surface-borne contaminants) and consistency, particularly in evening out year-to-year variations and allowing greater use of UK-grown wheat [89,91,92]. All the major UK millers have invested in the new technology, such that it has very quickly come to account for the majority of UK premium flour production and has dramatically changed the entire wheat-to-bread industry.

As highlighted earlier, the anatomical difference between wheat and rice, that the former has a crease and the latter does not, has required different approaches to milling these two cereals to separate bran from endosperm. Rice can be simply pearled or polished to remove the bran, but pearling is unable to remove crease bran from wheat, which can ultimately only be removed by a more demanding process involving breaking the wheat kernel open. However (following earlier work by Tkac [93]), the Satake Corporation of Japan, the rice milling engineers who in 1991 moved into flour milling through the purchase of the UK-based Simon Robinson Group, applied their rice pearling technology to wheat to develop and commercialise the PeriTec system [14,94–96]. This system was initially intended to simplify the milling process and increase mill capacity, but the bakers quickly noticed the superior bread resulting from the flour supplied by those millers who had invested in the new technology. The demands from the baking industry for this superior flour has caused the rapid uptake in the technology across the UK and increasingly elsewhere and the development of similar systems by the other major milling engineers. The reasons for the superior performance of flour from pearled wheat have not yet been elucidated, but this revolution in the milling industry has consequences for wheat breeding programmes and agriculture (to develop and grow varieties that perform well in pearling systems), for bakery ingredient functionality (ingredients may respond or perform differently in pearled flour doughs compared with conventional flours) and for non-food uses. The change also demands a revisiting of flour milling and breadmaking processes to understand and exploit fully the benefits of the new process. This is a challenging task, as the distance between the applied change (pearling of wheat at the beginning of milling) and the observed effect (better bread) is separated by two highly complex and interacting processes.

Understanding the consequences of pearling wheat kernels starts with the effects of pearling on First Break roller milling. The different breakage patterns produced at this point determine the flows through the rest of the flour milling process and therefore the proportions, compositions and characteristics of the numerous streams making up the final composite flour. As yet unreported work from our laboratories has therefore investigated the effect of pearling on breakage of wheat kernels and has developed adjuncts to the breakage equation for roller milling of wheat to account for the effects of pearling. Figure 16 illustrates

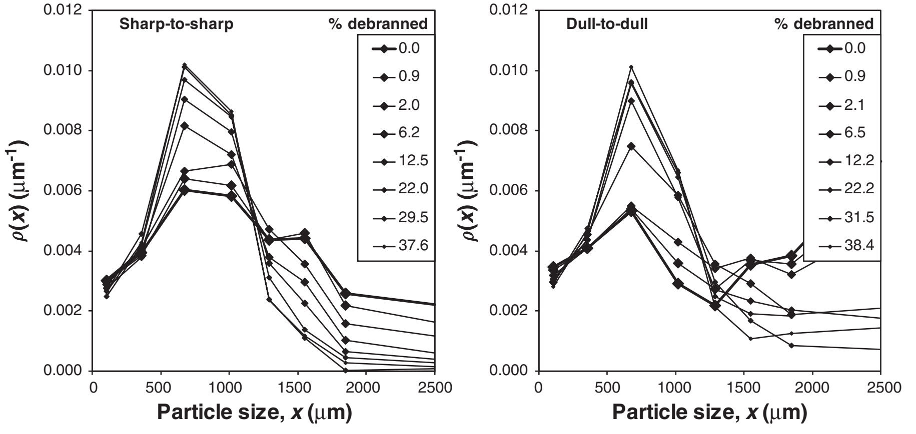

Fig. 16. Effect of the degree of pearling on the particle size distribution following milling of a hard wheat at a roll gap of 0.3 mm under S-S and D-D roll dispositions.

the effect of pearling a hard wheat to different extents on the subsequent particle size distribution following milling at a roll gap of 0.3 mm under both S-S and D-D dispositions. Clearly, the pearling reduces the proportion of particles at the larger end of the size range (as pearling removes bran material, and it is bran than forms the larger particles following breakage), boosts the proportion in the 500–1000 μm range and has little effect on the proportion of small particles. A cumulative pearling function, $c(x,G,z)$ of the form

$$c(x, G, z) = Az^3 + K_1Az^2 + K_2Az \tag{10}$$

where z is the degree of pearling and

$$A = (e_4G + f_4)x^4 + (e_3G + f_3)x^3 + (e_2G + f_2)x^2 + (e_1G + f_1)x \tag{11}$$

was developed for both a hard and a soft wheat under both S-S and D-D milling. This allows the effect of pearling to different degrees on subsequent milling to be predicted, relative to breakage without pearling as predicted by the equations developed above. This also allows the effects of pearling on the subsequent evolution of flour quality through the mill to begin to be understood.

As with the successful introduction of roller mills a century before, the principal driver for the current rapid uptake of pearling technology in flour milling is the superior bread that results. Once again this will have implications right back through the supply chain as breeders and farmers develop and grow new varieties specifically suited to the new process. Already it is giving a new impetus to understand the interactions within and between the flour milling and bread-making processes that give rise to bread quality, in order to maximise the benefits of the new technology. Pearling is also being successfully applied to durum wheat, where it gives superior pasta [14,90], as well as to other cereals including barley and oats [55,97].

The successful application of pearling also has implications for non-food uses of cereals as a renewable and sustainable alternative to oil. As with oil, economic processing of cereals for non-food products involves precise fractionation followed by conversion. In contrast with oil, cereal fractionation is undertaken on an initially solid raw material. Particle breakage is therefore a key issue, for which pearling offers an additional means of generating precise and selective separations of the kernel components. Bioconversion and extraction are then key technologies for maximising the value that can be derived from the fractions. A cereal biorefinery, analogous to an oil refinery, will fractionate, extract and convert cereal components to produce a varying portfolio of added value products, in response to the variable feed characteristics and the changing market opportunities. Using the empirical expertise and mathematical models developed for flour milling, the cereal fractionation technologies of pearling and roller milling are poised to play a key role in bringing about sustainable chemical and energy industries in the coming century.

8. CONCLUSIONS

Breakage of wheat kernels during roller milling has been modelled in terms of the distribution of kernel characteristics (hardness, size, moisture) and roller mill operation (roll gap, disposition). A correction function to account for the effects of pearling kernels prior to breakage has been demonstrated. The breakage equation for roller milling of wheat allows the effects of a constantly changing feedstock to be predicted and controlled. It also illustrates how multiple feed particle characteristics can be included in breakage equations.

International interactions and innovations at the end of the 19th century triggered a revolution that swept away crude millstones for the more precise and versatile roller mills. With the introduction of pearling technology, the ancient distinctions between wheat and rice milling have come together to create a new revolution for the 21st century. Once again this milling revolution is being driven by improved bread quality, but this time with opportune prospects for contributing to the urgent need for sustainable chemical and energy industries in an oil-depleted world.

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Nomenclature

a_n–d_n	coefficients in the breakage function
a_{nn}–d_{nn}	coefficients in the extended breakage function
A	coefficient in the cumulative pearling function
$B(x,D)$	cumulative breakage function describing the proportion of material smaller than size x in the output, originating from an input particle initially of size D
$B(x,D,H)$	extended cumulative breakage function describing the proportion of material smaller than size x in the output, originating from an input particle initially of size D and hardness H

$B(x,D,m)$	extended cumulative breakage function describing the proportion of material smaller than size x in the output, originating from an input particle initially of size D and moisture content m
$c(x,G,z)$	pearling function, describing the change in breakage patterns of pearled wheat kernels relative to unpearled kernels
D	size of input particle, SKCS diameter (mm)
D-D	dull-to-dull roll disposition
D-S	dull-to-sharp roll disposition
e_1–e_4, f_1–f_4	coefficients in the cumulative pearling function
G	roll gap (mm)
H	SKCS kernel hardness
$K(x,m-m_0)$	correction term to account for the variation in breakage that occurs at moisture contents other than a nominal moisture content m_0
K_1, K_2	coefficients in the cumulative pearling function
m	moisture content (%)
$m_{\max}$	maximum moisture content in the feed kernels (%)
n	an integer taking values of 0, 1 or 2
N	number of discrete size fractions into which kernels are separated for the purpose of calculating average values
p_i	proportion of kernels in size fraction i
$P_2(x)$	cumulative particle size distribution of the output
S-D	sharp-to-dull roll disposition
S-S	sharp-to-sharp roll disposition
x	size of output particle (μm)
z	percentage of kernel material removed by pearling (%)

Greek symbols

$\rho_1(D)$	particle size distribution of the feed (mm^{-1})
$\rho_1(H)$	hardness distribution of kernels in the feed
$\rho_1(m)$	moisture distribution of kernels in the feed
$\rho_2(x)$	particle size distribution of the output (μm^{-1})

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