How Wheat Breaks

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> *"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 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."*
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> Storck and Teague, *Flour for Man's Bread* (1952, p5)

> *"When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be."*
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> William Thompson, Lord Kelvin (1889)

This year I have been a chemical engineering academic for 30 years, about 15 of which were spent applying chemical engineering approaches to study wheat breakage. I recently took over teaching particle technology in my university's chemical engineering programme, giving me a nostalgic opportunity to reconnect with my earlier research on wheat flour milling. A wheat field and windmill grace the cover of my module booklet, and my students are (I suspect) the only chemical engineering students in the world who are told that "the wheat kernel is the world's most important particle", in terms of influence on civilisation, international relations and science and technology. Much of what we know about particle technology we have learned from milling of wheat into flour.

Modern flour milling starts with the initial breakage of the wheat kernels in what is called First Break, using counter-rotating fluted rollers to open up the wheat kernel. Roller milling breaks open the wheat kernel in such a way that the outer layer of bran tends to stay in large particles and the floury endosperm tends to break into small particles, so that flour and bran can be separated by size using sifting. Moisture content affects bran and endosperm breakage – optimally tempered wheat toughens the bran so that it stays as large particles, while softening the endosperm so that it breaks into smaller particles, facilitating the separation of bran from endosperm.

Figure 1 illustrates the production of large bran particles (still with floury endosperm adhering) and smaller endosperm particles, and the factors that influence the distribution of particle sizes – the properties of the wheat kernels (size, shape, hardness and moisture) and the design and operation of the mill. Through repeated milling and sifting, high yields of relatively pure flour are obtained in a dry (and therefore cheap) process.

The distribution of particle sizes produced by this initial breakage of the wheat affects the flows throughout the rest of the mill, and hence the yield and quality of flour. First Break is therefore a critical control point in the mill. Ideally if the particle size distribution from First Break were kept constant, the flows to the rest of the mill would be constant and the mill would run smoothly. The problem is, the wheat entering the mill is constantly changing. There is a need, therefore, to understand how wheat properties and mill operation affect the particle size distribution coming out of First Break.

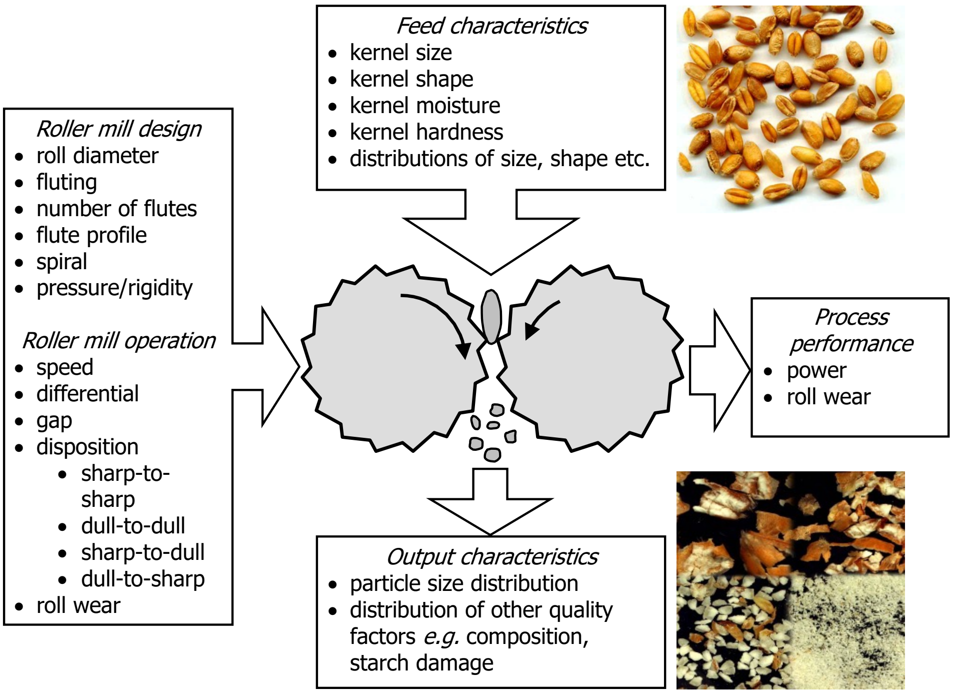


Figure 1. Factors affecting wheat kernel breakage during First Break roller milling.

Modelling wheat breakage

What lights my fire in research is combining mathematical modelling with elegant experiments to reveal insights that could not be achieved any other way. I apologise for bringing an equation into this article (Steven Hawking in *A Brief History of Time* recalls how he was warned that for every equation he included, the book's readership would be halved – hence he only included $E = mc^2$!). It is not necessary to understand the following equation, but it is helpful to be aware that the basis of my wheat milling research was a breakage equation I developed that relates the size distribution of the output particles, described by a function $\rho_2(x)$, to the size distribution of the wheat kernels, described by a function $\rho_1(D)$, via a breakage function $\rho(x, D)$:

$$\rho_2(x) = \int_{D=0}^{\infty} \rho(x, D)\, \rho_1(D) dD$$

My work extended this equation to include effects of wheat kernel hardness, moisture and shape as well as roll gap and disposition. (The flutes on rolls are asymmetrical, with a sharp and a dull edge, and the rolls rotate at different speeds. This allows milling to be undertaken under different dispositions – a sharp edge of the fast roll can "meet" a sharp edge on the slow roll, to give Sharp-to-Sharp milling, and so on for Sharp-to-Dull, Dull-to-Sharp and Dull-to-Dull, giving different breakage patterns.)

In a further extension, my students and I developed ways of predicting not just the size distribution of outlet particles from First Break, but also their composition (recalling that the point of roller milling is that large particles have more bran and small particles have more endosperm). At that point the maths and experimental work became very complicated!

The value of the work wasn't simply in allowing the size distribution of broken stocks to be predicted from input kernel properties and roll gap and disposition, it was in giving insights into how wheat kernels breaks, and allowing these insights to be quantified (hence the opening quotation from Lord Kelvin). In particular, the work identified two types of breakage, called (unimaginatively) Type 1 and Type 2.

Two types of breakage

Figure 2 illustrates a typical particle size distribution resulting from First Break milling of a soft wheat. The overall distribution (shown in the black line) shows a large quantity of small particles on the left, tailing off to a small quantity of very large particles on the right, and with a "hump" of middle size particles in the mid-range. This overall distribution can be described as made up of two underlying distributions. Type 2 (in red) is a wide, smooth curve that describes (perhaps surprisingly – we'll come back to this) both the production of the very large particles and the very small particles. Type 1, meanwhile, is a narrow peak that describes the mid-sized particles (blue).

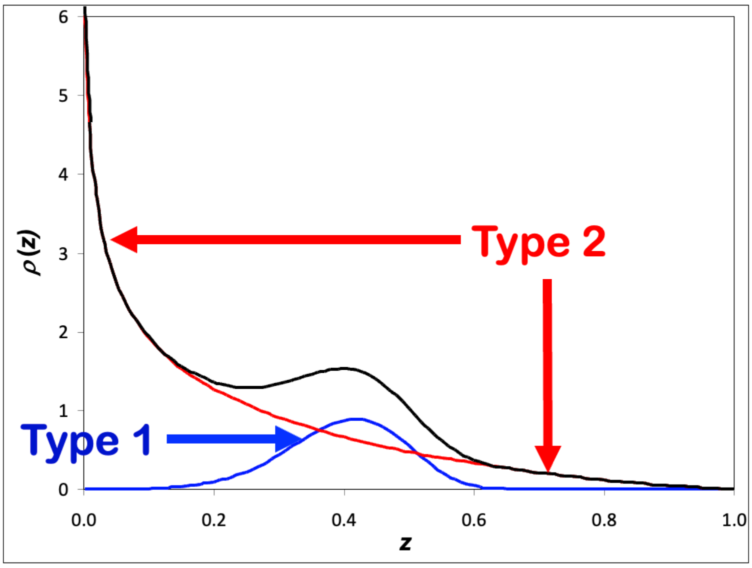


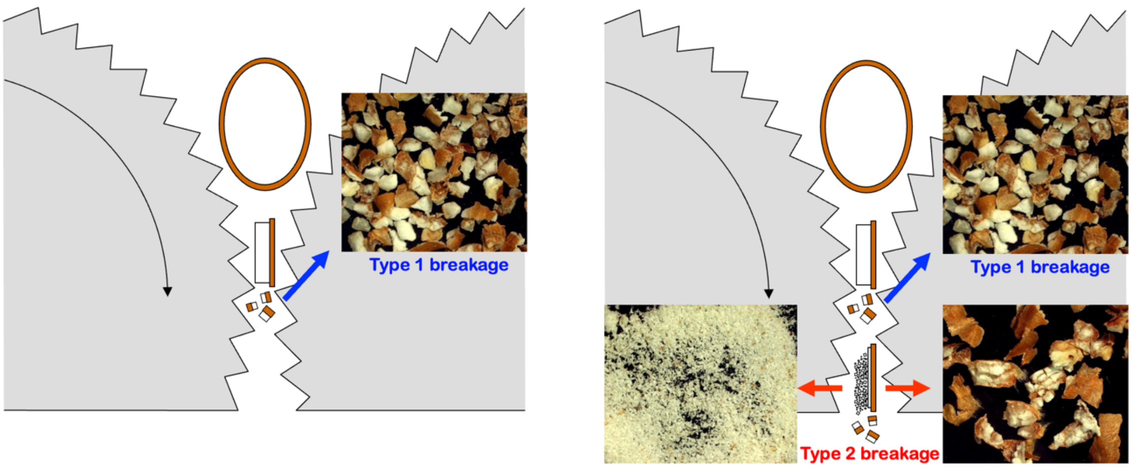
Figure 2. A typical distribution of particle sizes following First Break milling of wheat, showing two types of particles: Type 1 mid-sized particles, and Type 2 particles which cover both the very large bran particles and the very small endosperm particles. (The parameter *z* is a normalised particle size.)

The word "reification" (from the Latin "res" = "thing" and "facere" = "to make") means the act of treating an abstract concept as if it were a tangible, concrete thing; it is a "fallacy of ambiguity", when an abstraction is treated as if it were a physical reality. In my work the breakage patterns can be described by these two mathematical functions. That in itself does not mean that the mathematical functions relate to physical realities – they could just be a convenient description of the experimental data. However, there is evidence that the forms of these two functions do in fact relate to, and give insights about, two different breakage phenomena happening during milling.

Figure 3 shows a (simplified) picture of how the experimental data and modelling suggest wheat breaks during roller milling. The wheat kernel has a protective layer of bran. As it starts to enter the gap between the rolls, the kernel is broken open to create large bran particles with endosperm adhering, with some smaller particles also being produced (Figure 3(a)). These smaller particles continue through the narrowest part of the gap without breaking further, and emerge as mid-size particles comprising broken pieces of endosperm and bran – these are Type 1 particles.

Meanwhile, the large bran particles tend to align with the gap as they pass through the narrowest point (called the “nip”), where they are held by the slow roll and “scraped” by the flutes of the fast roll. This causes very small endosperm particles to be scraped from the large bran particles (Figure 3(b)). This explains the surprising observation that Type 2 particles can be described by a single function that covers both the large bran and very small endosperm particles, because the two types of particles arise from the same breakage mechanism – the small endosperm particles are created through the scraping mechanism from the large bran particles. Breakage that gives more large bran particles will therefore also give more small endosperm particles, and fewer in the mid-size range.

(Strictly speaking, Type 1 breakage and Type 1 particles (and Type 2 breakage and particles) are speaking about two different things – “breakage” refers to the mechanism, “particles” to the results. However, for ease of communication, I am using the two terms interchangeably, as a greater proportion of Type 1 particles implies more Type 1 breakage.)

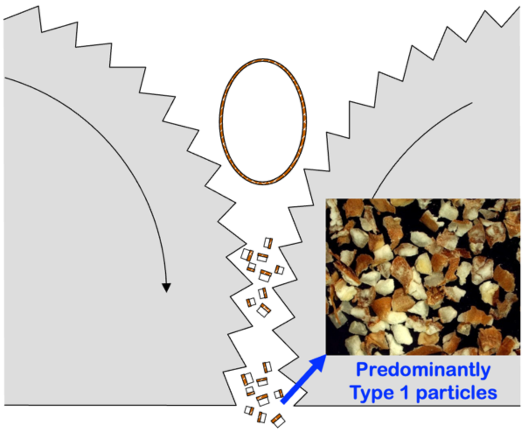


(a) Initial opening of the wheat kernel to create large bran particles and smaller Type 1 particles.

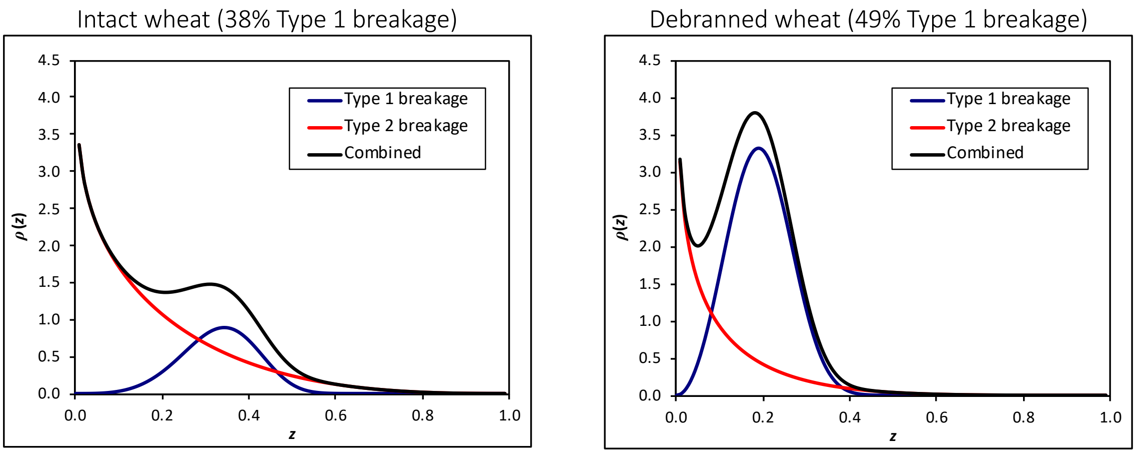
(b) Scraping of the large bran particles to produce very small endosperm particles (Type 2 breakage).

Figure 3. Mechanisms of wheat breakage during First Break roller milling.

Evidence for this picture of how wheat breaks arises from milling debranned wheat kernels – kernels that have had some of the bran polished off before roller milling. Figure 4(a) illustrates how debranning disrupts the integrity of the bran, so that on initial breakage, no (or few) large bran particles are produced. There can therefore be no (or little) scraping of these bran particles to produce small endosperm particles. Hence, few Type 2 particles are created, and the output consists predominantly of the mid-range Type 1 particles. Figure 4(b) shows how debranning results in a much greater proportion of Type 1 particles (as well as moving the entire particle size distribution to the left, *i.e.* towards smaller particles).



(a) Debranning of wheat before roller milling disrupts the bran layer, preventing production of large bran particles, and precluding scraping of small endosperm particles from the bran. Hence Type 2 breakage is compromised and Type 1 breakage predominates.



(b) Type 1 and Type 2 breakage of intact wheat (left) and of wheat debranned for 60 seconds (right).

Figure 4. Effect of debranning on production of Type 1 and Type 2 particles.

Figure 5 illustrates the effects of kernel hardness and roll disposition on the proportions of Type 1 and Type 2 breakage. Hard wheats and Sharp-to-Sharp milling tend to give more production of Type 1 particles, while soft wheats and Dull-to-Dull milling favour the Type 2 breakage mechanism, producing large bran particles from which small endosperm particles are effectively scraped.

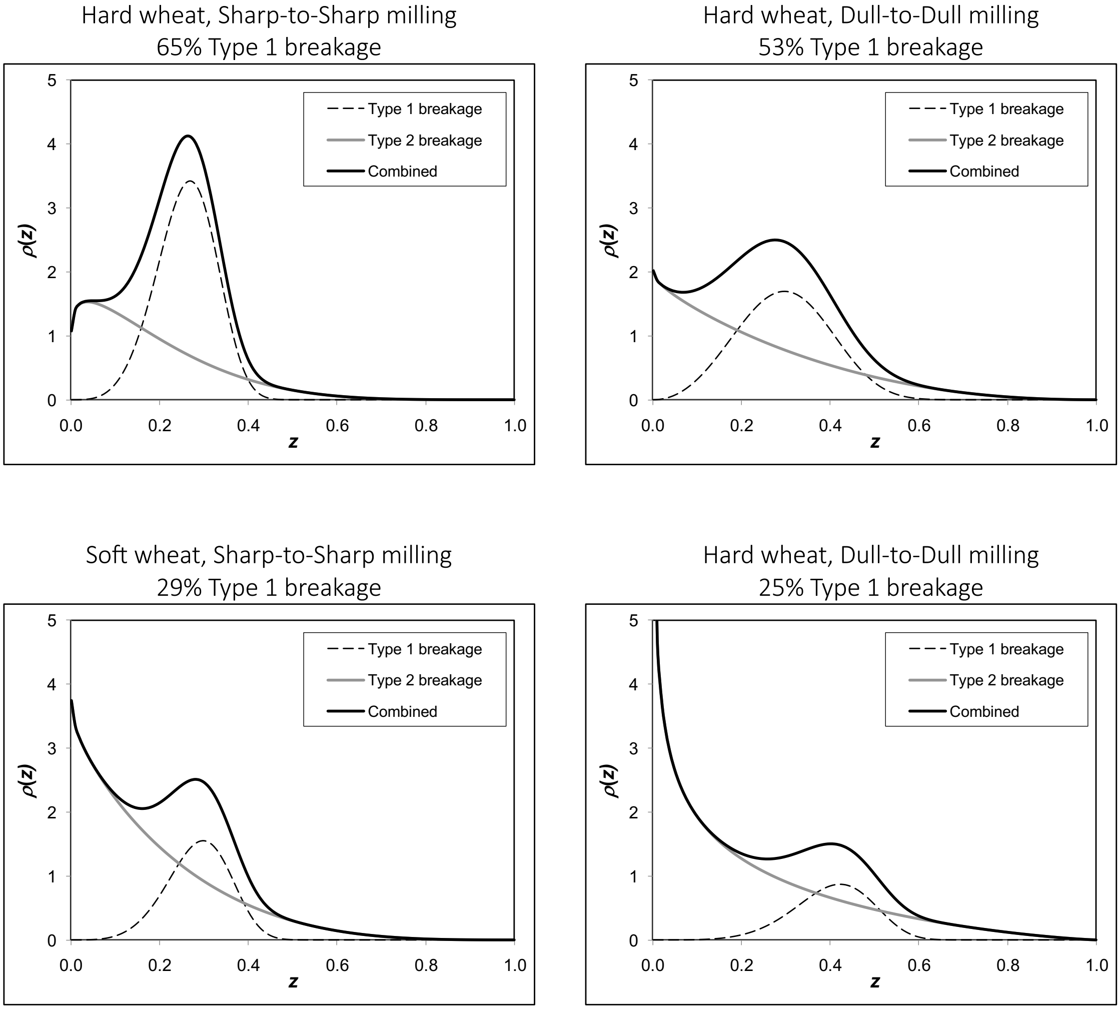


Figure 5. Hard wheats and Sharp-to-Sharp milling favour production of Type 1 particles, while Soft wheats and Dull-to-Dull milling favour Type 2 breakage.

A quantitative science of wheat milling

Our further work on the composition of the different sizes of particles hinted at some further subtleties. Bran is made up of several botanical layers (Pericarp, Intermediate layer and Aleurone being the main three). Our work suggested that in hard wheat, these layers break together, such that the bran component of particles have similar proportions of the three layers. In soft wheat, the layers are more likely to delaminate, such that particles of different sizes have different proportions of these bran components, suggesting different breakage patterns for the bran of soft wheat compared with hard wheat. (The compositional work also identified very fine bran dust – bran breaks to give large particles, but inevitably some of the bran shatters into dust that collects with the finest endosperm flour.) Understanding these subtleties would give a firmer basis for breeding, growing and milling wheats with greater depth of insight and effectiveness of practice.

Milling of wheat into flour is one of the cornerstones of civilisation and of modern society. An accurate understanding of how wheat breaks, in terms of meaningful mental pictures and the ability to model and quantify effects, is therefore central to an effective science of wheat milling that can continue to underpin the health, security and affordability of the global food supply chain.

The picture of wheat breakage presented here is the result of modelling and experimental work described in the following publications (with grateful acknowledgement to numerous co-authors and to the Satake Corporation of Japan who generously supported this research):

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